A Century of

INNOVATION

National Energy Technology Laboratory

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

By Sherie Mershon and Tim Palucka

U.S. DEPARTMENT OF ENERGY

Table of Contents

Foreword –
A Century of Innovation

I am pleased to present this rich and detailed history of the National Energy Technology Laboratory (NETL) on the 100th anniversary of the founding of its original predecessor organization, the United States Bureau of Mines.

This comprehensive account chronicles NETL's organizational history since 1910. To understand our history is to truly understand our organization, and, throughout this journey, *A Century of Innovation* is an invaluable guide to NETL's mission, vision, priorities, and structure.

Our founding organization, the Bureau of Mines, was often a leader in technological advancements that benefitted American industries and consumers. Commencing as a small agency dedicated to making coal mining safer, it developed into a nationwide network of experiment stations supporting petroleum and natural gas production, mining and refining of rare metals, and the conversion of coal into gas and liquid fuels. From energy conservation efforts in the Great Depression, through urgent World War II research into aviation fuels, explosives, and nuclear materials, to its more familiar focus on developing new technologies to secure the Nation's energy future, NETL's path has had many pioneering twists and turns.

NETL's efforts and accomplishments have been impressive in their breadth and scope, and our history encompasses a wide range of programs and activities. However, one constant over the years has been the tremendous dedication of the people who have made this organization what it is today. As this book attests, each time a new problem or challenge presented itself, NETL's managers, researchers, and engineers were ready to roll up their sleeves and find a solution. The universal commitment of NETL's people to a cause greater than themselves has been the hallmark of this organization.

Anthony V. Cugini

In 2010, many aspects of NETL would be unrecognizable to its predecessors. But our reputation for innovation has remained consistent. Beginning with the creation of the Pittsburgh Experiment Station in 1910, our evolution has paralleled the transformation of the U.S. energy economy from a system almost entirely dependent on fossil fuels to the current mix of fossil energy, hydropower, nuclear energy, and renewable resources. Our work reflects this mix, as our scientists, engineers, and analysts advance not only coal- and natural gas-based power systems, but also vehicle technologies, fuel cells, hydrogen turbines, water conservation technologies, and the potential of methane hydrates and fossil-biomass blends as new energy feedstocks.

Our research activities continue to help assert America's leadership in solving the world's energy and environmental issues. Building on nearly a century of Federal energy research, we are developing and deploying modern technologies, creating jobs, and preparing our Nation's next generation of scientists and engineers.

I am proud to be part of the important work carried out by NETL and to be able to work alongside such exceptional colleagues. Within this history, I see our dedication mirrored in the people from NETL's past who helped make us what we are today. I am truly honored to be carrying on this legacy at such an exciting time in the organization's history.

Anthony V. Cugini, Director

National Energy Technology Laboratory

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

Chapter One: Pittsburgh, the Center for Coal

Chapter One:

Pittsburgh—the Center for Coal

"There was a dull rumble far down in the bowels of the earth. Flames burst from the drift and spurted from the airshaft. The fanhouse went down with a crash. Dense volumes of black smoke poured into the open and the heavens were ablaze. It was terrifying to the laymen. The Government's effort had apparently been successful."

--New York Times, *October 31, 1911*

On October 30, 1911, Joseph Austin Holmes blew up a coal mine just to make a point.

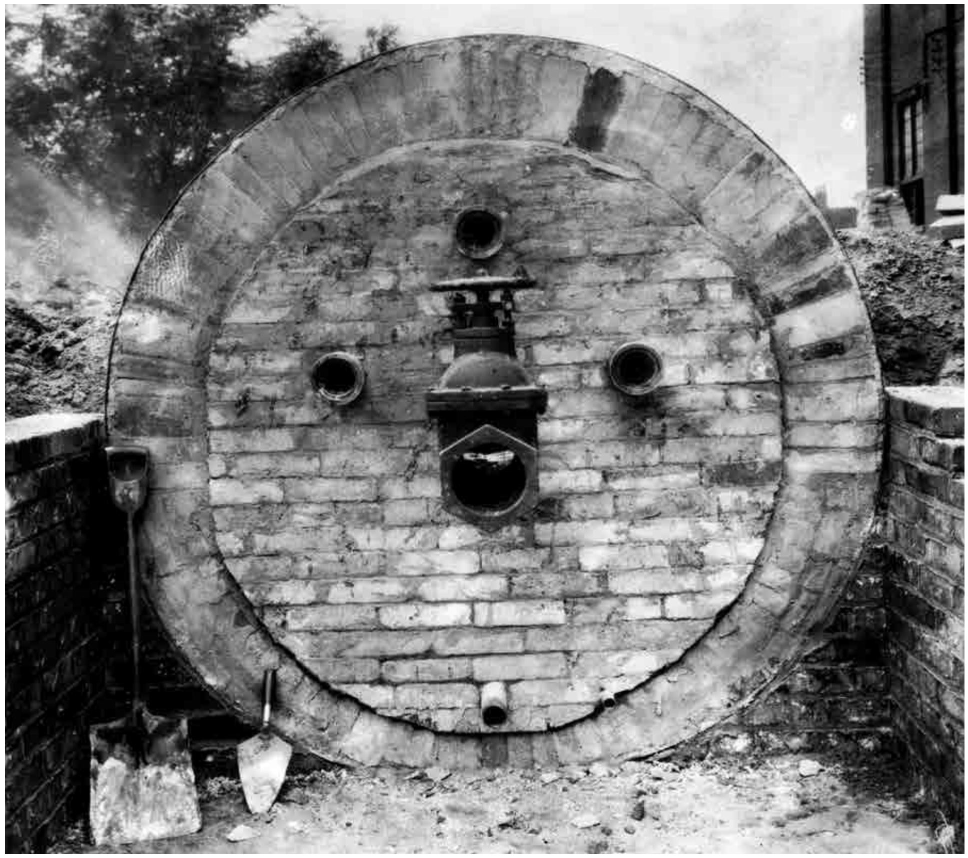
Holmes was no anarchist, but the respected Director of the fledgling United States Bureau of Mines, and the point he was trying to make was a scientific one. He had invited more than 1,500 coal operators, miners, and reporters from all over the world to witness his "well-planned explosion."

Mine workers and operators in front of the Bruceton Experimental Mine, October 30, 1911.

The mine of choice was the Bruceton Experimental Mine located 13 miles south of Pittsburgh, Pennsylvania, on 38 acres of land that the Bureau had leased from the Pittsburgh Coal Company in 1910. It had been constructed precisely for this type of experiment. Three horizontal shafts as long as 750 feet had been dug into a coal seam, along with several rooms for conducting tests. Earlier on that cold, rainy day the group had toured the Bureau's Pittsburgh Explosives Station at the Allegheny Arsenal, located at Fortieth and Butler streets in the Lawrenceville section of Pittsburgh. For the technical portion of the program, researchers performed experiments on fuels and demonstrated an explosion in a 100-foot concrete shaft set up to simulate a coal mine. But simulations left many unconvinced that the same results would be obtained in a real coal mine. Holmes was determined to end all skepticism with his experiment at Bruceton.

Following the activities at the Arsenal, a special Baltimore and Ohio Railroad passenger train left Pittsburgh at 2:00 PM for the Bureau's Experimental Mine. At 2:30, a driving rain greeted the group of about 1,500 riders in Bruceton, who

Entrance to the mine fire gallery at the Arsenal Station.



External view of mine fire gallery at the Arsenal Station.

got off the train and hiked the half-mile to the test site. About 1,200 spectators toured the mine shaft, inspecting the coal dust distribution and the position of the detonation shots. Holmes and a few of his men had been working for hours to make sure the conditions were perfect. The shots were positioned at the back of the mine, 725 feet from the entrance. Four shots were used: three were lodged in the coal seam and one was placed on the floor in front of the working face. A total of nine-and-one-quarter pounds of black powder were distributed among the four shots, and 852 pounds of coal dust was spread on shelves in both the main and diagonal courses.

A partially loaded mine car, positioned 40 feet from the mouth of the mine, was thrown over a fully loaded car twenty-five feet away. After hitting the ground and tumbling four times, it came to rest 229 feet from its starting point.

After the mine tour, the crowd gathered in a clearing a safe distance from the entrance. The crowd consisted of government bureaucrats, elected officials, explosives experts, journalists, coal producers, and miners from thirty U.S. states, as well as Mexico, France, and other countries.

The detonation apparatus was housed in a reinforced concrete observatory with a two-foot-thick wall on the side facing the mine and a roof constructed of railroad rails covered in concrete. To prevent accidental detonation, engineers had installed a set of redundant locking switch boxes: one at the mouth of the mine and another in the observatory station. Explosions could not be triggered unless both switches were closed by a key, both of which were held by the engineer in charge of the mine, who was responsible for making certain that all personnel were clear before the detonation button in the observatory was depressed.

At 3:45 PM, warning sirens sounded and three gun shots rang out, signaling that the moment had arrived. A chemist in the observatory pushed the firing button. Nothing happened. An inspection revealed that the foot traffic during the mine inspection had disrupted the detonation wires. When this problem was corrected, the chemist pushed the button a second time. Again silence. When another inspection of the wiring showed no evidence of a short, Holmes had a new firing wire run directly from the observatory to the shot.

Mine explosions could happen by the ignition of coal dust alone, with no methane present.

Finally, at about 5:45, just after sunset, Holmes pushed the detonation button himself. A deafening boom accompanied by flames estimated to be 500 feet in length and 200 to 300 feet high suddenly burst from the mine's three openings. A partially loaded mine car, positioned 40 feet from the mouth, was thrown over a fully loaded car twenty-five feet away. After hitting the ground and tumbling four times, it came to rest 229 feet from its starting point. The loaded car, burdened with two tons of coal and with its brakes engaged, was driven 70 feet before it derailed. Support timbers flew through the air like cannon fire. Wooden posts 6-inches in diameter and 6-feet long flew across the ravine as far as 413 feet from the entrance of the mine. A tree positioned 153 feet from the main entrance caught fire 46 feet above the mine's mouth. As the crowd cheered in astonishment, mine rescue workers began to flock toward the mine to test their skills.

Holmes, covered in mud from the day's work, emerged from the observatory to talk to the reporters and the miners gathered around. "No amount of writing or talking," he said, "could be so forcible in the teaching of great lessons."

The lesson taught that day was this: Mine explosions could happen by the ignition of coal dust alone, with no methane (also known as "firedamp") present. A debate had long raged in the coal industry about whether only "gassy" mines containing methane were in danger of exploding, or whether "non-gassy" mines with significant amounts of coal dust in the air were also susceptible. Like Holmes, many believed that the dust alone was enough if it was exposed to a flame or spark of sufficient energy for a suitable duration. But the opposition argued that without methane in the air no amount of coal dust could cause an explosion. By carefully controlling the experiment so that the miners could see clearly that no methane was in the experimental mine, Holmes settled the debate forever, which he summed up in a statement that night:

> *The great value of this experiment to the mining industry was in demonstrating…the fact:*
>
> *That ordinary bituminous, or soft, coal dust will explode from a charge of black powder badly placed in a mine;*
>
> *That dust will explode with a violence sufficient to wreck the mine and kill every person working in the mine; and*
>
> *That poisonous gases are given off from such an explosion in sufficient quantities to suffocate and poison any person in the mine who may have escaped the violence of the explosion.*

The Experimental Mine at Bruceton would be used for many other mining experiments over the next eight decades, but perhaps never one so important.

The Founding of the Bureau of Mines

This moment of vindication was a long time coming for Holmes. Since serving as the Director of the Department of Mines and Metallurgy at the Louisiana Purchase Exposition at the St. Louis World's Fair in 1904, where his main duty was to perform experiments and give demonstrations on the properties of metal ores and carbon fuels such as coal, he had become acutely aware of the increasing number of mining accidents and deaths each year. He knew that a lot of the carnage was due to the lack of regulations for operating coal mines in the United States, and to the lack of scientific understanding of what caused mine explosions.

Although some countries in Europe had national mining regulation in place by 1839, similar safety legislation was not enacted in the United States until 1869, when Pennsylvania passed the nation's first miner protection bill. Not surprisingly, perhaps, the legislation came after a mine explosion in September of that year near Wilkes-Barre, Pennsylvania, in which 179 miners died in a fire in what was thought to be a "safe mine." While other states soon followed Pennsylvania's lead, the federal government took no immediate action. It wasn't until 1891 that Congress finally addressed mine safety, albeit tentatively, by granting the Department of the Interior (DOI) authority to regulate mining activity in the federal *territories* (this distinction meant that federal regulation did not apply to the states already in the Union). In 1896, the American Mining Congress, a trade organization representing mining interests, proposed the establishment of a federal bureau of mines, followed by a similar call from the United States Geological Survey (USGS) in 1899. Both were ignored.

In 1902, Congress authorized the DOI to establish and administer a reclamation program within the USGS in order to facilitate the growth of the American West. Mine inspection responsibilities for the federal territories were assigned to the newly established Reclamation Service. This was the first step in the eventual transition of mining oversight to the USGS.

Holmes found a much more regulated industry in Europe...Instead of black powder, coal miners were required to use certain "permissible explosives," which burned cooler and for a shorter time.

As annual U.S. coal production rose from 270 million tons in 1900 to 480 million tons in1907, coal mining fatalities also rose, climbing from 1,489 to 3,242. In response to this relentless increase in fatalities, on June 10, 1907, the Secretary of the Interior transferred responsibility for coal mine safety in the federal territories from the Reclamation Service to the Technological Branch of the USGS, which just happened to be headed by Joseph Austin Holmes. When the 1904 St. Louis World's Fair closed, he had stayed on there as chief of the USGS laboratories for testing fuels and structural materials.

Tragically, December 1907 would prove to be the worst month in history for coal mine disasters in the United States. Between the first and the nineteenth days of "Bloody December," as it came to be called, 692 miners died in four mine explosions in Pennsylvania, West Virginia, and Alabama. The explosion at Monongah, West Virginia, left 362 men dead, making it the worst coal mine disaster in U.S. history. In response, in 1908 Congress designated funds (but still no regulatory power) for the USGS Technological Branch to investigate mine explosions. Holmes moved to Pittsburgh in 1908 when the USGS established laboratories for mining research at the Pittsburgh Arsenal in the Lawrenceville section of the city.

Holmes was well prepared for this new responsibility. He had spent a lifetime in various forms of investigation, from botany to geology to fuels. He was used to relying on physical data and statistics to prove his points. Some observers had tried to pass off the increasing mine fatalities as the expected cost of doing business. The increase in casualties, they said, was merely proportional to the ever-increasing coal market: more men digging more coal in more mines meant more accidents. But Holmes knew better, and he unearthed the numbers to back his arguments, which he revealed in a report detailing statistics on worldwide mining accidents. Calculations showed that, in 1906, 3.40 men out of 1,000 employed in mines in the United States were killed in accidents in the United States. This ratio represented a significant increase over the 2.67 deaths per thousand recorded in 1895, just 11 years earlier. In what Holmes described as "the deeper and more dangerous mines" of Belgium, only 0.94 per thousand were killed in 1906, and the numbers had decreased from a high of 1.40 per thousand in

1895. Belgium had experimental stations to test mining techniques, and mining regulations based on these findings to protect miners. The United States did not.

Holmes traveled to Europe to consult with mining experts there, and found a much more regulated industry. Instead of black powder, coal miners were required to use certain "permissible explosives," which burned cooler and for a shorter time. They were allowed to use only a prescribed amount, and not more. In the United States, miners frequently and cavalierly used excess powder to cause more of the coal face to crumble, increasing their yield of coal per day. Given their low wages and the fact that they were paid by the ton, it was easy to understand why miners took this approach. But the consequences could be deadly. Under the right conditions, if too much energy from the blast made it out from the coal face into the room, an explosion could occur. Even without an unexpected explosion, an unnecessarily large coal-face blast could weaken the mine roof and cause a deadly collapse in the future.

Congress passed the Organic Act in 1910, authorizing the creation of the U.S. Bureau of Mines to "increase health safety, economy, and efficiency in the mining, quarrying, metallurgical, and miscellaneous mineral industries of the country."

Holmes brought the lessons of Europe back to the United States—with a distinct twist of his own. The Europeans conducted experimental explosions in artificial tunnels or "galleries." But according to George S. Rice, who would become the chief mining engineer at the Bureau of Mines, Holmes "was impressed that coal dust explosion testing should be conducted in an actual mine …in order to obtain the proper surrounding conditions." Rice further described Holmes's pursuit of his testing concept:

> *Mine experiment station investigators in some of the European countries, to whom he presented the idea, tried to discourage him on the ground of its being impracticable. Nevertheless, he was not discouraged, and later decided favorably on the establishment of the Experimental mine, that unique mine near Bruceton, Pa., where explosion tests are conducted under conditions which duplicate those which cause great loss of life in commercial coal mines, and which are followed by tests of preventive devices and methods. The results have not only been spectacular, but extremely fruitful so that the work has begun to be recognized as authoritative to a degree that no gallery testing could ever be.*

Holmes's role as head of the USGS Technological Branch also gave him a first-hand view of the tremendous waste of mineral resources in both state and territorial mines. In response to this state of affairs, he formed an alliance with two mining industry leaders: United Mine Workers President John L. Lewis and American Mining Congress Executive Secretary James F. Callbreath. Convinced that the practical problems of miner safety and natural resource conservation were beyond the purview of an agency whose primary concern was the administration of federal land use policy, Holmes and his newfound colleagues eventually prevailed upon Congress and the recently elected president, William Howard Taft, to create an agency dedicated to the establishment of mineral conservation policies and uniform standards of safety practices for mines throughout the nation.

However, it took another steady stream of mine catastrophes to provoke Congressional action. One accident, in November 1908 at a mine in Marianna, Pennsylvania, killed 154. Another took the lives of 259 miners in Cherry, Illinois, in November 1909. Finally, on May 16, 1910, Congress passed the Organic Act, authorizing the creation of the U.S. Bureau of Mines as a branch of the Interior Department. The act stated that "the general aim and purpose of the inquiries and investigations made by the bureau under the terms of the organic act are to increase health safety, economy, and efficiency in the mining, quarrying, metallurgical, and miscellaneous mineral industries of the country."

When it took effect on July 1, 1910, the Organic Act prescribed the duties of the bureau as largely advisory in nature, authorizing such activities as investigating mining methods in relation to miner safety; evaluating mining appliances for accident prevention; assessing methods to improve working conditions, beneficiating ores; using explosives and electricity safely; and, most significantly, reporting the Bureau's work and making recommendations to mine owners, operators, and workers. Notably, the act contained a specific provision forbidding any assertion of authority to inspect or supervise any mine within the states. Those powers remained in the hands of state governments.

Following passage of the Organic Act, the Bureau of Mines set up headquarters at Eighth and G Streets NW, in Washington, D.C. In San Francisco, the bureau established a small laboratory in the customhouse for the evaluation of fuel oil for government use. Officially, the Bureau's activities were distributed among three divisions: mine-accidents investigations, fuel investigations, and other technologic investigations. Congressional appropriations for the fiscal year ending June 30, 1911, were $502,200, by which time the Bureau had 230 employees.

Concurrently, the assets, responsibilities, activities, and personnel of the Pittsburgh Explosives Experiment Station at the Pittsburgh Arsenal were transferred from the USGS Technological Branch to the Bureau of Mines. The chemical laboratories were housed in Building 21, immediately above Butler Street, with the remaining buildings located on the banks of the Allegheny River

Dedication Ceremony at the opening of the Arsenal Station in the Lawrenceville section of Pittsburgh.

One of the Pullman cars outfitted as a mine safety car.

Mine rescue workers disembarking from a mine safety car.

First national mine safety demonstration at Forbes Field, home of the Pittsburgh Pirates baseball club, October 31, 1911.

below Butler Street. A spur of the Pennsylvania Railroad entered the grounds for delivery of coal and equipment. The structures close to the river included Building 10 for investigations of electricity in its applications to mining, and Building 17 for explosives and mine rescue work. The fuels testing laboratory in Building 13 performed the much needed task of assaying the fuels purchased by the federal government.

In 1911, Holmes reported that more than 8,000 samples of coal and fuel oil intended for the use of the government were analyzed by the Bureau in the prior fiscal year. "The benefits to the Government from this work of the Bureau have been both general and special," Holmes noted a year later. "In the case of the purchase of coal by the Isthmian Canal Commission for the Panama Railroad during 1910 and 1911 the actual sum of money saved by the Government was nearly $75,000, and the real saving was probably several times these figures, because the method of purchase insured deliveries of coal of a higher grade than otherwise would have been obtained."

The First National Mine Safety Demonstration

If Holmes had been a man of ego, the success of the "well-planned explosion" on October 30, 1911, would no doubt have been a heady time for him. But by all accounts he was a humble man with a singular mission: to make mining safer for miners. He coined the phrase "Safety First" in an era when some coal mine owners clearly valued the profits from coal over the loss of easily replaceable human life. This catchphrase kept his focus on both sides of the equation of mine safety: preventing accidents from occurring and rescuing miners when they did.

So it was appropriate that on the next day, October 31, 1911, he gathered thousands of miners and coal operators at Forbes Field, home of the Pittsburgh Pirates professional baseball team, for the first national mine safety demonstration. President William Howard Taft was the guest of honor. Despite more rain, the president insisted upon sitting at the front rail of the spectators' stand, where he looked on with delight as dozens of khaki and blue-clad relief and rescue workers sorted their equipment, supplies, and apparatus on blankets set out on the soggy field. As the first National Mine Safety Demonstration progressed, the president stood and applauded vigorously when competing demonstrators passed his stand carrying wounded and bandaged enactors on stretchers.

The most spectacular event of the morning came with the ignition of coal dust by 154 pounds of black powder in a mammoth cylinder, which, when President Taft pressed a detonation button, produced great tongues of flame and a thunderous blast said to be heard for miles. Immediately following the explosion, twenty rescue workers, arrayed in oxygen helmets and carrying tanks on their backs, entered the cylinder while a pair of black horses drew a clanging Red Cross ambulance to the mock disaster.

"True conservation is a wiser and more efficient use of our natural resources."
--Joseph Austin Holmes

Holmes took the opportunity to show off one of four Pullman railroad cars that he had outfitted as experimental mine rescue stations. The Pullman cars were used as traveling mine safety training stations most of the time, but were quickly dispatched as rescue centers—hooked up to the next available train that was heading in the direction of the troubled mine—when real mine disasters occurred. The railroad companies granted them free passage on their lines in times of emergency. Eventually the Bureau would have eight mine rescue cars and seven permanent mine safety stations located in the larger coal fields, where mine accidents were more likely.

At Forbes Field that day, miners were trained in first aid, the use of artificial breathing devices that were just being developed, safety lamps, and mine rescue techniques. They were trained in the Schaeffer method of resuscitation, in which the non-breathing miner was placed on his stomach and the rescuer tried to restore breathing by pushing rhythmically on the back of his rib cage. Studies at the time had shown this to be the best method of resuscitation, partially because it avoided the problem of the patient swallowing his tongue.

At 11:30 AM, as he presented medals and trophies to the participating rescue crews, the president pronounced that "[w]e must stamp out the spirit of carelessness and the happy-go-lucky idea that I am afraid is too common with Americans generally."

This first mine safety demonstration day would lead to local, national, and international mine rescue competitions that continue today. The competitions test the knowledge and rescue capabilities of teams from mines all over the country, with prizes awarded to the team that is quickest to solve the rescue problem. Though perhaps more prosaic than the mighty explosion of the night before, the day's demonstration activities were no less important to Holmes.

Conservation

From its inception, the Bureau of Mines had a mandate to help the nation conserve its national resources, although the interpretation of "conservation" was sometimes a point of argument. John Muir and his followers in the early twentieth century believed that conservation meant protecting the beauty of the planet by preserving it in its natural state. Muir and his followers in the growing conservation movement succeeded in getting large tracts of land designated as National Parks.

While he appreciated the natural beauty of his country, and did not disagree with preservation efforts, Holmes was also very practical in understanding that the nation also needed access to the natural resources in the ground to power the industrial plants, homes, automobiles, ships, and trains of a growing population. As he once wrote, "True conservation is a wiser and more efficient use of our natural resources." (These words came to be so closely associated with Holmes that they were set in tile on the mantle piece in the library of the Bartlesville Petroleum Experiment Station many years later.) The emphasis here was on "efficient use"; Holmes had no patience for wasting natural resources, which was rampant at the time. He decried coal mining practices that reduced most of the coal face to dust instead of usable chunks of coal, and the waste of oil and natural gas in the petroleum fields. In his third annual report, published in 1913, Holmes called such practices "criminal":

> *The most urgent need for investigation and reform is in connection with the unnecessary waste of oil and natural gas that still prevails in many parts of the country. Even with the limited facilities at its disposal the bureau has, as stated before, been able during the current year to stop a waste of natural gas valued at not less than $10,000,000, an amount that exceeds by six times the total cost of the bureau's investigations to date. There is urgent need of enlarged facilities with which to push this work more rapidly. A few years of further delay and this valuable source of national wealth will have been wasted—permanently lost.*
>
> *The individual operators in causing this waste have followed their natural bent for temporary gain. The States have permitted this criminal waste without protest, fearing that interference might retard development. Will the National Government do the same? The savings already accomplished was the result of inquiries and researches that enables the engineers of the bureau to demonstrate to the oil and gas men in one of the Oklahoma fields that much waste of gas could be prevented without stopping the drilling for oil. . . . Of the total waste of gas in the different oil fields of the country more than 80 percent is believed to be easily preventable.*

In the same report, Holmes estimated coal waste to be 250,000,000 tons per year. He was convinced that a thorough underground survey of mining practices in each of the major coal fields in the country could reduce the loss by at least 50,000,000 tons per year.

Holmes traveled extensively and worked long hours in his efforts to make mines safer, often to the detriment of his own health. Following a particularly arduous trip to Alaska, he developed tuberculosis and died on July 13, 1915, at the age of 55 in Denver, Colorado (see page18). The *New York Times* obituary called him a "martyr to miners."

His assistant, Van H. Manning, stationed in Washington, D.C., succeeded him as the next Director of the Bureau of Mines. H. M. Wilson led the mining experiment station at Pittsburgh, chief chemist F. G. Cottrell headed the San Francisco office, and R. B. Moore, a physical chemist, acted in a similar capacity for the more recently established Denver office. The Bureau now had five organizational entities: the mining division, the metallurgical division, the mineral-technology division, the fuels and mechanical equipment division, and the petroleum division.

Safety

Laboratory work at the Arsenal in Lawrenceville focused on the development of "permissible" explosives. As described in the First Annual Report of the Bureau of Mines (July 1911), these explosives "give a short, quick, and relatively cool flame that is less likely to ignite inflammable gas or coal dust than is the flame of dynamite or that of black powder." By this time, 88 explosives had passed the tests required by the Bureau and had been placed on its list of permissible explosives. The standards for explosives would grow stricter as more shorter- and cooler-burning materials were discovered.

Major resources were invested in the development of breathing apparatus that would allow miners to survive the toxic gases that flooded a mine after an explosion, should they be lucky enough to survive the initial blast.

These better-burning materials would lead to a rapid decrease in the number of mine disasters throughout the 1910s, and the Bureau's growing expertise in explosives would serve the government well in times of war.

Bureau researchers also investigated ways to make the use of electricity in mines safer, mainly through the development of explosion-proof motors. These motors had metal covers over areas of the machinery likely to produce sparks. The researchers tested numerous varieties of safety lamps that would provide light for the miners while reducing the risk of setting off an explosion. Generally, a "safe" lamp used metal gauze or another protecting device to separate the lamp flame from explosive gases while still allowing the lamp to glow.

Major resources were invested in the development of breathing apparatus that would allow miners to survive the toxic gases that flooded a mine after an explosion, should they be lucky enough to survive the initial blast. Researchers such as the chemist Arno C. Fieldner investigated various absorbent compounds for "gas masks" that filtered out toxic organic compounds and let breathable air through to a miner's lungs. These efforts gained broader relevance when World War I broke out in 1914 and toxic gases such as chlorine and mustard gas began to be used as weapons of war.

"A great experiment station was developed…," Manning reported, "for devising and testing gases and smokes used in warfare, gas masks, flame throwers, incendiary bombs, signal lights, and other war material."

Manning raised war gas research to a new level in 1917. While the Ordnance and Medical Departments of the Army performed parallel research, he established a Chemical Section of the Bureau of Mines at the American University outside of Washington, D.C. "A great experiment station was developed…," Manning reported, "for devising and testing gases and smokes used in warfare, gas masks, flame throwers, incendiary bombs, signal lights, and other war material."

More than 1,700 American chemists contributed in some way to this project, whether as employees of the Bureau or as consultants. This highly visible research soon caught the eye of President Woodrow Wilson, who saw the benefits of consolidating the various efforts under one roof. On June 29, 1918, Wilson wrote Manning a letter:

> *My Dear Dr. Manning:*
>
> *I have had before me for some days the question presented by the Secretary of War involving the transfer of the Chemical Section established by you at the*

> *American University from the Bureau of Mines to the newly established Division of Gas Warfare, in which the War Department is now concentrating all the various facilities for offensive and defensive gas operations. I am satisfied that a more efficient organization can be effected by having these various activities under one direction and control, and my hesitation in acting in the matter has grown only out of a reluctance to take away from the Bureau of Mines a piece of work which thus far has so effectively performed. The Secretary of War has assured me of his own recognition of the splendid work you have been able to do….*

Thus the Bureau's Chemical Section was transferred from the DOI to the War Department under General William L. Sibert on July 1, 1918. Sibert placed Manning's Research Division at American University under the newly established Chemical Warfare Services. This work with gases led to spinoff projects for the Bureau after the war. The agency's experts were consulted about problems with newly developed anesthetic gases exploding in hospital operating rooms, and about the best way to ventilate carbon monoxide from underground shafts in industrial and transportation facilities.

After World War I, the Bureau's experts were consulted about problems with anesthetic gases exploding in hospital operating rooms and the best way to ventilate carbon monoxide from underground shafts in industrial and transportation facilities.

A New Pittsburgh Station

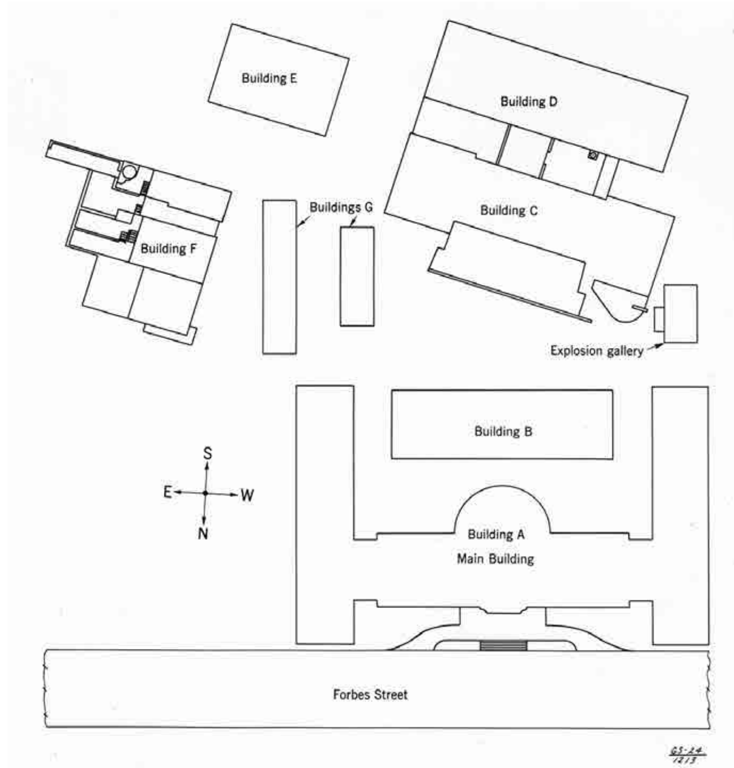
From the beginning of the Bureau of Mines in 1910, it had been recognized that the Arsenal facilities donated temporarily by the Department of War were insufficient for the Bureau's long-term research purposes. By 1916, the Department of War was requesting that the Bureau find other space for its work, so that the Arsenal could revert to its original purpose. Congress worked out a trade: some government-owned grounds adjacent to the Arsenal were transferred to the City of Pittsburgh in exchange for a tract of land near the Carnegie Institute of Technology in the Oakland section of the city.

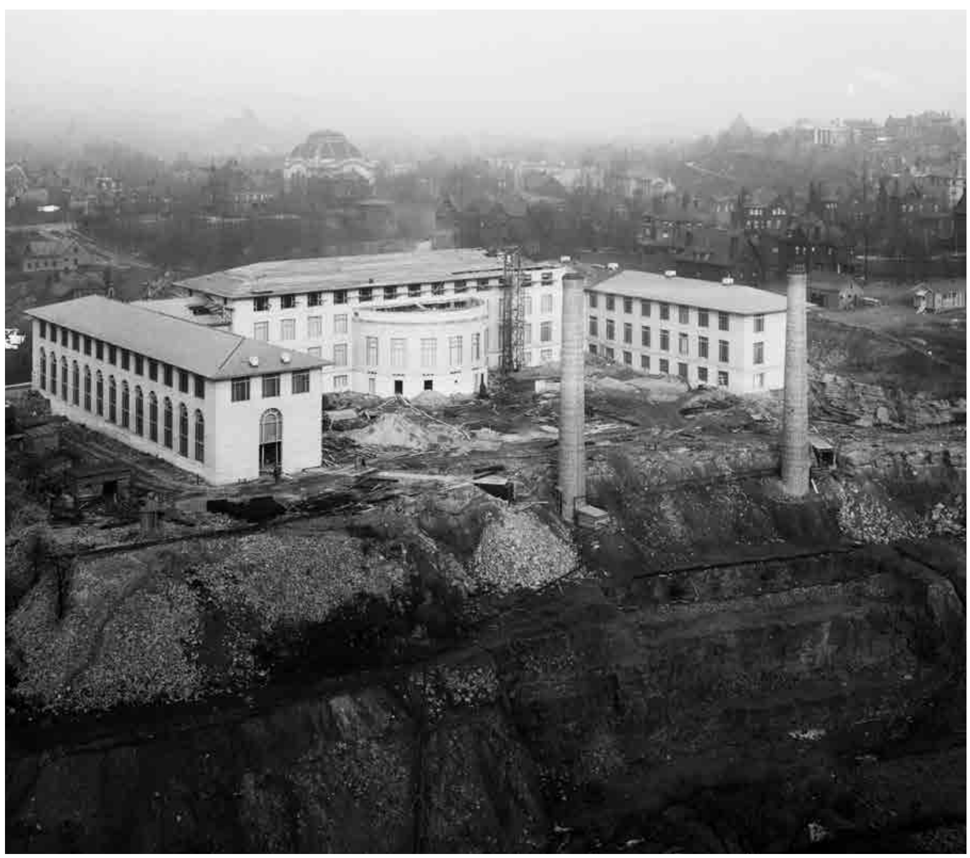
Manning called the keys to the new Pittsburgh Experiment Station "a symbol of the function of the Bureau to unlock the secrets of nature for the benefit of all mankind."

The new Pittsburgh Experiment Station of the Bureau of Mines (now Hamburg Hall of Carnegie Mellon University) was built in a squared-U shape, with the main hall of the building—the bottom of the U—fronting on Forbes Avenue. This main section housed the offices of the administrative, mining, mine safety, and explosives sections. The east wing held chemical, physical, and metallurgical laboratories, while the west wing was home to the mechanical, electrical, and fuels investigations laboratories.

Although the building was completed and operational in 1917, World War I forced the postponement of the formal dedication of the new Pittsburgh Experiment Station until September 29–October 1, 1919. Director Manning accepted the keys to the building in a ceremonial transfer of the property, say-

Diagram showing layout of buildings of the new Pittsburgh Central Experiment Station in the Oakland section of the city, 1917




New Pittsburgh Station under construction.

Dedication of the new Pittsburgh Experiment Station in Oakland section of the city, 1919

Entrance to the main building of the Pittsburgh Central Experiment Station

ing, according to a report in *The Journal of Industrial and Engineering Chemistry*, that they were "a symbol of the function of the Bureau to unlock the secrets of nature for the benefit of all mankind."

Joseph Austin Holmes

Joseph Austin Holmes, first Director of the Bureau of Mines

"While he was interested in the conservation of American natural resources and endeavoring to assist our citizens in the business of mining or agriculture, the human side of it all was always to the front; lifesaving and the uplift of poor and ignorant employees were the things which seemed nearest to his heart."

--Holmes's friend and associate, Dr. A. E. Ledoux of New York

In the spring of 1910, just when his long-held dreams of leading the fledgling Bureau of Mines should have been coming to fruition, Joseph Austin Holmes watched from the sidelines as the names of other candidates were trotted out one by one, with no mention of his own. The omission was a glaring and painful one for him. He had acquired the nickname of "Safety First" based on the slogan that drove his efforts to make mines safer. He had also spearheaded the charge to enact the legislation passed by Congress in May 1910 to authorize the establishment of the Bureau of Mines within the Department of the Interior. Holmes was the logical choice, but his name was not on President William Howard Taft's list of candidates.

The reason was purely political. "[I]t was known that [Holmes] was one of the Interior Department men who was regarded by Secretary [of the Interior] R.A. Ballinger as inimical to him," the *New York Times* reported in 1915. Why Ballinger was opposed to Holmes was not reported, but the disagreement was probably rooted in a controversy that was raging at the time about whether the Secretary was sufficiently committed to the ideal of conserving natural resources. However, Ballinger clearly had Taft's ear in this matter. So Taft repeatedly nominated other men whom Ballinger felt were qualified for the position, and watched as they all respectfully turned down the offer. According to Dr. I.C. White, the State Geologist of West Virginia, in subsequent remarks made at a memorial service for Holmes in 1915, the "American men of science, the men to whom it is rumored this important position was offered, refused to accept a gift which all knew belonged of right to the one man whose untiring labors had created the Bureau."

White recalled that Holmes had visited him at his Morgantown, West Virginia, home in 1910 at the height of what White called Holmes's "long and disappointing vigil." Despairing of not being named to head the Bureau of Mines, Holmes had stopped by to inquire if the State University of West Virginia, which was looking for a new president, might consider him for the position. White agreed to place his name before the University Regents, but decided to wait until Taft had irrevocably appointed someone else to the coveted Bureau position. White's conviction that Taft would eventually see through the "veil of misinformation with which his vision had been beclouded" was affirmed a few days later when Holmes received word from Washington that his wait was over. The *New York Times* called the appointment "surprising." Holmes would lead the Bureau of Mines through its formative years in spectacular fashion.

"American men of science, the men to whom it is rumored this important position was offered, refused to accept a gift which all knew belonged of right to the one man whose untiring labors had created the Bureau." --I. C. White .

Joseph Austin Holmes was born in Laurens, South Carolina, on November 23, 1859, the eighth of twelve children of Nancy Catherine Nickles and Zelotes Lee Holmes, a Presbyterian minister and teacher. Following a traditional small-town education in grammar school and high school, he worked his way through Cornell University and graduated with a Bachelor of Agriculture degree in 1881. Holmes accepted an appointment as professor of Geology and Natural History at the University of North Carolina at Chapel Hill, where he mainly taught botany courses, with a unique emphasis on laboratory and field work as opposed to the book-learning method used at most universities. "Seeing and examining an object gives a student a further understanding of it than does reading about it," Holmes wrote. He began a small collection of plants that grew to become the renowned University of North Carolina Herbarium. One of his students later honored him by naming two tree species in his honor, *Hicorius holmesia* and *Crataegus holmesiana*.

Following a reorganization of the university in 1886, Holmes's teaching duties began to involve more of the geological pursuits suggested by his title. By 1890 he was teaching General Geology and Mineralogy, Advanced Geology, and Advanced Mineralogy, in addition to courses in zoology and botany. He also maintained the University Museum, which contained over 3,000 specimens of rocks, ores, and minerals. His geological expertise would eventually lead to his appointment as Director of the Bureau of Mines.

The first step along this path was his resignation from the university in 1891 to become the State Geologist with the North Carolina Geological Survey. In this capacity Holmes distinguished himself by championing the building of roads, eventually being responsible for the development of over one thousand miles of macadamized roads in North Carolina. He and his colleagues also surveyed and reported on the ore and mineral resources of the state.

With the approach of the St. Louis World's Fair, also known as the Louisiana Purchase Exhibition, in 1904, the organizers began searching for a distinguished geologist to serve as Director of the Department of Mines and Metallurgy. Holmes was offered and accepted this position in 1903, and performed experiments and gave demonstrations at the Fair. When the Fair closed in 1905, he stayed on in St. Louis as chief of the U.S. Geological Survey laboratories. Holmes moved to Pittsburgh in 1908 to continue this work at the newly established USGS laboratories there, and quickly became a leader in the movement for the establishment of a federal Bureau of Mines.

Taking full advantage of a $150,000 appropriation by Congress "for conducting such investigations as will increase safety and efficiency in mining operations," Holmes traveled to Europe in 1908 to study the more advanced state of mining there. Speaking in 1915, George S. Rice, the chief mining engineer of the Bureau, said that Holmes "constantly wanted to get to the root of matters in scientific investigations, and saw far ahead of many others in such matters."

In 1909, even before the Bureau of Mines was established, Holmes was rewarded for his contributions to mankind with two honorary doctorate degrees: an LL.D. (doctor of law) degree from the University of North Carolina at Chapel Hill, and a D.Sc. (doctor of science) degree from the University of Pittsburgh.

With the authority vested in him as the Director of the Bureau of Mines, Holmes was tireless and comprehensive in his efforts to make mining safer. He directed investigations into safer, "permissible" explosives, mining lanterns, breathing apparatus, and other safety appliances. He published the results of this research in an annual report of the Bureau of Mines, and in monographic bulletins throughout the years, so that all miners and mine operators around the world would have access to the data. His attention encompassed not only coal miners but also metal and mineral miners, who had similar accident and fatality rates.

His duties frequently took him across the United States and to Europe, away from his wife Jeannie and their four children, so he could attend conferences, observe first-hand better mining practices, and assess the resources of various parts of the United States. Ultimately, this sustained high level of effort led to his early demise. The Alaska Territorial Mine Inspector W. R. Maloney described what happened to Holmes on a trip (circa 1914) to assess the mineral resources and mining practices of that territory:

> *I knew him on the trail to be a man who did his duty and his part of the work, and more. He was handicapped from the start of our trip to the Alaskan Range by a horse stepping on his foot. From that time on he had to ride, making it very uncomfortable to the Doctor, as anyone who knew him knows how well he liked to walk around and see the surrounding country wherever he might stop, but nevertheless he was an indefatigable worker in the camp. He would cut wood and build fires and do anything he could to make things pleasant. At the time most of us in the party recognized that his constitution would hardly stand the trip, lying on the ground at night and traveling under difficult conditions in the day time.*
>
> *We had to go through the snow and storm the better part of the time, and because of the snow and the thawing, and because of chills, it was a most disagreeable trip. We were making forced journeys of 35 and 40 miles a day, where ordinarily 15 miles was considered a good day's travel.*

Holmes emerged from the journey with tuberculosis, which would lead to his retirement from the Bureau of Mines in 1915 and his death in Denver, Colorado, on July 13, 1915, at the age of 55. The headline to the obituary in the *New*

York Times read: "J. A. Holmes Dies Martyr to Miners. Director of Federal Bureau of Mines Lost His Health Seeking 'Safety for Men.'" He was buried in Rock Creek Cemetery in Washington, D.C. More than 100 friends and colleagues convened in the Civic Auditorium in San Francisco on September 21, 1915, to eulogize Holmes at a "Memorial Exercise" held during the American Mining Congress.

How to pay tribute to such a man? On January 15, 1916, a group led by Holmes's successor, Van H. Manning, met at the Bureau of Mines offices in Washington, D.C., to discuss this matter. Distinguished representatives from all of the mining, engineering, labor, and safety organizations attended. Instead of commissioning a statue or naming a building after Holmes, the group resolved to establish a permanent organization to be called "The Joseph A. Holmes Safety First Association," which would annually award "one or more medals which, together with honorariums, shall be termed The Holmes Award for the encouragement of those originating, developing and installing the most efficient 'safety first' devices, appliances or methods in the mineral industry…." Special medals for heroism or distinguished service in the mineral industry were also to be awarded from time to time. The Association remains in operation to this day in Arlington, Virginia, as a lasting tribute to the first Director of the Bureau of Mines.

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

Chapter Two:
Bartlesville, Oklahoma—the Center for Oil

Chapter Two:

Bartlesville, Oklahoma—the Center for Oil

"For six decades after Drake punched down the first successful oil well, the industry went on a producing binge, overdosing on spewing gushers, huge gas flares, and water disposal by evaporation from surface reservoirs. When the tap ran low in a reservoir, operators simply plugged the hole and headed for new oil country. In 1917, some 33,000 wells had produced only 4 billion bbl of oil, in some cases leaving 90% of the oil still in place at the end of operation."

--Bill Linville, Oil Editor for the Bartlesville Energy Technology Center's publication Petroleum Engineer International, *August 1979*

Although the initial emphasis of the Bureau of Mines was on coal, the growing petroleum industry soon attracted its attention. "Early tasks of the Bureau of Mines included field studies of oil and gas waste, research on the use of cement to keep water out of the producing wells, and methods of analyzing gas," the *Bartlesville Examiner-Enterprise* noted in a 1968 article celebrating the fiftieth anniversary of the Bartlesville Station. "Problems of the petroleum industry were multiplying rapidly. The small force of petroleum technologists working for the Bureau was laboring at frantic speed under tremendous pressure, but they had few guidelines to follow. The results were sporadic."

Bartlesville, Oklahoma, in 1906, before the arrival of the Bureau of Mines.

After several representatives of the oil industry visited Holmes in 1913, he was convinced of the need for a separate petroleum division in the Bureau. On July 1, 1914, Holmes appointed William A. Williams, a Stanford University graduate in geology and mining, to the job of Chief Petroleum Technologist, with authority to start such a division. In 1915, the petroleum division was given $25,000 in funding to prevent waste of oil and natural gas, extend well life, develop improved field practices, and determine the physical and chemical nature of petroleum.

New legislation would soon upgrade the petroleum division to a separate mining experiment station within the Bureau. On March 3, 1915, President Woodrow Wilson signed the Foster Act, authorizing the establishment of 10 new experimental centers across the nation devoted to different valuable raw materials. One of these centers would be devoted to petroleum studies.

But though it was the law of the land, no funding was immediately available to carry out the provisions of the Foster Act. Two years later, the situation changed.

Any town interested enough in securing what would likely become a prestigious national research center ought to be able to raise the approximately $50,000 needed for land and construction costs—or so the thinking went in Congress.

Clarence Burlingame, President of the Bartlesville, Oklahoma, Chamber of Commerce, happened to be in Washington, D.C., in 1917, meeting with the Fuels Administration to discuss aviation fuels for the war effort, when Congress finally appropriated the funds to open a petroleum experiment station somewhere in the Mid-Continent region of the United States. The Mid-Continent, which included Oklahoma, Kansas, and Texas, was the most active oil region in the country after the discovery and development of major oil fields such as the Cushing field near Depew, Oklahoma; the Glenn pool in Butler County, Kansas; and the famous gusher Spindletop in Texas. By 1915, the Cushing field alone was producing 300,000 barrels of oil a day.

The appropriation, however, came with a catch. It provided $75,000 for the *operation* of a new petroleum center, but not one cent for the *building* of it. Any town interested enough in securing what would likely become a prestigious national research center ought to be able to raise the approximately $50,000 needed for land and construction costs—or so the thinking went in Congress.

"The enthusiasm displayed by the Bartlesville group and their willingness to back their enthusiasm with financial assistance won the case and the oil experiment station came here." --The Bartlesville Enterprise, *1937.*

Burlingame hurried home and marshaled the local petroleum producers to strike first with a bid to establish the petroleum experiment station in their small town. He was one of Bartlesville's "best known citizens," according to the *Bartlesville Enterprise*. Realizing that "a big opportunity was presenting itself," the newspaper said, "he unhesitatingly threw his unusual executive ability into building a campaign to prove to the men who had the authority to place the station, that it should come to Bartlesville." Burlingame knew that the assignment was most likely to go to one of the bigger cities in the region, such as Kansas City, Tulsa, or Dallas, so his town's bid had to be strong.

Rallying to the opportunity, Henry Doherty of Empire Gas and Oil, a local independent oil producer, pledged $25,000 from his company's coffers, and George Keeler, a co-founder of the town of Bartlesville, donated 4.5 acres of his land for the proposed site. The Chamber of Commerce solicited donations from local businesspeople in an attempt to raise the remaining $25,000, but received a tepid response.

Knowing that the city of Tulsa had gotten off to a strong start in the fundraising process, Burlingame was anxious to move quickly. On the morning of

November 10, 1917, he assembled the members of the Chamber of Commerce to make a bold proposal: they should personally guarantee the $50,000 even though only about $30,000 had been raised at the time. Following the meeting, Burlingame wrote this letter to D.A. Lyon, his Bureau contact in the negotiation process:

November 10, 1917
Mr. D.A. Lyon
Bureau of Mines
Minneapolis, Minn.

Dear Mr. Lyon:

Have been away for the past three or four days and on my return to Bartlesville this morning had a little meeting with the chamber of commerce and have arranged to make the donation for the petroleum department if located at Bartlesville in a concrete form, in other words aside from guaranteeing it by the chamber of commerce and citizens of Bartlesville, will take up the subscription and have everything signed as per your regulations, and in the course of the next two or three days this will be forwarded to your address....

Yours very truly,

C.E. Burlingame.

By taking the gamble and striking quickly, Burlingame impressed the government officials. "The enthusiasm displayed by the Bartlesville group and their willingness to back their enthusiasm with financial assistance won the case and the oil experiment station came here," the *Bartlesville Enterprise* recalled in a 1937 article. On December 19, 1917, Secretary of the Interior Franklin K. Lane announced that Bartlesville had been awarded the new petroleum research station. But even when the official agreement was signed by the Bartlesville Chamber of Commerce and the Bureau of Mines on March 28, 1918—the official birth date of the Bartlesville Petroleum Experiment Station—"the $50,000 was not in sight," according to the newspaper. "Mr. Burlingame had every confidence that it would be and although it was not forthcoming that week, not the next, it *was* provided [italics added], and the president of the chamber of commerce never slackened in his efforts until every requirement had been met…"

Rodney P. Carlisle and August W. Giebelhaus summed up the significance of the agreement in their book, *Bartlesville Energy Center: The Federal Government in Petroleum Research, 1918-1983*: "Rockefeller had based the Standard Oil Trust on Pennsylvania and Ohio oil…. By 1916, however, the center of oil activity had shifted westward….The already independent producers in Oklahoma, therefore, viewed the selection of their own territory for the Bureau's oil station as an affirmation of the industry's new center."

Other Mining Experiment Stations Created by the Foster Act

- The Birmingham, Alabama, Mining Experiment Station for non-metallic minerals and coke by-products investigations
- The Columbus, Ohio, Mining Experiment Station for ceramics (based on local clays)
- The Fairbanks, Alaska, Mining Experiment Station for lode and placer mining and metallurgy investigations
- The Minneapolis, Minnesota, Mining Experiment Station for iron mining and beneficiation investigations
- The Reno, Nevada, Mining Experiment Station for rare and precious metals investigations
- The St. Louis, Missouri, Mining Experiment Station for lead and zinc mining and metallurgy investigations
- The Salt Lake City, Utah, Mining Experiment Station for metal mining, metallurgy, and smoke abatement investigations
- The Seattle, Washington, Mining Experiment Station for electrometallurgy, ceramics, coal washing, and mining methods investigations
- The Tucson, Arizona, Mining Experiment Station for copper mining and metallurgy investigations
- The Urbana, Illinois, Mining Experiment Station for coal mining, fuels, and coal preparation investigations

Problems with Petroleum

Though the petroleum industry was still relatively young—the first oil well had been started in 1859 by Edwin Drake in Titusville, Pennsylvania—fears had already begun to spread of an impending oil shortage that would be disastrous for the American economy. The rage for driving automobiles was in its first full swing, thanks in large part to Henry Ford's popular and affordable Model T, which had been introduced in 1908. Evidence of the American love for cars was clear from the production numbers: the millionth Ford automobile was built in 1915, the five-millionth was built just six years later.

Where would the gasoline needed to power all these vehicles come from? The search for petroleum had led big companies and independent "wildcatters" from Pennsylvania along a southwestern route, leasing the mineral rights to land from farmers and other landowners. Their standard method of looking for seepages of oil on the ground and drilling nearby was a hit-and-miss proposition, and the waste of petroleum and natural gas that often accompanied oil wells was rampant. Natural gas was usually burned off in huge flares as a waste product; in 1910, the estimated loss of natural gas was 500 billion cubic feet. Occasionally an oil fire would lead to a large loss of petroleum in a rather dramatic display. Oil was allowed to sit in large pools on the ground to separate it from water by evaporation, but in the process the more volatile components of the oil also evaporated. Furthermore, petroleum producers were capping wells that still contained up to 90 percent of their original oil because it had become

A petroleum fire in an Oklahoma City oil field, 1924.

economically unprofitable to continue pumping it out of the ground. With a new, promising well location just down the road, the emphasis was on leasing rights, drilling quickly, and extracting the easy oil that rushed to the surface. Better to not waste too much time on pulling the "dregs" of an old well to the surface—even if those dregs amounted to the majority of the oil at the site.

These practices obviously could not continue indefinitely. By 1917, the dismal production rates of most U.S. oil wells—33,000 wells had produced only 4 billion barrels of oil nationwide—emphasized the need to develop scientific knowledge of the nature of petroleum reservoirs in order to extract a greater percentage of available petroleum from any given field. This need was a major factor in the establishment of the Bartlesville Petroleum Experiment Station in 1918. If the mostly small, independent oil producers of the Mid-Continent could not afford to construct and run a research laboratory, the federal government would do it for them in the national interest. While the Bureau's goal in petroleum at this time was similar to that of the oil producers—getting more of the valuable liquid to the surface and into refineries—a government-owned laboratory could ignore the profit-making pressures that the producers faced and concentrate on developing the science of petroleum.

By 1917, the dismal production rates of most American oil wells—33,000 wells had produced only 4 billion barrels of oil nationwide—emphasized the need to develop scientific knowledge of the nature of petroleum reservoirs.

In a retrospective to mark the fiftieth anniversary of the Bartlesville Station in 1968, the *Bartlesville Examiner-Enterprise* recalled the prevailing doubts that had surrounded the Bureau's early efforts to promote the application of scientific knowledge in the petroleum industry: "In 1918, little attention was given by oilmen to observations by scientists and engineers. Petroleum technology wasn't exactly ignored, it just didn't exist. There was none. Oil producers and operators were skeptical of anything that smelled of textbooks procedures."

But this view was an exaggeration. By 1915, the Bureau's Petroleum Division under William A. Williams had already begun investigating such issues as the prevention of waste, prolonging the life of oil and gas wells, cementing practices, use of drilling mud, reservoir energy, the flashpoint of oil, and the physical and chemical properties of oil. Technologists went into the fields and refineries and worked closely with industry. But the modest commitment of $25,000 was not enough to make a significant difference to the problems of the oil industry. It would take the founding of the Bartlesville Petroleum Experiment Station in 1918, and its early record of success in solving petroleum problems, to convince the remaining skeptics of the value of science to this industry.

The First Year

The Bartlesville Petroleum Experiment Station was officially established on March 28, 1918, with J. O. Lewis as the first Superintendent. Lewis had been working at the Bureau's San Francisco office before his appointment to Bartlesville by Bureau Director Van H. Manning. Manning directed Lewis to operate the station as "a laboratory for practical research for solving problems, devising new methods, preventing wastes, effecting economies and for collecting and disseminating information." Lewis and a staff of five worked out of temporary offices in the large Chamber of Commerce room of Bartlesville City Hall at 4th and Dewey Streets while permanent quarters were being designed and constructed. His staff included W. P. Dykema, natural gas engineer; Clarence Netzen, chemical engineer; R. O. Neal, chemical engineer; W. G. Haitt, junior chemist; and Noel Hubbard, clerk. Their furnishings were used desks and chairs that had been donated by local oil companies and businessmen. Lewis was the right man for the job because of his familiarity with the petroleum industry in various regions of the United States. His career had started in Bradford, Pennsylvania, where he learned about the new "waterflooding" technique for extracting more oil from reluctant wells. Waterflooding involved injecting a large volume of water into several input wells surrounding a central "producing" well. The pressure from the water forced oil out of the producing well, which had appeared to be near the end of its useful life. Waterflooding was thus a form of "secondary recovery," and it extended the working life of many wells. Lewis had also worked in the oilfields of Marietta, Ohio, where an alternate method of injecting compressed air into a well to force out additional oil was in use. Finally, in San Francisco he had learned how to cement well shafts to prevent unwanted water from a non-oil-producing stratum of rock from intruding (the technique had been invented by Frank Hill of the Union Oil Company of California in 1903). So by the time of his appointment as Superintendent of the Bartlesville Petroleum Experiment Station, Lewis had a wealth of relevant experience.

J.O. Lewis, first Superintendent of the Bartlesville Station, 1918.

Lewis's broad knowledge proved to be a key to the Bartlesville Station's early success. Information did not travel fast in those days, and independent oil producers had no incentive to share proprietary inventions with their competitors. Acting as a government agent, Lewis brought the cementing technique he learned in California to Oklahoma, which was still trying to solve the problem of water infiltration. Looking back on this era, the *Bartlesville Examiner-Enterprise* wrote in 1968: "The use of cement for plugging back wells to shut off water was one of the first contributions of the Bartlesville Petroleum Research Center to the oil industry. Reports about using Bureau cementing techniques were among the first technical reports to come from authors located in the Mid-Continent area."

"The use of cement for plugging back wells to shut off water was one of the first contributions of the Bartlesville Petroleum Research Center to the oil industry." --Bartlesville Examiner-Enterprise 1968.

In a tribute to Lewis, the same issue of the newspaper also noted the following:

> *One of the most important contributions to the oil industry was a bulletin by Lewis titled "Methods of Increasing the Recovery from Oil Sands." When this 128-page bulletin was published in 1917, the industry knew that as much as from 20 to 60 per cent of the oil in place probably could not be recovered by any process then practiced. Application of vacuum, air-gas drive, and waterflooding each had been used, and it was a report on these improved recovery techniques that comprised the principal objective of the Lewis publication. His studies and writings on increasing oil recovery were epoch-marking.*

Searching for a Role

If there was skepticism about scientists and textbook solutions, the independent oil producers of the region soon got over it; within a month of the opening of the Bartlesville station they were clamoring for the Bureau's help with problems in the field. In April 1918, Empire Fuel and Gas and the Gypsy Oil Company requested help to prevent intrusion of water into their drilled wells.

Within a month of the opening of the Bartlesville Station, oil producers were clamoring for the Bureau's help with problems in the field.

Lewis hired an expert oil well driller named Thomas Curtin to deal with this challenge. Curtin began demonstrating the California cementing technique to the mid-continent oil producers. But soon the oil producers began taking advantage of Curtin's expertise. He was spending all his time in the field, advising the producers one by one. Lewis had trouble reconciling this activity with his mandate to develop technologies to help the region and the nation, not just particular oil companies. By December 1918 he had reined in Curtin's services, restricting the Bartlesville station to experimental work and avoiding any activity that, in Lewis's own words, "savors of a political or regulatory nature."

This policy paid off in 1919 when Assistant Petroleum Engineer W.P. Dykema, collaborating with Phillips Petroleum, developed a method of absorbing gasoline fractions that occurred naturally in the natural gas associated with the petroleum wells. This so-called "casinghead gasoline" was well known at the time, but it was typically vented as waste because it was too costly to capture. The absorption technique solved this problem. Soon the 100-octane casinghead gasoline was being blended with lesser grades of petroleum fractions to raise their octane levels. Here was a process that demonstrated the profitable collaboration that could occur when government and industry worked together. Because the method was not proprietary, the Bureau shared the absorption technique with other oil producers to the benefit of the nation.

Only one year into its history, the Bartlesville Station had found its purpose: to become an agent of information transfer to the entire petroleum industry.

Only one year into its history, the Bartlesville Petroleum Experiment Station had found its purpose: to become an agent of information transfer to the entire petroleum industry. Though the needs of the industry would change drastically over the years—from the need to "get it out of the ground" to the equally important need to" keep it in the ground" during times of an oil glut—the Bartlesville station would continue to be a central disseminator of petroleum information in the decades to come.

Physical Plant

The architectural design of the Bartlesville Petroleum Experiment Station was awarded through competitive bidding to the firm of Keene, Simpson, and Everman of Kansas City and Bartlesville; the construction contract went to A.E. Madorie of Kansas City, who bid $34,688. The architects designed two red-brick buildings: a two-story administration building with eight rooms, and a one-story laboratory building that also housed a machine shop, along with a calorimeter room in the basement. Sheet-iron outbuildings contained a small experimental refinery with three one-barrel stills and one five-barrel still, a blueprint house, and a store house.

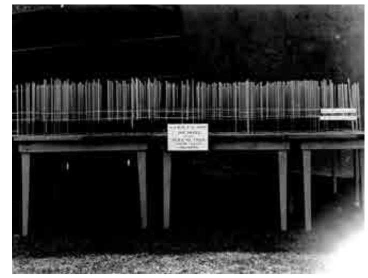
Experimental refinery at the Bartlesville Station in 1919.

The first two buildings of the Bartlesville Petroleum Experiment Station, 1918.

World War I interfered with the initial completion date of December 1, 1918, but in January 1919 the buildings of the station were ready to be occupied. No doubt Lewis had looked forward to the new, spacious offices of the administration building, but he was never to enjoy them. In February 1919 he was called to Washington, D.C., to assume the role of Chief Petroleum Technologist. W. P. Dykema took over as Superintendent in 1919.

Bartlesville Enters the 1920s

The 1920s was a tumultuous decade for the petroleum industry and for the Bureau's petroleum research station in Bartlesville. The decade started with an oil boom as new fields were rapidly located, drilled, and abandoned as soon as the "easy" oil was brought to the surface. It ended with a stock market collapse and a dumping of Texas oil onto the market that would plunge oil prices to the lowest levels ever seen.



Three-dimensional peg model of the Slick Oil Field in Oklahoma, showing the depth of oil sands, 1920.

The first half of this decade saw a rapid turnover in superintendents at Bartlesville and a growing staff. Superintendents rarely lasted more than a year before moving on. W. P. Dykema was succeeded in 1920 by J. W. Ambrose. Ambrose rescinded Lewis's decision to focus on laboratory work, and soon had his staff back in the field. They numbered 15 in all in 1920. Ambrose's specialty was in "working up" a field, which meant developing structure contour maps, geologic cross sections, and "peg models" showing three-dimensional underground formations. These models used thin wooden dowels, or pegs, of various lengths arranged in a two-dimensional array to represent the surface of an oil field. The lengths of the pegs provided the third dimension—depth—to the model. The tops of the pegs showed the ground contours, while the bottoms revealed the contour of an important underground geological structure. In between, important cross-sectional layers—such as the sand layer known to contain oil—were indicated by lateral lengths of string around the perimeter of the model. One length of string would represent the top of the oil-containing layer, and another the bottom; rises and dips in this layer would be indicated by varying the height of the string on adjacent pegs. A century later, three-dimensional computer software models would allow oil producers to rotate a simulated oil field and look at it from any angle. Peg models could not provide that level of sophistication, but in 1920 they gave drillers more precise information with which to determine drilling and shot depths. The Ardmore Chamber of Commerce paid $1,000 for such a study in July 1920, to Ambrose's great satisfaction. To him, it proved the value of the Bureau's field work to the petroleum community.

But Ambrose was called to Washington, D.C., in 1921 to serve as the Chief Petroleum Technologist of the Bureau; later he would serve as chairman of board of Cities Service Oil Company. He was replaced as Superintendent by H. H. Hill, who followed a similar path, moving on to the nation's capital in 1922, and eventually to the Standard Oil Company of New Jersey. T. E. Swigart held the Superintendent's position from 1922 into 1924, when he joined the Shell Oil Company. M. J. Kirwan then took over from 1924 to 1925, leaving to work for the Indian Territory Illuminating Oil Company.

Bartlesville had three superintendents in 1925: R.A. Cattell, who moved to Washington, D.C., later in the year; W.W. Scott, who left to join Humble Oil and Refining Company; and E.P. Campbell. Nineteen-twenty-five proved to be a dramatic year in relations between the federal government and the petroleum industry. It was the year of the sensational Teapot Dome scandal, in which Secretary of the Interior Albert Fall was caught accepting money to open the Teapot Dome Naval Oil Reserves to private companies. To emphasize the role of energy research and development in economic growth, President Calvin Coolidge took control of the Bureau of Mines away from the DOI and gave it to the Department of Commerce under Secretary Herbert Hoover.

N.A.C. Smith, Superintendent of the Bartlesville Station 1926 to 1945.

Despite the shakeup in organizational structure, however, 1925 also brought the first measure of stability to the leadership of the Bartlesville station after Nicholas A. C. Smith succeeded Campbell at the helm. Smith, who had started working for the Bureau as an assistant chemist in Pittsburgh in 1918, had arrived in Bartlesville in 1924 from the Washington, D.C., office as a petroleum technologist. He was soon promoted to Acting Superintendent and then to Superintendent in 1926. Smith would remain in the top position through 1945, guiding the station more in the direction of laboratory research than field work. He would create what he called an "independent and professional petroleum research center," with an emphasis on publication of results. He was an impeccable writer and editor who ensured that any manuscript written in Bartlesville was of the highest quality. In a 1937 article, the *Bartlesville Examiner* declared, "Mr. Smith is a quiet, unassuming sort of chap, but his associates and chemical engineers in the Mid-Continent field who come in contact with him declare he is one of the most brilliant men in this section of the country with an uncanny insight on the problems of the petroleum industry."

Smith appeared on the scene at the right time, because the Bartlesville station was in need of a stabilizing force. He summed up the situation in July 1926: "During the past year this station has seen the arrival of three superintendents and the departure of two." The mid-1920s was a period of rapid employee turnover at all levels, not just at the top. Well-trained Bureau personnel were quickly snatched up by private petroleum companies who could afford to pay them more than the government, especially during an oil boom. Between July of 1925 and April of 1926, 14 people left the Bureau to be replaced by 12 others, leaving a total of 38 employees at the Bartlesville station.

One of these employees was to play a major role as Smiths's right hand man throughout most of his tenure: Ludwig Schmidt, who joined the Bartlesville station in 1921 after graduating from the University of Oklahoma with a degree in chemical engineering. Schmidt had served in the Company A Engineers of the Oklahoma National Guard Mexican Border service in 1916-1917, and was later a First Lieutenant in the 544th Engineers during World War I. He later added a Professional Engineer credential from the University of Oklahoma in 1924.

Projects during Smith's Reign

"Nick" Smith, as he was known around the station, presided over three distinct phases of oil production during his command in Bartlesville, corresponding to three different economic and political eras. These were the 1920s, characterized by increasing production and an eventual oil glut as the Texas fields came into play; the Great Depression, during which demand and prices fell, leading to heavy curtailment of Bureau research; and the World War II era, when unprecedented forces and funds were poured into Bartlesville as scientists and engineers tried to maximize the supply of petroleum products to aid in production of aviation fuel, lubricating oils for motorized equipment, and asphalt for military roads and airport runways. Throughout these eras, safety in the petroleum fields continued to be a major focus of Bartlesville's efforts, including the production of training films to teach petroleum field workers safe working habits.

To help with the workload, the Laramie Station was established in 1922 and would soon come to be seen as Bartlesville's "sister station."

The major goal of the petroleum companies in the 1920s was extracting more oil. While the Bartlesville Station aided this effort with projects titled "Methods of Increasing the Recovery of Oil," "Investigation of the Use of Gas for Lifting Oil," and "Application of Vacuum to Oil Wells," it was also interested in understanding the properties of crude oils and the nature of the geological formations in which oil could be found. Scientists used the methods outlined by J. O. Lewis in 1917 to analyze more than 300 samples of crude oil by 1928. To help with the increasing workload, the Laramie, Wyoming, Petroleum Experiment Station was established by the Bureau in 1922. In time, Laramie would come to be seen as Bartlesville's "sister station," with much cooperation and occasional transfer of employees between the sites.

Perhaps the biggest fundamental contribution made by Bartlesville in its early years was the formulation and confirmation of the "law of equal expectations": "If two wells under similar conditions produce equal amounts during any given year, the amounts they will produce hereafter, on the average, will be approximately equal regardless of their relative ages." First articulated as a hypothesis by petroleum researchers in 1918 following their analysis of data obtained from producing wells, it had achieved the status of a scientific "law" by 1925. Curves depicting the rate of decline of oil production showed that the future production could be predicted based on the amount of oil currently being produced and the rate at which production had declined. Such prediction capabilities were clearly a benefit to oil companies in their decisions to continue pumping or abandoning a well, and in estimating resources.

Several areas of investigation were so important that they were pursued extensively throughout the Smith years. Increasing the recovery of petroleum headed the list. In 1926, the Bureau estimated that only 20 percent of the original "oil-in-place" was being brought to the surface, with 80 percent left behind. To combat this clearly unacceptable scenario, in 1927 the Bureau announced a four-pronged approach: "(1) increasing recovery from producing fields, (2) repressuring exhausted fields, (3) mining the oil sands, heating, vacuum, and

In 1927, compressed-air repressuring at the Elliott, Oklahoma, oil pool increased production 240 percent in less than 18 months.

(4) fundamental studies of the flow of oil, gas, water, and mixtures of the three through the sands, studies of the porosity of sands."

Addressing the first point—increased recovery from active wells—involved understanding the best methods of drilling wells, along with their optimal spacing; developing improved explosives to fracture reservoirs, thereby releasing more of the oil and natural gas trapped inside; and discovering methods to dissolve or otherwise remove the paraffin waxes that built up in the reservoir and clogged the pores through which the oil and gas moved. It was also important to develop methods of controlling natural gas flow in oil wells, since pressurized natural gas was a major driving force in pushing oil to the surface; this topic fell under the category of natural gas "conservation."

The second approach was called "secondary recovery"—the recovery of additional oil from wells that had already been abandoned as spent. The earliest methods of secondary recovery involved injecting air or natural gas into an old well to force out more oil. The Bureau began investigating this "air-lift" or "gas-lift" method in 1925, beginning by studying the solubility of air and natural gas in crude oils. Dissolving gases in oil could reduce the viscosity of the oil, thereby making it easier to pump. In 1927, compressed-air repressuring at the Elliott, Oklahoma, oil pool increased production 240 percent in less than 18 months. The Seminole area in Oklahoma, one of the largest and most prolific oil fields in the country up to that time, reached its peak production of 529,000 barrels of petroleum in one day on July 30, 1927, aided by the natural gas-lift method. Gas lifting was used in the Seminole area early in the field's production life, which accounted for this record output; its production was expected to decline more rapidly than normal because of this unusual procedure.

In an effort to help Eastern oil producers in Pennsylvania, Ohio, and West Virginia resurrect their spent wells during 1926, the Bureau recommended "looking at increasing production through compressed air or natural gas or by *flooding with water* [emphasis added]." Considerable efforts had been made to this point to keep water out of oil wells, but new information indicated that flooding a well with water could force remaining oil out of an adjacent well. This reference was the first time the "waterflooding" method was mentioned in an annual report of the Bureau of Mines. Waterflooding would later become a highly successful and popular method of secondary oil recovery.

The third approach, the vacuum method, was perhaps the most interesting, though short-lived, process investigated. Bartlesville engineers began studying how pulling a vacuum on a well affected the production of oil and natural gas. By 1927, they were able to report that the effectiveness of vacuum recovery depended on local conditions. "If the sand is open textured, vacuum may increase production; but if the sand is tight, vacuum is useless, and may sometimes be harmful," the 1927 annual report stated. After a final report was issued the next year, the 1929 annual report noted, "In view of new methods of oil recovery, vacuum is becoming obsolete." Field studies of production problems kept Bureau engineers busy and oil companies happy. At the Powell field in Texas in 1925, Bureau personnel assisted in repairing 31 wells in order to exclude water; 25 of these repairs resulted in increased production. That same year, in the Wortham Field of Texas, the Bureau produced a detailed study including cross sections and structure-contour maps, and helped to plug leaks in 38 wells. "One well in the field was producing 100 percent water before it was plugged on February 15, 1925," the annual report for that year stated. "From the date of plugging to June 26, 1925, it produced 20,105 barrels of oil, an average of 159 barrels per day." By 1929, thirty-one fields in the Rocky Mountains, Texas, Oklahoma, Louisiana, and Arkansas alone had been improved through the Bureau's engineering field studies. The activity was abandoned in 1934 due to lack of funding in the Great Depression, but was pursued again with abandon immediately prior to and during World War II as oil production again became a priority.

By 1929, thirty-one fields in the Rocky Mountains, Texas, Oklahoma, Louisiana, and Arkansas alone had been improved through the Bureau's engineering field studies.

A better understanding of the physical and chemical properties of crude oils, which differed from field to field, was essential to the Bureau's efforts to develop improved recovery, transportation, storage, and refining methods. Samples of crude oils from different fields across the United States, and eventually the world, were analyzed every year to determine essential properties such as viscosity, volatility, density, and chemical composition. "Samples came from almost every producing field around the world and from every geologic age," the Bureau reported in 1927. "[The] Bureau's system classifies them into four main groups, and can tell the relationship between geologic age and the probable refinery yields of valuable products." In 1928, the Bureau published the results of the analysis of 300 crudes worldwide in Bulletin 291.

The Bureau also conducted motor-gasoline surveys. "With enormous growth in automobile traffic, quality of gasoline produced at different refineries using different crudes or different methods is a matter of public interest," the 1925 annual report observed. "As in previous years, the Bureau conducted semi-annual survey of motor gasolines sold in six cities." In 1927, researchers analyzed samples of gasoline sold to consumers in 10 cities. In 1930, plans were made to increase the number of audited sites to 300 per year, but the realities of the Great Depression led to the temporary suspension of the program in 1931.

"With enormous growth in automobile traffic, quality of gasoline produced at different refineries using different crudes or different methods is a matter of public interest." --1925 Bureau of Mines annual report.

The Bartlesville Petroleum Experiment Station conducted many other investigations throughout these years, including efforts to detect and prevent leaks in natural gas pipelines, investigation of geophysical methods of prospecting for oil and gas, prevention of petroleum and gasoline losses through evaporation while in storage, improvement of the fractional distillation process, isolation and identification of sulfur compounds in petroleum, and determination of the influence of the viscosity-volatility ratio of oils on engine service, among others.

The Great Depression

Toward the end of the 1920s, petroleum was plentiful, due to the improved methods of production developed by the Bureau and by private company

Experimental refinery at the Bartlesville Station in 1919.

A 1929 Model A Ford coupled to a device to lower a bottom-hole sampler into a well. (Bartlesville, 1932) laboratories, as well as to the continued discovery of new reservoirs, especially in Texas. Instead of conserving oil for times of higher demand, producers put their oil up for sale, thereby depressing prices. After the stock market crash of October 1929, Texas oil flooded the market, sending prices to new lows. The Bureau's 1931 annual report noted, "During the year the natural gas industry has expanded, extending its market to industrial centers and bringing gas into competition with other fuels. Concurrently, the petroleum industry experienced drastic economic adjustments, brought about by intensive development of prolific fields and resulting overproduction of crude oil."

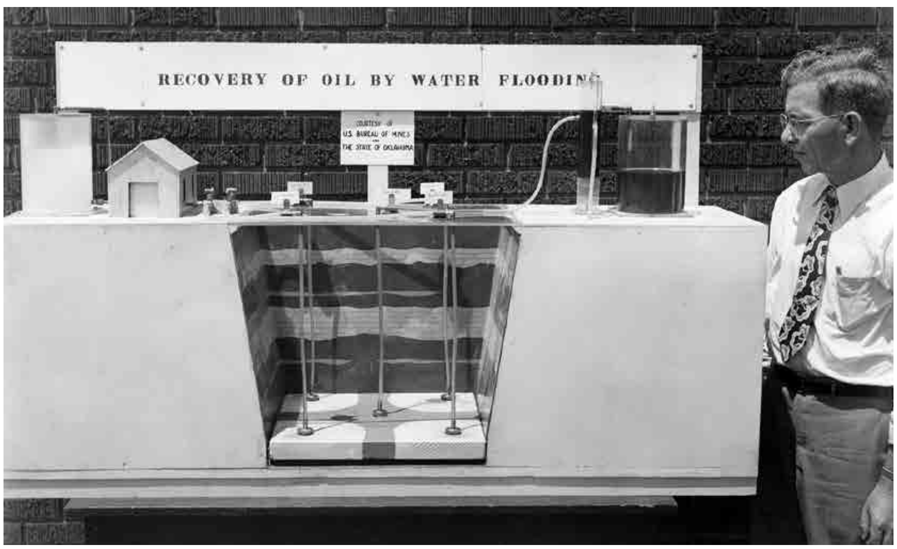
Remarkably, all the work at Bartlesville through the 1920s, as described above, was done with limited experimental space and resources. Nick Smith formally brought this situation to the attention of the Bureau in 1931: "In its present scope of activity the Petroleum Experiment Station, Bartlesville, Oklahoma, is restricted owing to lack of proper working quarters. In the temporary corrugated iron structures on the property it is almost impossible to obtain necessary constant-temperature conditions, and the floor space in these temporary buildings is altogether inadequate. The Bartlesville station needs an engineering research laboratory building."

Smith made his plea at precisely the worst time, as the effects of the Depression started to be felt more deeply. The motor-gasoline surveys were discontinued in 1931. In his 1932 report, Smith wrote, "Necessity requires indefinite suspension of research upon which years of development have been expended. Further effort will be made to unify and centralize all production and refining studies to place as many of the collected data as possible in form usable by the oil and gas industry." In lieu of further research, most employees were tasked with collecting and publishing data from past research. The Laramie Petroleum Experiment Station was closed in 1933 for lack of funds.

Still, Bartlesville made significant progress in a few important areas. Research into mathematical formulas to calculate the flow of natural gas in pipelines had begun in 1927; the goal was to find a formula that was sufficiently accurate but not too theoretical or complicated to discourage its use. In 1931, the Bureau published a report stating that the Weymouth flow formula was sufficiently accurate for all practical purposes for the pipeline sizes used commercially. By 1934, further work and refinements made it possible for Bartlesville to publish a report containing simplified calculations, along with curves and charts, to help gas company engineers design pipelines.

In the 1932 annual report, Smith was able to announce that "[t]he Bureau of Mines method of determining the potential capacities of gas wells has proved its economic value." He was referring here to the "back-pressure" method devised in Bartlesville, whereby special instruments developed to measure the back-pressure of a gas well could be used to calculate the rate of gas production. Based on 656 tests made on 489 gas wells, Smith wrote, "In 90 percent of these tests a straight-line relationship has been established between rates of delivery from the wells and pressure condi-

Dedication of the new adminstration and research building at Bartlesville in October 1937.



A table top display showing the "five-spot" method of waterflooding—four flooding wells surround the producing well in the center.

The new administration and research building at Bartlesville in 1937, built by the Public Works Administration.

tions in the wells. Company officials and others are now evidencing interest in the subject, and cooperative efforts are being made to eliminate the factors causing inaccuracies in well data. ... When this method was first proposed, some gas company engineers, State conservation officers, and others questioned the validity of the results." The previously used "open flow" tests, which wasted large quantities of natural gas by venting it to the atmosphere to determine the rate of gas delivery, had been replaced by the Bureau's back-pressure method, which produced no gas loss.

In 1933, a chemical method for removing elemental sulfur from petroleum was demonstrated for the first time. In his conclusion to that year's annual report, Smith wrote, "Many uneconomical practices, based upon rule-of-thumb methods, have been eliminated in oil and gas fields because basic knowledge regarding reservoir conditions has been obtained and reported by the Bureau of Mines…Work on oil and gas has been seriously crippled by termination of studies that had been developed to the point where definite results of practical value were assured." He also remarked once again on the lack of adequate laboratory space.

Nick Smith finally got his wish in 1936 when funds for a "greatly needed office-laboratory building" were provided through the New Deal's Public Works Administration.

The year 1936 proved to be a good one for Bartlesville. Smith finally got his wish when funds for "the long-requested and greatly needed office-laboratory building" were provided through the New Deal's Public Works Administration. The new building was dedicated in October 1937. Also, on July 1, 1936, the University of Wyoming at Laramie opened a new petroleum experiment station on its campus to replace the Bureau's office that had closed in 1933. The semi-annual motor-gasoline survey was also revived in 1936.

The March 10, 1937, edition of the *Bartlesville Enterprise* carried a story under the headline, "Oil Comes Back as Repressure Methods Used: Plan of Flooding Old Holes with Water to Force Out Oil Is Successful." "Repressuring is done under the 'five spot' method of drilling four wells to get one producer," the newspaper reported. "Sections are staked out in squares and at each corner a well is drilled and water forced under pressure into each of the wells. A fifth well is drilled in the center of the square and is known as the producer. The water pressure on the four outside points pushes the oil up through the middle well." The technique held out the promise of reviving old oil fields, increasing the country's production of oil, and creating new jobs—something on everyone's mind in the 1930s.

The Bartlesville Petroleum Experiment Station survived the 1930s, despite an oil glut and a worldwide economic depression, with a staff of more than 60 employees. N.A.C. Smith had carefully guided the station through the political and economic minefields of the era by focusing his limited research funds on studies that were sure to be of value to the petroleum and natural gas industry once the depression ended. Developing a fundamental understanding of the relationship between natural gas well pressures and expected production levels, building a database of motor gasoline characteristics, and investigating the possibilities of secondary oil recovery through waterflooding would all be of value when the Depression yielded to another world war.

C. Kenneth Eilerts

C. Kenneth Eilerts joined the Bartlesville Petroleum Research Center in 1930 as a junior chemist. In February 1934, having risen to the rank of research scientist, he was assigned a project that would dominate his life for more than 20 years, and in the process make him one of the most renowned scientists in Bartlesville.

Eilerts began studying the phase relationships of natural gas condensates in 1936 for a joint project between the Bureau and the American Gas Association called "Properties and Flow of Reservoir Fluids." Natural gas condensates are mixtures of liquid hydrocarbons that condense from a natural gas well when the temperature falls beneath the hydrocarbon dew point of the gas. Because these condensates frequently contain light hydrocarbons within the gasoline boiling range, they are sometimes called natural gasolines. Phase relationships describe the pressure-volume-temperature properties of these condensates, which varies depending on the conditions in the well.

Measuring temperatures and pressures in gas condensate wells using the crude temperature sensors and pressure gauges available at the time, Eilerts began assembling data on the phase relationships of gas condensates in numerous wells. In the late 1930s there was great interest in these properties, because gas producers had a market for gas condensates, which they could produce in significant quantities by "cycling" natural gas back into the well it came from. Understanding the physical-chemical properties of these substances could help them produce more. However, developments during World War II that made transportation of natural gas over long distances through pipelines possible ended the need for cycling, and Eilert's data lost some of its relevance.

Still, the project continued. Around 1951, approximately 15 years into the project, Eilerts began compiling his data for publication. In the meantime, he had become interested in the new computers that Oklahoma State University had acquired, and began experimenting with mathematical modeling of gas condensate fluid flow in underground reservoirs. He was scheduled to present the results on October 9, 1953, at the meeting of the Society of Petroleum Engineers in New Orleans. However, Eilerts suffered a heart attack on June 28, and spent the next month in bed recovering. This didn't stop him from continuing work on his paper, though. He fought through the setback and was able to deliver his paper entitled "Integration of the Partial Differential Equation for Transient Linear Flow of Gas-condensate Fluids in Porous Structures" on the scheduled date. The *Bartlesville Examiner-Enterprise* reported this series of events in November, but was most fascinated by the method Eilert's employed. "This paper," the newspaper said, "would have taken one person over 300 years to complete working by hand. But Eilerts, one of the first scientists at the bureau to become proficient in using the electronic computer, completed most of the work on the computer at Oklahoma State University before having his attack."

Eilerts finally published a two-volume book of his data "Phase Relations of Gas-Condensate Fluids," in 1958. By then his more than 20 years of work on the subject had made him an international expert, but some of his colleagues believed that he should have been working on other, more important investigations over the years. The book was irrelevant by the time it was published, they contended, because the window of opportunity for commercial application of the data had passed in the early 1940s.

Undeterred, Eilerts continued working on computer modeling of the flow properties of gas condensate fluids in the 1960s. He received recognition for his life's work on March 12, 1969, when the Natural Gas Processors Association presented him with its Hanlon Award for "outstanding industry contributions through research into the physico-chemical properties of natural hydrocarbon mixtures, condensate-well corrosion phenomena, and production characteristics of gas-condensate fields." A few months later, on July 13, the Bureau of Mines awarded him for his "Engineering Excellence" with the Arno C. Fieldner Award for his mathematical modeling work.

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

Chapter Three:
Safety and Health Work at Pittsburgh, 1920–1939


N.J.-1920
24246

Chapter Three:

Safety and Health Work at Pittsburgh, 1920–1939

From its years of study of coal-dust explosions the Bureau of Mines can say that great explosions should not be considered as normal occupational hazards.

--Bureau of Mines, Annual Report, *1923*

At noon on September 16, 1920, a massive explosion on Wall Street in New York City killed 38 people, injured 400 others, and shattered buildings in the financial district. George S. Rice, the chief mining engineer of the Bureau of Mines, was in the city at the time and went to the scene. "All physical evidence," he reported, suggested an act of terrorism—a bomb blast that was "planned with intent to destroy life" and "worked out with great cleverness." Rice based his assessment on the pattern of damage at the site and his long experience with observing the consequences of mine explosions. Within days, two other Bureau experts arrived in New York: Charles E. Munroe, chief explosives chemist, and S. P. Howell, chief explosives engineer. They arranged for tests at the Pittsburgh Experiment Station, which supported the theory that a bomb containing about 100 pounds of dynamite had caused the destruction. The case was never solved, although an anarchist group was believed to have been responsible. But the Wall Street bombing was duly listed in the Bureau's 1920–1921 annual report, alongside six other explosives-related disasters that the staff had investigated.

Crime-scene reconstruction was just one example of the scientific sleuthing that the Pittsburgh station undertook during the 1920s and the 1930s to help protect public health and safety.

Consequences of an explosion: Wall Street after the September 1920 bombing. (photo credit: Bettman/Corbis)

This venture into crime-scene reconstruction was just one example of the scientific sleuthing that the Pittsburgh station undertook during the 1920s and the 1930s to help protect public health and safety. As they continued to learn about sources of and remedies for accidents in coal mines, the chemists and engineers of the station found that their knowledge applied far beyond the mining industries. Rapid urban and industrial growth was creating new artificial environments, from pipelines and tunnels to power plants and congested city streets, where the dangers of fire, explosion, and noxious gases resembled the hazards that miners had long known. The Bureau's expertise in analyzing things that tended to blow up or poison people was thus helpful in solving engineering problems that affected millions of Americans.

Many of these problems centered on making the everyday use of coal, petroleum, and natural gas safer. Fossil fuels, whose concentrated energy helped to make modern industrial society possible, were also major sources of explosive dust and toxic byproducts that infiltrated homes and workplaces. Through public-private cooperative agreements, the Pittsburgh station investigated such issues as detecting odorless gases, ventilating tunnels that carried motor-vehicle traffic, and evaluating the safety of leaded gasoline. The Bureau publicized the findings and recommendations of these inquiries, following the strategy that it had first defined in mine-safety work to exert significant influence over public attitudes and behavior despite its lack of regulatory power.

Organization

The leadership of the Bureau of Mines changed hands several times in the immediate aftermath of World War I. Van H. Manning, who had directed the agency since 1915, resigned in mid-1920 to accept the position of director of research for the American Petroleum Institute. A talented civil engineer and administrator, Manning had overseen the expansion of the Bureau's experiment stations and was instrumental in creating the federal Chemical Warfare Service during the war. He was briefly succeeded by Frederick G. Cottrell, who had formerly served the Bureau as its chief physical chemist and chief of the Investigations Branch with a focus on research concerning helium and synthetic ammonia. Cottrell stayed for only six months before he departed to become the chair of the National Research Council's chemical research division. Following the arrival of H. Foster Bain as the next director in May 1921, greater stabil-

Bureau of Mines Directors Van H. Manning (left) and Frederick G. Cottrell (right). (photo credit: National Archives and Records Administration) ity set in. Bain, a geologist and Bureau veteran who had been the assistant director during 1918–1919, remained on the job until June 1925.

In 1919, the Bureau adopted a reorganization plan, establishing a structure whose basic logic would endure for the next three decades. This redesign was, as the 1920 annual report explained, necessary "because of the increasing variety of investigations conducted, the many changes following the war, and the need of closer coordination of the work of the experiment stations and that of the several divisions." Two broad units were established: the Investigations Branch—comprising the experiment stations and the technical divisions that were actively engaged in scientific research and development—and the Operations Branch—consisting of divisions that performed administrative services. Most of the Bureau's work on fuels and energy came under the umbrella of the Investigations Branch. However, the certification of permissible explosives and the management of the Bureau's mine-rescue stations and railroad cars were assigned to the Operations Branch.

The Pittsburgh Experiment Station occupied a pivotal place within this structure. Like the other eleven experiment stations that the Bureau operated as of 1920, it was a regional service center, bringing federal resources to bear on analyzing and developing the mineral industries that were specific to its part of the country. For the Central Appalachians, those regional mineral specialties were coal and iron. Bureau scientists and engineers from several different technical divisions, such as the Fuels Division and the Metallurgical Division, were assigned to Pittsburgh to work on problems related to the mining and use of coal or the manufacture of iron and steel. Pittsburgh was the base for District A of the Mining Division, whose field engineers studied mining activities and investigated mine disasters from Maine to Kentucky.

However, the Pittsburgh station, the largest of all the experiment stations, also provided specialized functions for the entire Bureau of Mines organization. Its outstanding chemistry laboratories, such as the Chemical Research Laboratory, the Analytical Laboratory, and the Coal Inspection Laboratory, were central hubs. For example, whenever field engineers captured samples of air from a mine, they sent the samples to Pittsburgh to be analyzed for toxic gases or excessive dust levels. The Explosives Laboratory and the Experimental Mine made Pittsburgh the focus of research on fires and explosions. Certain services of the Operations Branch were also handled there, including the publication and distribution of official reports and educational films. Thus Pittsburgh was second only to the Bureau's national headquarters at Washington, D.C., in administrative importance.

From 1920 to 1924, the superintendent of the Pittsburgh station chaired an inter-divisional mine safety committee, which met monthly to pool information from all units of the Bureau that dealt with health and safety issues. This coordinating function passed in 1924 to a Mine Safety Board, headed by the chief mining engineer in Washington, that issued official Bureau policy statements about safety equipment and mining methods. The same 1924 administrative order established the Safety Service, which unified responsibility for publicizing the Bureau's recommendations and conducting the first-aid and mine-rescue training programs, and provided for cooperation between the Bureau and the U.S. Public Health Service. It also recognized a Division of Mining Experiment Stations to administer the facilities of all twelve stations, including Pittsburgh.

On June 4, 1925, President Coolidge signed an executive order that transferred the Bureau of Mines from its original home in the Interior Department to the newly created Commerce Department.

On June 4, 1925, President Calvin Coolidge signed an executive order that transferred the Bureau of Mines from its original home in the Interior Department to the newly created Commerce Department. Two rationales justified this move, which took effect on July 1 of that year. The Coolidge administration had identified overlaps between the Bureau and the Commerce Department, such as the fact that both agencies compiled statistics on minerals production and sponsored research on petroleum. Efficiency and cost-saving advantages therefore favored consolidation. Furthermore, administration officials—especially Secretary of Commerce Herbert Hoover, who was trained as a geologist and mining engineer and had wide experience in the mining industries—argued that the main purpose of the Bureau was to assist private mining interests in improving productivity and increasing the output of useful minerals. The Bureau, in this view, should be grouped with other business-oriented federal agencies.

Supporting the emphasis on service provision to industry was a mechanism that had gradually evolved since the mid-1910s to permit collaboration between the Bureau and organizations outside the federal government. Under a contract known as a *cooperative agreement,* an organization that desired technical assistance from the Bureau could agree to pay all or part of the cost of an investigation that Bureau personnel directed and conducted. All findings of any such inquiry would be made public. This system, which had originated in efforts to improve the enforcement of state mining laws, was well received. By 1920, the Bureau had cooperative agreements with eleven state agencies, twelve universities, and four private companies, and the number continued to rise over the subsequent decade.

Scott Turner, a mining engineer and personal friend of Secretary Hoover, directed the Bureau from mid-1925 through the rest of the Coolidge administration and through Hoover's presidency (1929-1933). During this period, the Bureau increased its focus on the economics of the mineral industries. It took over responsibilities that had previously belonged to the U.S. Geological Survey for collecting and analyzing statistics about commercially valuable minerals, including fossil fuels. Another reorganization in 1926 formally established the Economics Branch, which led to the inauguration in 1933 of one of the Bureau's most popular and important publications: the annual *Minerals Yearbook*. Most of the former Investigations Branch became the Technologic Branch, the Operations Branch was renamed the Administrative Branch, and the activities of the Safety Service, liaison with the Public Health Service, and the mine-rescue stations were placed in a new Health and Safety Branch.

This committee was appointed by Secretary of Commerce Herbert Hoover to oversee the transfer of the Bureau of Mines from the Interior Department to the Commerce Department in 1925. (photo credit: Library of Congress)

Bureau of Mines Director Scott Turner (right) with Chief Mining Engineer George S. Rice (left) at the Experimental Mine, 1930. (photo credit: National Archives and Records Administration)

During the late 1920s and the 1930s, the Pittsburgh Experiment Station remained the center of federal research and development on coal, explosives, and mining safety. A description in 1928 tallied at least seven distinct subgroups within the station that contributed to the Bureau's health and safety mission: the Health Laboratory, the Explosives Section, the Fuels Section, the Metallurgical Section, the Physical Section, the Experimental Mine Section, and the Mining Research Section. Budget cutbacks during the worst phase of the Great Depression temporarily forced the reduction or cancellation of projects and programs. The annual report for the 1933–1934 fiscal year observed that "the explosives work of the Bureau was at the lowest ebb in its history," and most Health and Safety Branch activities were suspended between 1933 and 1935. But with gradual economic recovery and increased funding under the administration of Franklin D. Roosevelt, the tempo of activity at the station picked up again.

The Roosevelt administration moved the Bureau of Mines back to the Interior Department in 1934.

The Roosevelt administration moved the Bureau of Mines back to the Interior Department in 1934 and appointed John W. Finch as the next director, a position that Finch held until 1940. Rejecting its predecessors' vision of the Bureau as primarily an instrument of economic development, the new administration emphasized that the agency had multiple functions, including conserving natural resources and protecting workers and communities. The Pittsburgh station received appropriations to modernize its physical plant and carry out new initiatives, notably a program of sealing abandoned coal mines to prevent water contaminated with acidic coal byproducts from seeping into the rivers and streams of the Ohio Valley. In 1936, a new Coal Division, separate from the rest of the Mining Division, was created within the Technologic Branch to highlight the distinctive importance of the coal research that Pittsburgh had pioneered and that remained foundational to the identity and work of the Bureau of Mines.

Controlled explosions at the Bruceton site virtually ceased during the hard times of the early 1930s, but increased again in the late 1930s as the threat of war loomed.

Advancing Mine Safety

Building on its signature prewar discoveries about the explosiveness of coal dust, the Pittsburgh station continued to study why and how mine explosions occurred. Most of its research on this subject migrated to new quarters near the Experimental Mine in Bruceton, for safety reasons and to improve coordination between laboratory work and the unique facilities at the mine. The Bureau of Mines purchased the Experimental Mine site and nearby lands from the Pittsburgh Coal Company in 1924, ending its previous leases and clearing the way for expanded operations. Controlled explosions at the site totaled over 500 by June 1923, reached a single-year peak of 122 during 1925–1926, virtually ceased during the hard times of the early 1930s, and increased again in the late 1930s as the threat of new war loomed.

Research on explosions had three major components. The first was analyzing the chemical reactions that took place when dust or mixtures of dust and mine gases ignited and exploded. The second was identifying the upper and lower flammability limits—which defined the range of concentrations that created a fire hazard—for various combinations of gases, vapors, and dusts that could be found in the air of coal mines. The third involved studying the physics of what happened when an explosive charge went off in an atmosphere that contained flammable gases.

Photography was a valuable ally in probing the dynamics of explosions. New methods of image capture made the invisible visible, exposing the patterns that flames, sound waves, and hot gases and particles made as they spread outward from the initial site of a detonation. "As the duration of the flame from a permissible explosive is less than one one-thousandth second, the use of photography in the study of the flame is particularly desirable. . . ." the Bureau's 1926 annual report noted. "Photographs of the flames produced when charges of explosives are fired from a cannon show graphically the increased safety of certain explosives and certain methods of loading." In 1938, the Explosives Division captured on film the tracery of sparks that an explosive charge released and demonstrated that these tiny incendiary particles could ignite balloons filled with natural gas (methane) and oxygen up to 23 feet away.

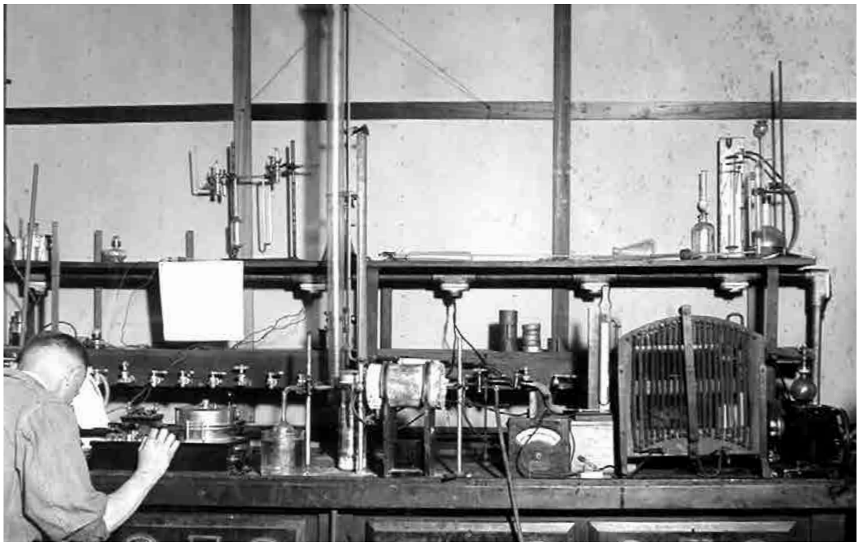
Photography was a valuable ally in probing the dynamics of explosions...exposing the patterns that flames, sound waves, and hot gases and particles made as they spread outward from the initial site of a detonation.

To reduce the frequency of mine explosions, the Bureau maintained its focus on eliminating common sources of ignition or modifying them so that they became less likely to touch off an accidental blast. The Pittsburgh station continued to test commercial explosives for conformance with the permissibility standards. In 1929, the official active list of permissible explosives contained 130 different products; in 1937, it stood at 195. The list changed frequently when manufacturers formulated new explosives or took older ones off the market.

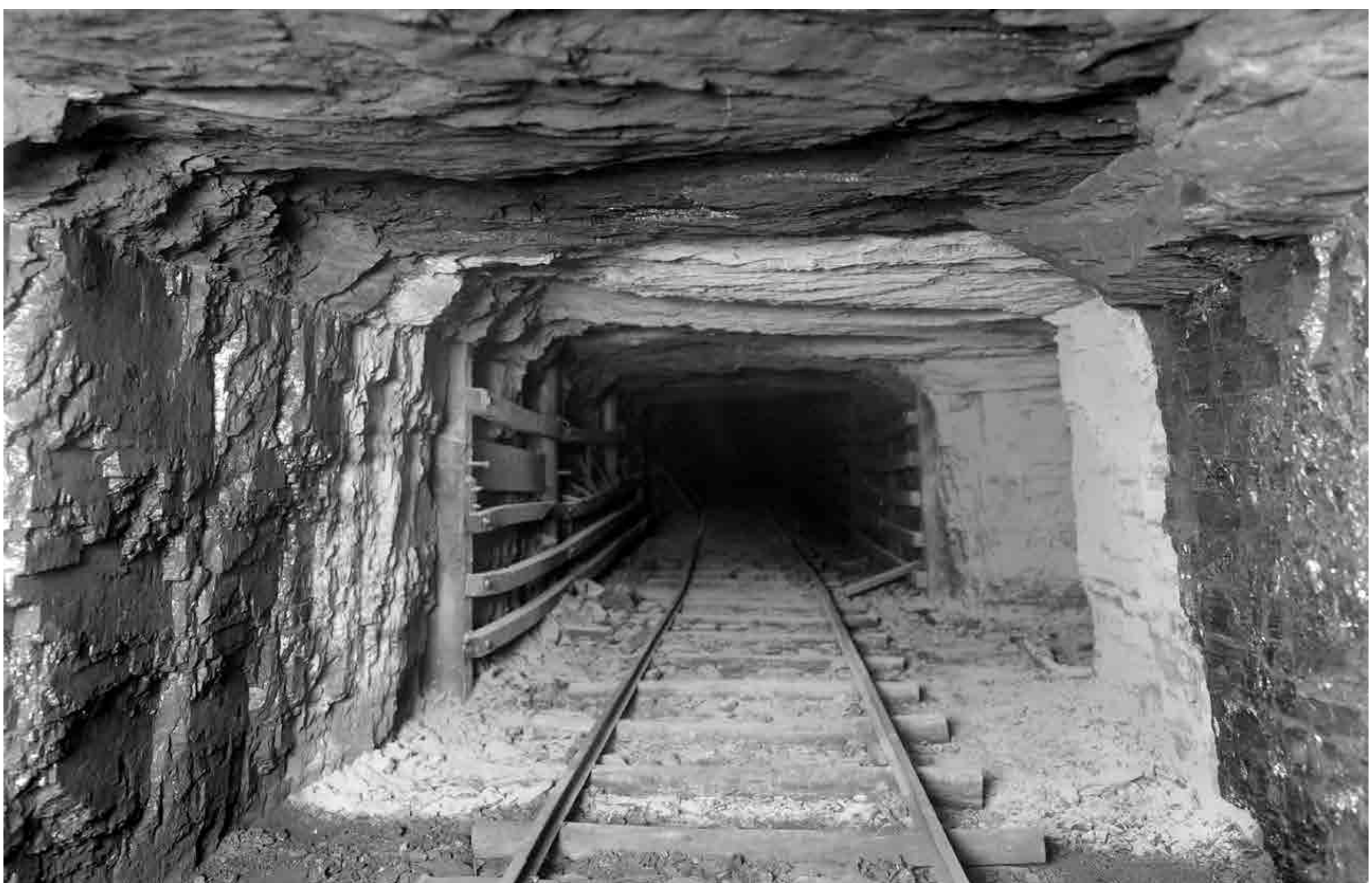
The Pittsburgh station defined and implemented similar permissibility standards for electrical equipment. As American coal-mine operators embraced mechanization and electrification to improve productivity, sparks from exposed motors and short-circuits in wiring soon rivaled explosives and open flames as triggers of catastrophic mine accidents. By 1920, the Bureau had developed permissibility lists for common electrical devices, and new types of electrical machinery were constantly added to the evaluation process over the next two decades: electric coal-cutting machines, automatic coal loaders, pumps, and battery-powered locomotives.

By 1920, the Bureau had developed permissibility lists for common electrical devices, and new types of electrical machinery were constantly added to the evaluation process over the next two decades: electric coal-cutting machines, automatic coal loaders, pumps, and battery-powered locomotives.

But permissible equipment and explosives could only reduce, not eliminate, the menace of gas and dust explosions. Thus the Bureau also aggressively promoted ways to contain any fire or explosion that did get started, in order to prevent entire mines from being engulfed. Three practical methods, all dependent on controlling coal dust, existed for halting the propagation of an explosion through a coal mine. Water could be sprayed on interior surfaces so that an initial shock would not raise clouds of dust to carry the explosion farther. Humidification, in which warm, moist air was blown into the mine, likewise relied on moisture to limit airborne coal dust. The cheapest, most effective technique was rock dusting, in which interior surfaces were coated with a layer


Laboratory equipment for determining the flammability limits of gases. (photo credit: National Archives and Records Administration)


High-speed photography revealed branching patterns in the paths of sparks thrown off by an explosion. (photo credit: Bureau of Mines publication)


A mine tunnel partially coated with light-colored rock dust. (photo credit: National Archives and Records Administration)

of powdered limestone, gypsum, shale, or some other mineral that would not catch fire. By diluting coal dust with this inert mineral dust, the mine operator could prevent the general concentration of coal dust in the mine air from reaching flammable levels.

After a wave of mine disasters in the early 1920s, such as the March 8, 1924, explosion of the Castle Gate No. 2 coal mine in Utah that killed 172 people, the Bureau set out to persuade all American coal companies to rock-dust their mines. The campaign emphasized personal contact with mine operators and field demonstrations of rock dusting. Bureau officials cited the example of Great Britain, which had mandated rock dusting in 1920 and had subsequently experienced a drop in fatal mine explosions. They helped mine operators determine how much rock dust a particular mine needed and locate rock-dust suppliers. This effort had some impact, especially among large coal producers. A few mines had been rock-dusted even before World War I, but the practice became far more widespread beginning in the mid-1920s. As of 1937, Bureau statistics indicated that 8.5 percent of U.S. coal mines, accounting for 43 percent of coal-mining employment and almost half the country's coal output, used rock dusting.

The cheapest, most effective technique was rock dusting, in which interior surfaces were coated with a layer of powdered limestone, gypsum, shale, or some other mineral that would not catch fire.

Continuing improvements in personal protective gear and rescue techniques saved lives that would otherwise have been lost during mine accidents. By 1939, the Bureau had given emergency first-aid training to over 1.3 million individuals, including almost a million coal miners. Thousands of mine workers, local first responders, and private civic groups had received advanced instruction in mine rescues and accident prevention. Permissibility standards for devices such as respirators and gas masks guided mine operators in choosing effective safety equipment. The Pittsburgh station experimented with radio and the geophone, a machine that translated earth movements into electrical signals, to locate and communicate with miners who became trapped underground.

By 1939, the Bureau had given emergency first-aid training to over 1.3 million people, including almost a million coal miners.

The overall results of these mine-safety initiatives were modestly positive. A sustained drop in the annual number of explosions and accidents involving explosives began in the 1930s. In 1937, the Bureau reported that "[e]xplosions in the coal-mining industry have grown so infrequent that during the year it was necessary to stage 'artificial' explosions in the Bureau's Experimental Mine so that safety engineers could be given some experience in coping with conditions accompanying actual disasters." But no comparable declining trend was evident in total coal-mining fatalities from all causes, or in the rate of deaths per hours worked. Coal mining remained one of the most dangerous industries in the country as new hazards—such as electricity—replaced older ones and as mines grew larger and more complex.

Most casualties came not from dramatic explosions but rather from small, little-noticed events that accumulated over time: a collapsed roof here, a derailed coal car there, an electrocution or asphyxiation in some remote section of a mine. The Bureau's 1923 report observed that in roof falls and coal falls, "men are picked off, one by one, as by snipers on a battlefield, but the total reaches nearly 50 per cent of all deaths." These problems were hard to deal with. The Mining Division did not begin studying roof-fall accidents until 1927, and the solutions—better mine design and construction, and pervasive attention to safety in all aspects of mine operation—required commitments of time and money that mining companies often hesitated to make.

Even proven safety techniques, such as rock dusting and permissible explosives, took hold slowly. At the Bureau's thirtieth anniversary in 1940, permissible explosives still accounted for only 45 percent of the explosives that American coal mines used. Eleven states required either watering or rock-dusting of mines to suppress coal dust, and many more authorized insurance discounts for mines that adopted Bureau-approved permissible equipment. But most safety work still consisted of laborious efforts to coax mine operators and mine workers into voluntarily making safety a high priority. The Pittsburgh station never slacked in that task.

Explosive Situations

Mining was not the only industry in which changing technology and organization created new explosion hazards that attracted the Bureau's attention. During the 1910s, operators of furnaces and boilers began using pulverized coal, made by grinding coal into small particles that formed a coarse powder. This practice expanded during the 1920s to become the standard fueling method in the electrical-power generating industry, thus introducing the dangers of coal dust into factories and power plants across the country. The Pittsburgh station studied the properties of pulverized coal and advised plant managers on how to store and burn the fuel efficiently while minimizing the risks of fire and explosion. It also analyzed explosive industrial materials other than coal. For instance, during the late 1930s it performed flammability tests on innovative synthetic chemicals that were entering commercial use, such as vinyl chloride and a promising new refrigerant that would soon be known as Freon.

Sewers, manholes, and vaults for electrical equipment were prime locations for volatile dusts and gases to accumulate in urban and industrial areas. On January 18, 1922, a sewer-gas explosion in Lower Manhattan caused a panic as people wrongly assumed that bomb-wielding anarchists had struck again. Short-circuits in underground electrical conduits caused multiple blasts in downtown Boston on February 14, 1929, injuring 40 people. In response, the Pittsburgh Experiment Station teamed up with the Boston Edison Company and the Boston Consolidated Gas Company on a long-term study of explosion hazards in urban utility networks. This cooperative agreement, which began in 1929 and continued through the 1930s, produced many useful findings on sampling air quality in manholes and improving ventilation in underground spaces.

Methane, that ancient peril to miners, also endangered surface dwellers in its guise as the main component of natural gas. Between 1920 and 1940, output of natural gas in the U.S. more than tripled, rising from insignificant levels to become an important component of the nation's energy supply. This fuel was widely used only in four regions that had abundant local supplies of it: the Central Appalachians, the Gulf Coast, the Mid-Continent, and Southern California. Advances in long-distance pipeline technology, however, were steadily extending its range; for example, metropolitan Chicago and Washington, D.C., gained access to natural-gas supplies in 1931. Natural gas was prized for use in industrial process heating and for domestic heating and cooking, where its cleanliness and efficiency made it a superior replacement for coal.

That very cleanliness made natural gas potentially lethal. Unlike coal or coal-based manufactured gas, which had a characteristic smell, methane-rich natural gas was odorless and undetectable without special equipment. It could easily reach dangerous concentrations inside an occupied building before anyone recognized its presence. Asphyxiations, fires, and explosions attributed to natural-gas leaks rose during the 1920s and the 1930s as the fuel found wider markets. Among these cases were several horrific mass-casualty events. Hundreds of Pittsburghers were injured and 28 died when gas-storage tanks on the city's North Side exploded on November 14, 1927. At New London, Texas, an elementary school that had been improperly connected to a natural-gas disposal line belonging to a local petroleum company blew up on March 18, 1937, killing approximately 300 people (the exact total was not known). Leaking natural gas in a school at Barberton, Ohio, on May 31, 1939, triggered an explosion that resulted in 44 injuries but no fatalities. Bureau of Mines experts from the Pittsburgh station investigated these and other disasters.

Keenly aware of the havoc that methane caused in mines, Bureau personnel were anxious to stem the proliferation of similar catastrophes above ground. The solution to the problem of stealthy, explosive natural gas was simple in concept: Add a *warning agent*, an artificial attention-getting substance, to the gas stream. Warning agents had been studied in Europe since the 1880s, but American chemical engineers paid little heed until chemical-warfare research during World War I stirred interest in the topic. The Pittsburgh station published three papers during 1919 and 1920 on the use of warning agents to detect es-

A natural-gas pipeline under construction in 1922. Advances in pipeline technology during the 1920s and the 1930s made long-distance distribution of natural gas to American towns and cities possible.

caping gas in mines, industrial plants, and urban gas-distribution lines. By 1926, gas leaks had become such a wasteful and deadly problem that the American Gas Association (AGA) asked the Bureau to make a thorough investigation.

The inquiry was to examine the pros and cons of odorants and irritants, the two main types of warning agent. An odorant is a chemical that produces a stench—a smell so distinctive, so obnoxious, that people cannot help noticing it and wanting to escape it. An irritant is a chemical that disturbs the eyes or the upper respiratory tract, causing itching, weeping, sneezing, coughing, or some miserable combination thereof. Hardly any scientific data existed to indicate which type was better for alerting people to danger. So the Chemical Research Laboratory at Pittsburgh set out to establish baseline information by identifying 89 different smelly or irritating chemical compounds that had potential to be warning agents and choosing 57 of them for further analysis. Between 1926 and 1930, the station evaluated these compounds according to five criteria: effectiveness, safety, lack of reactivity (so that the substance would not corrode pipes and equipment), ability to travel over long distances without losing strength, and cost.

Using an odorimeter that two Bureau staff members designed, the laboratory exposed volunteers to measured concentrations of unpleasant compounds.

Using an odorimeter that two Bureau staff members, S. H. Katz and V. C. Allison, had designed, the laboratory exposed volunteers to measured concentrations of the unpleasant compounds. The odorimeter infused a vaporized sample of a test substance into a known volume of air, diluted this mix to the level the experimenters wanted, and blew the resulting gas through a glass funnel that fit over a person's nose. Volunteers used a standard five-point intensity scale to record their observations about the strength or weakness of the odorants or irritants. At a nearby fraternity house and in laboratory space at the Mellon Institute of Industrial Research, the investigators also tested the ability of several warning agents to awaken sleeping people. Irritants proved to be better than

With the help of volunteers, the Bureau of Mines used the odorimeter to study human reactions to odorants and irritants. (photo credit: National Archives and Records Administration)

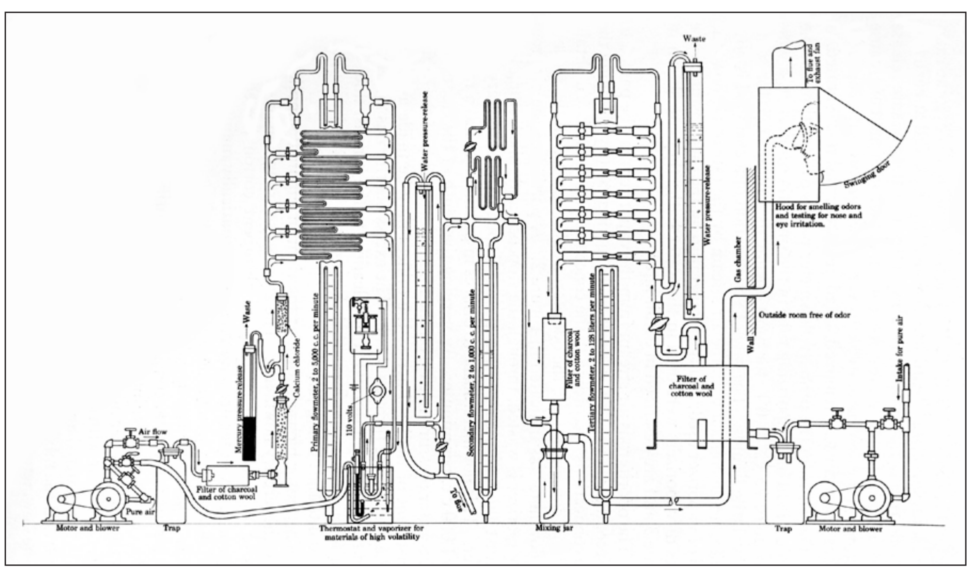


Diagram of the odorimeter for evaluating potential warning agents. (photo credit: Bureau of Mines publication) odorants for that purpose.

The testing revealed some especially promising options: crotonaldehyde, an irritant; ethyl mercaptan, an odorant; and a set of odorants, notably the hydrocarbons butylene and amylene, that closely resembled the then-familiar smell of manufactured gas. All these chemicals were effective warning agents that did not seriously corrode metal and, at least in tiny concentrations, did not create health or safety hazards. To see how well the substances carried through actual gas pipelines, researchers from Pittsburgh conducted field tests with the cooperation of utility companies in a large East Coast manufactured-gas system (Baltimore) and several small Midwestern cities that used natural gas or combinations of manufactured and natural gas. Warning agents were added to the normal flow of gas through the cities' distribution networks, and Bureau personnel took samples at multiple locations over several days to check how fast and far the agents spread.

The field tests demonstrated that crotonaldehyde, ethyl mercaptan, and the hydrocarbons all diffused easily and remained intense even at distant sites. Warning agents identified many gas leaks in the host cities, and the official report noted that the tests averted a potential catastrophic explosion at Linton, Indiana:

> *Another complaint [in Linton] was made the day before the addition of crotonaldehyde to the gas was stopped and the second day of the use of ethyl mercaptan. This came from a fireman at a theater who said there was a decided irritating atmosphere in the basement. Observation showed this to be due to a gas leak 100 feet distant under the floor, and the concentration of the crotonaldehyde near the leak was so strong that it could not be approached. In attempting to repair the leak two days later the irritation had abated, but a strong odor of ethyl mercaptan was present. Inspection showed a corroded pipe with a ¼-in. hole. This was a very bad leak and jeopardized many persons.*

Ethyl mercaptan stood out for its success in making residents notice even small leaks. During a field test with the natural-gas supply at Middletown, Ohio, in July 1929, people quickly learned to associate this odorant with escaping gas and to contact the local gas company when the stench appeared. Nine days of testing resulted in 1,722 documented complaints, 94 percent of which accurately flagged defects in pipes, meters, burners, and appliances. Utility workers could much more easily find leaks, both above ground and underground, when the warning agent was present. Other odorants and irritants also greatly improved leak detection, but the sheer repulsiveness of ethyl mercaptan, which residents who encountered it described as "terrible," seemed to give it an edge in goading people to seek immediate help. Rough estimates also indicated that it had a cost advantage over alternatives such as crotonaldehyde.

The Bureau of Mines report, which the AGA published in 1931, did not conclusively recommend any single warning agent. It summarized information about the several chemical compounds that the Bureau had found to be suitable and concluded that further trials would "be necessary before final judgment can be reached as to the practical value and commercial feasibility of adding warning agents to fuel gases." That final judgment was a long time in coming. As with permissible explosives and rock-dusting in mines, the adoption of warning agents was a slow process. A few states—notably Texas, after the 1937 New London school disaster—soon began to require their use, and some utility companies adopted them voluntarily. But not until the late 1940s and the 1950s would the practice of adding warning agents, usually ethyl mercaptan or its relative methyl mercaptan, become the norm throughout the country.

Despite all precautions, explosive gases and vapors remained capricious menaces, and the Bureau of Mines itself was not immune. On March 30, 1936, residents of Pittsburgh's East End awoke in the night to the terrifying spectacle of an outbuilding behind the main Pittsburgh Experiment Station laboratories on Forbes Avenue blowing up. The outbuilding, which had been used to store flammable gases and chemicals, was utterly obliterated. Supervising Engineer W. P. Grant had only one response to inquiries about the causes of the blast: We don't know. The destruction was so complete, and the possible causes so numerous, that the Bureau's expert explosion detectives could not definitely solve the mystery that had erupted in their own backyard.

Invisible Dangers of the Motor Age

In 1919, the New York State Bridge and Tunnel Commission and the New Jersey Interstate Bridge and Tunnel Commission had a problem. The two agencies wanted to build a tunnel that would carry motor vehicles under the Hudson River between Jersey City and New York City. Consisting of twin cast-iron-and concrete tubes that extended for over 8,000 feet and plunged 60 feet beneath the average low-tide level of the river, the project was the largest-diameter underwater tunnel yet attempted in North America and the first such tunnel in the world to be designed expressly for automobiles. But engineers with the Tunnel Commissions were not sure how to prevent deadly concentrations of exhaust fumes from forming inside the tubes. Ordinary methods of using natural air currents or mechanical fans to blow air from one portal of a tunnel straight through to the other could not work in such long, deep shafts. A new type of forced-air ventilation system was needed to convince motorists and the general public that the new civil-engineering marvel would be safe.

The Bureau of Mines, which had acquired extensive knowledge of tunnels and poisonous gases through its mining-safety research, was a logical source of advice. Accordingly, the Tunnel Commissions asked the Bureau to help implement a ventilation research program outlined by Clifford Milburn Holland, the chief engineer for the trans-Hudson tunnel. Laid out in two cooperative agreements between 1919 and 1921, this effort resulted in the most comprehensive set of data and analyses that had ever been prepared on automotive exhaust gases and underground air circulation.

The joint research program had four components. First, the investigators had to estimate the volume and composition of the exhaust gases that tunnel traffic would produce. Arno C. Fieldner, the capable and ambitious supervising chemist of the Chemical Research Laboratory at the Pittsburgh station, took charge of this work. He and his staff devised a program of road-testing vehicles over two carefully planned courses, laid out on Pittsburgh city streets, that approximated the range of speeds and grades proposed for the tunnel. Federal agencies, the City of Pittsburgh, car dealers, and private owners donated cars and trucks for the experiments.

Volunteers sat in a gas chamber for an hour at a time, breathing controlled mixtures of air and pure CO while fidgeting gently to mimic the actions of driving a car.

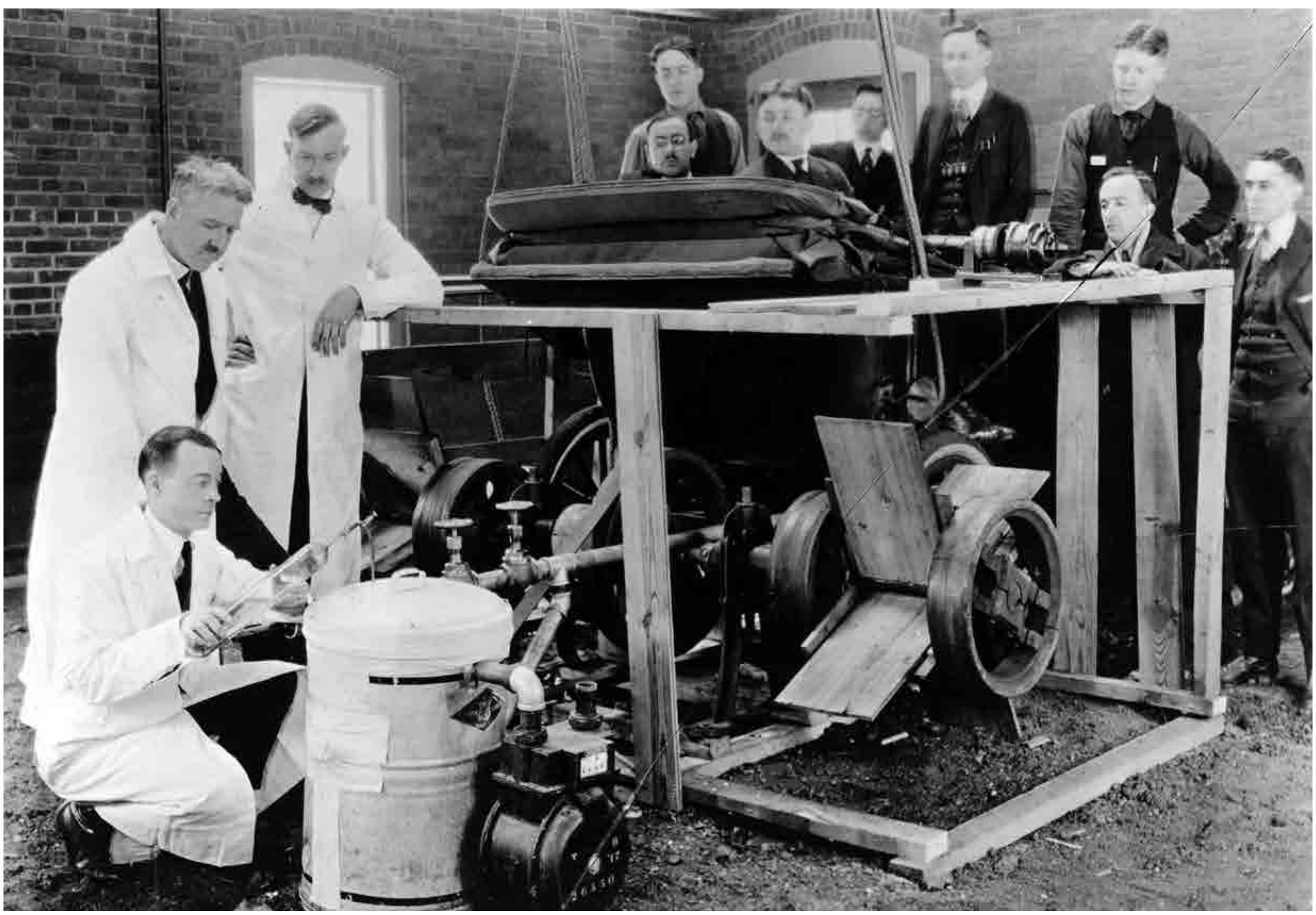
Between December 1, 1919, and September 30, 1920, 101 different vehicles were operated on the test courses. Each carried instrumentation to determine the amount of gasoline consumed and to capture samples of exhaust gas. From these data, the Chemical Research Laboratory calculated the amount of carbon monoxide—CO, the principal toxin in the gas—that the vehicles emitted under various conditions: idling fast or slow, moving uphill or down, operating in summer or in winter.

This evidence revealed that cars and trucks in an urban environment generated exhaust with CO content that ranged between 5 percent and 9 percent and averaged 6.5 to 7 percent—a higher level than the researchers had anticipated. Unburned gasoline vapor was also present in quantities large enough to create an explosion hazard. The findings were initially disconcerting because they suggested that the tunnel ventilation system would require a larger capacity, and therefore greater expense, than Chief Engineer Holland and the Tunnel Commissions had anticipated.

But how much carbon monoxide could human beings safely tolerate? The second phase of the investigation addressed this question, and the answer would establish the clean-air standard that the ventilation system had to meet. With the help of Dr. Yandell Henderson, a physiologist at Yale University, the Bureau and the Tunnel Commissions sponsored tests of human reactions to CO. Volunteers sat in a 226-cubic-foot gas chamber at Yale's Laboratory of Applied Physiology for an hour at a time, breathing controlled mixtures of air and pure CO while fidgeting gently to mimic the actions of driving a car. Inside a second, 12,000-cubic-foot gas chamber that represented a section of the trans-Hudson tunnel, a stationary Ford car was placed, with its running engine operating paddle fans for air circulation. A dozen or more volunteers sat or walked around near the car, breathing the exhaust-laden air. Blood tests taken before, during (in the small chamber), and after the experiments measured the concentration of CO in the subjects' bloodstreams, and the physical effects of the exposure were observed.

The findings of these tests, and of other experiments with animals, were clear and consistent: A ratio of 6 parts CO to every 10,000 parts of air was the outermost tolerable level before symptoms of poisoning appeared. A ratio of 4 parts CO to every 10,000 parts of air was an appropriate safety threshold, the allowable maximum for short-term exposure. The investigators disagreed

A Brockway five-ton truck participating in the Pittsburgh road tests that yielded vital data on motor-vehicle exhaust emissions. (photo credit: National Archives and Records Administration)



An experiment on the toxicity of carbon monoxide in the Laboratory of Applied Physiology at Yale University. (photo credit: National Archives and Records Administration) with earlier studies that had proposed an even lower safety threshold. Those studies, they noted, had dealt mostly with situations where long contact with foul air in confined spaces was likely. Since drivers in the trans-Hudson tunnel would be exposed for only a brief time, expected to be less than 45 minutes, a somewhat higher concentration of CO was deemed to be acceptable in the tunnel than would be acceptable in a mine.

Next, the inquiry turned to determining the volume and speed of airflow for clearing contaminated air in order to maintain the safety threshold. Heating and ventilation engineers had standard formulas for making such computations, but more specific information about the characteristics of the tunnel was needed. At Urbana, Illinois, a team led by A. C. Willard of the University of Illinois Engineering Experiment Station built a scale model of the ductwork that Chief Engineer Holland and his colleague Ole Singstad proposed to use for forcing air into and out of the tunnel at high speeds. Studies of this model revealed the good news that earlier laboratory tests had greatly overestimated the amount of friction created by air passing through the ducts. It was thus possible to move the requisite air with less power than originally anticipated. The research also revised existing theories about how air behaved in long passages and led to an improved vent design for circulating air from the ducts across the tunnel roadways.

Researchers created a larger model of the entire trans-Hudson tunnel inside the Experimental Mine at Bruceton, dubbed the "underground speedway."

Finally, the researchers created a larger model of the entire tunnel inside the Experimental Mine at Bruceton. In 1921, Bureau of Mines engineers connected two existing parallel mine tunnels with new curved passages to form a fully enclosed oval track 135 feet long, 110 feet wide, and 130 feet below ground. The floor and the walls of the enclosure were lined with concrete, and a slightly elevated roadway was built so that cars could circulate in single file around the track. Two airlocks that connected to other sections of the Experimental Mine allowed cars and other equipment to enter and exit. A network of sensors and sampling devices monitored air volume, CO levels, humidity, and temperature throughout the track and in nearby areas of the mine.

Dubbed the "underground speedway," the track allowed the engineers to double-check their earlier calculations in a controlled environment that resembled the expected conditions in the trans-Hudson tunnel. The Bureau conducted 17 tests at the Bruceton facility between September 19 and October 26, 1921. Trained drivers piloted Ford cars around the speedway, with the number of cars circling the track at any given time ranging from one to eight. Technicians matched data on gasoline usage and exhaust gases against data from the road tests in Pittsburgh to see if there was a reasonable similarity. There was. CO concentrations in the cars, the tunnel, and the blood of the participants also accorded well with the findings previously obtained at Pittsburgh and New Haven.

Another purpose of the underground speedway was to settle a raging dispute over the best way to manage the airflow within a tunnel. Some ventilation experts favored an updraft design, in which fresh air came up from below the roadway and fouled air exited through ducts in or near the ceiling. Others insist-

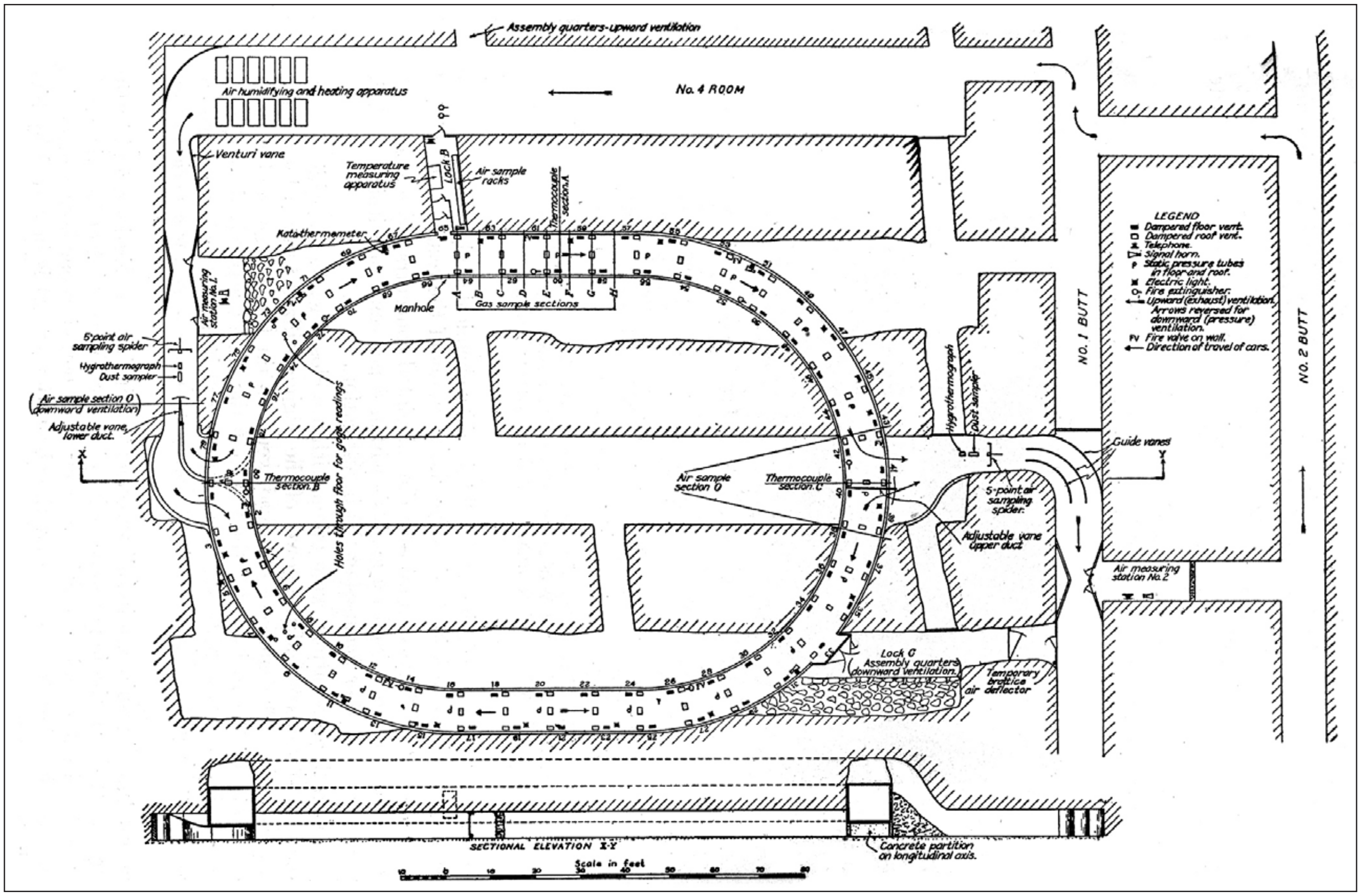


Diagram of the oval "underground speedway" inside the Experimental Mine at Bruceton. (photo credit: Bureau of Mines publication)

Ford Model Ts circling the underground track at Bruceton in 1921. (photo credit: National Archives and Records Administration) ed that a downdraft design, in which fresh air entered at the top and fouled air was drawn out at the bottom, was preferable. The ventilation ductwork at the Bruceton track could easily switch between the updraft and downdraft patterns in order to compare the two. Although the differences turned out to be modest, the updraft design—which the Tunnel Commissions had preferred all along—performed somewhat better in removing smoke and fumes from the roadway.

Knowledge gained through the cooperative research program guided the final ventilation plan that the Tunnel Commissions adopted. An 8,558-foot-long north tube for westbound traffic and an 8,371-foot-long south tube for eastbound traffic were linked to ventilation towers on the New York and New Jersey sides, where a total of 84 intake and exhaust fans handled the airflow through the ductwork. The diameter of the tubes was increased by half a foot to accommodate ducts beneath and above the roadway for updraft-type air circulation. When the ventilation system was completed in 1927, it worked even better than its engineers had expected. It easily kept the level of CO in the tunnels below 1.6 parts per 10,000 parts of air, far less than the safety threshold. The Bureau of Mines provided underground safety and rescue training to tunnel employees, just in case something went wrong.

Less well known to the public was the continuing value of the joint Bureau of Mines-Tunnel Commissions ventilation inquiry for the Holland Tunnel. This body of knowledge was unsurpassed anywhere else in the world prior to World War II.

Preparation of the tunnel site had begun in 1920, while the ventilation studies were still underway, and the boring of the twin tubes through bedrock under the Hudson River started in March 1922. By 1925, the basic structure of the tubes was completed, and on November 12, 1927, the tunnel opened to traffic. Unfortunately, Chief Engineer Holland did not live to see that day. He had died prematurely from a heart ailment in October 1924, leaving Ole Singstad, the principal designer of the ventilation system, to complete the project. The facility was named the Holland Tunnel in his honor.

The Holland Tunnel was widely recognized—then and later—as a great achievement of American civil engineering.[1*] Less well known to the public, but much appreciated among engineers, was the continuing value of the joint Bureau of Mines-Tunnel Commissions ventilation inquiry. This body of knowledge was unsurpassed anywhere else in the world prior to World War II. It assisted the designers of other long tunnels such as the underwater Posey Tube in Oakland, California (1928), the underwater Lincoln Tunnel in New York City (1934), and the overland Liberty Tunnels in Pittsburgh (1924). The Bureau of Mines consulted frequently with private and municipal organizations on tunnel projects. For example, it conducted air sampling and analysis for the 6.2-mile-long Moffat Tunnel, which opened in 1928 to carry the Denver and Salt Lake Railroad and an aqueduct across the Continental Divide in Colorado.

Experience in Pittsburgh demonstrated the importance of good tunnel ventilation and the practical significance of knowledge gained from the joint inquiry. When the Liberty Tunnels first opened, local authorities yielded to political

1* In 1984, the American Society of Civil Engineers and the American Society of Mechanical Engineers designated the Holland Tunnel as a National Engineering Landmark, and in 1993 the U.S. Department of the Interior identified it as a National Historic Landmark, largely because of its innovative ventilation system.

pressure and allowed motorists to use the new route before the ventilation system was fully operational. That mistake led to a crisis on May 10, 1924, as severe traffic congestion diminished air quality in the tunnels. People who were (or at least *thought* they were) suffering from carbon-monoxide poisoning panicked and fled, abandoning their cars. A Bureau of Mines rescue team went to the scene, and twelve people were hospitalized.

In response to this incident, Bureau engineers set up a portable CO monitor—developed at the Pittsburgh station as a direct outgrowth of the Holland Tunnel studies—in the Liberty Tunnels on August 1, 1924. The device automatically detected, and recorded on paper, even very low concentrations of CO. Its "work . . . would have required many chemists," a Bureau report noted, "and its continuous record cannot be duplicated by laboratory methods." Remaining in place for a year, the monitor reassured the public and local officials that as long as the tunnels were properly ventilated, no danger existed. Similar monitors were later installed in the Holland Tunnel, and in the spring of 1932 one was briefly reinstalled at the Liberty Tunnels due to concern that the situation there had changed for the worse as the volume of traffic grew. The 1932 tests showed that CO in the Liberty Tunnels did spike toward unsafe levels during rush hours, thus requiring changes in ventilation and traffic management.

Other investigations at the Pittsburgh station during the 1920s and the 1930s documented the perils of CO buildup in above-ground confined spaces such as parking garages, auto-repair shops, and even private homes that had faulty heaters or furnaces. "It is suicidal to run an automobile engine in a closed private garage for ten minutes," Arno Fieldner warned in 1926. The Bureau developed a portable testing kit for quickly determining CO levels in human blood. In cooperation with the U.S. Public Health Service, it conducted physiological studies of CO poisoning, including a look at what happened to people who were regularly exposed to small amounts of CO. These studies took Bureau personnel back to the Holland Tunnel, where they examined tunnel maintenance workers and police officers who spent hours each day in polluted air. No conclusive evidence of ill effects was found.

The station also examined potential dangers from tetraethyl lead, which became common in motor-vehicle exhaust after leaded gasoline arrived in the early 1920s. Lead additives improved the performance of internal-combustion engines by preventing "knocking," or premature detonation of the fuel. But lead was a well-known poison, and leaded gasoline aroused public fear and opposition. Worried officials of the General Motors Research Corporation, which had invented this new product, entered a cooperative agreement with the Bureau of Mines in 1923 for an independent safety evaluation. The inquiry took on greater urgency when injuries and deaths among workers at lead-additive refineries during 1924 and 1925 prompted some local governments to ban leaded gasoline and obliged the manufacturer, the Ethyl Gasoline Corporation (a joint venture of General Motors and Standard Oil), to stop production temporarily.

Between 1923 and 1925, tests done on animals at Pittsburgh suggested that the small amounts of tetraethyl lead present in exhaust fumes were not necessarily dangerous if the exhaust was diluted to levels that kept CO below the 4-parts-in-10,000 safety threshold. Even animals that inhaled doses two and a half times higher than the levels resulting from commercial lead additives did not consistently develop symptoms of lead poisoning—although some did, and autopsies found evidence of harm to their internal organs and storage of lead in their tissues. Concentrated vapors from ethyl gasoline appeared to be more toxic. Other experiments found that the addition of lead did nothing to alter the Bureau's previous conclusions about the behavior of carbon monoxide and gasoline vapors from motor vehicles.

The main limitation of the tests was that they said nothing about the impact of chronic exposure to leaded gasoline. Based on its short-term data, the Bureau concluded that leaded gasoline in normal use was not a definite health hazard. It reported this assessment to General Motors and the Ethyl Corporation—and to a committee appointed by the U.S. Surgeon General's office, which concluded in 1926 that there was not enough evidence to justify keeping lead additives off the market. But the early experiments at Pittsburgh hinted that leaded gasoline could damage human health, especially in higher concentrations and over long durations. Later research would confirm this danger.

"The atmospheric pollution of thoroughfares by automobile exhaust-gas is a matter of present concern," the Bureau's 1928 annual report stated.

Smoke from coal-burning locomotives was hazardous in confined spaces such as this Baltimore and Ohio Railroad tunnel. The Bureau of Mines developed gas masks to help keep railroad personnel safe. (photo credit: National Archives and Records Administration)

The Bureau could not require the use of protective gear, so its role was to relentlessly educate, persuade, and hope for the best. Good science and a demonstrated track record of saving lives were on the Bureau's side.

As motor-vehicle traffic increased in American cities and towns, even seemingly clean outdoor air became suspect. "The atmospheric pollution of thoroughfares by automobile exhaust-gas is a matter of present concern," the Bureau's 1928 annual report stated. In 1931, the Pittsburgh Experiment Station used a device that the *New York Times* called a "robot" to sample the air in downtown Pittsburgh. The portable CO detector from the Liberty Tunnels was relocated to the downtown area in 1932 to continue gathering data on invisible pollutants. Again the investigators found no cause for immediate alarm, but they noted the lurking possibility that combinations of toxic gases might harm people who regularly spent time on busy streets.

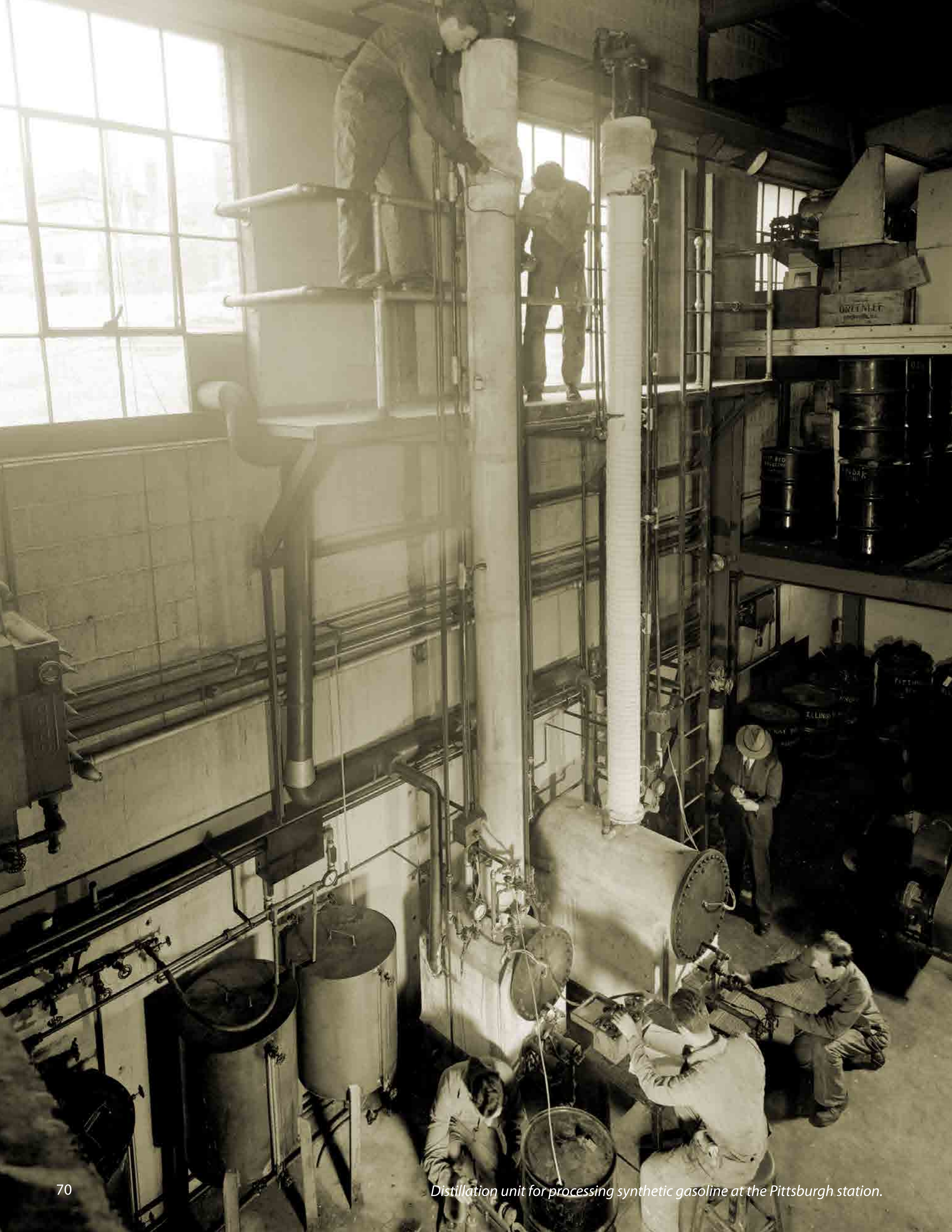
Personal protective equipment that the Pittsburgh station initially developed for mine rescues had application to contaminated spaces in the surface world as well. Recognizing that the gas masks the Army used during World War I could not defend against CO buildup in enclosed areas, Bureau engineers designed their own masks for general and specialized use and subjected commercial masks to permissibility tests. So-called universal masks filtered out low concentrations of virtually all known dangerous gases in atmospheres where there was still enough oxygen for humans to breathe. Other masks were made to protect firefighters and mine rescue workers in more intensively polluted environments. The Bureau even created a compact mask, able to fit inside a coat pocket, for railroad crews to use when their trains passed through long tunnels where invisible pools of CO might collect.

The Bureau could not require private firms or state and local governments to use only permissible protective gear, so its role was the same as in the campaign for rock-dusting coal mines: Relentlessly educate, persuade, and hope for the best. Good science and a demonstrated track record of saving lives were on the Bureau's side. So was a general tendency toward institutionalizing safety precautions throughout American industry. The historian Mark Aldrich has identified the first half of the twentieth century as the era of a "safety revolution," in which protecting the health and safety of workers became a recognized management responsibility and an important political issue. By making safety technologies and information about them widely available, the Bureau, and especially the Pittsburgh station, contributed much to this trend.

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

Chapter Four: The Beginnings of Synthetic Liquid Fuels Research, 1920-1939



Distillation unit for processing synthetic gasoline at the Pittsburgh station.

Chapter Four:

The Beginnings of Synthetic Liquid Fuels Research, 1920-1939

The rapid strides made in recent years in the consumption of petroleum and its products, the difficulty of equalizing production and consumption, and the resulting economic conditions have stimulated interest in other possible sources of supply.

--Bureau of Mines, Tenth Annual Report, *1920*

During the winter of 1922–1923, an energy crisis hit the northern United States. Labor disputes in the coalfields, coupled with problems in the railroad system, disrupted the transportation of coal from the mines to consumers. People in Newark, New Jersey, stood in line for hours to buy small amounts of coal at exorbitant prices. As local stockpiles dwindled, town officials in Saratoga, New York, seized shipments of coal that were originally bound for Canada. Communities around the Great Lakes struggled to find new supplies after losing their normal access to anthracite-coal providers in eastern Pennsylvania. The coal shortage encouraged households and industries to switch to natural gas or petroleum fuel oil, but this trend worried energy experts who believed that American petroleum and natural-gas resources could not support growing demand. The U.S. Geological Survey estimated in January 1922 that the country's petroleum reserves would be largely exhausted within twenty years.

The Bureau of Mines took the lead in exploring two potential substitutes for petroleum: liquid fuels from oil shale and liquid fuels from coal. Both had ancient roots and had benefited from modern advances in organic chemistry.

Such events prompted the Bureau of Mines and other agencies of the federal government to consider whether the country needed an overall fossil-fuels policy. Instead of analyzing coal, petroleum, and natural gas separately, scientists and politicians began to think about how the supply and use of one fuel affected the supply and use of others. The rise of petroleum had costs as well as benefits. By reducing demand for coal, it contributed to hardship and conflict in coal-mining areas, and it increasingly tied the national economy to an energy source that was prone to boom-bust cycles. Early notions of energy planning, which first surfaced in the 1920s and expanded in the 1930s, stressed the importance of conserving petroleum, keeping the coal industry viable, and finding alternative liquid fuels that could fill in if petroleum ran out.

The Bureau of Mines took the lead in exploring two potential substitutes for petroleum: liquid fuels from oil shale and liquid fuels from coal. Both had ancient roots and had benefited from modern advances in organic chemistry. To gain insight into these technologies, Bureau officials looked to Europe. British and German chemical engineers helped the Americans learn the latest methods of artificially synthesizing liquids from solid coal and shale. The Bureau did laboratory research and built pilot plants in Pittsburgh and on the western slopes of the Rocky Mountains. Although they indicated that synthetic liquid fuels were unsuitable for mass production in the U.S. any time soon, these experiments yielded knowledge that had scientific, industrial, and military value.

The Changing Energy Mix After World War I

Coal remained the preeminent energy source in the United States during the 1920s, although its relative importance gradually declined. In terms of heating value (measured in BTU), it accounted for 73 percent of total American energy consumption in 1920, 66 percent in 1925, and 58 percent in 1930. It was the dominant fuel for industrial use, for long-distance transportation, and, in most places, for heating homes and businesses.

However, the coal industry was in distress, and its troubles rippled through the American economy. Too many new coal mines had opened during and soon after World War I. This overcapacity compounded the industry's fragmentation and internal rivalries. Mining companies competed fiercely on an individual basis and at the regional level—for example, non-unionized Southern mines versus unionized Northern mines—for access to stagnant or declining markets. Under the pressure of wage reductions and of job cuts due to mine mechanization, mine workers repeatedly went out on strike. In 1919–1920 and again in 1922–1923, widespread labor-management disputes interrupted coal production and caused temporary price spikes.

The erratic price and availability of coal made other fuels more attractive. In addition to the growing use of natural gas, petroleum fuel oil emerged as a strong competitor of coal during the 1920s. Supplies of fuel oil doubled between 1919 and 1929 as petroleum output rose. Refiners marketed this product as an inexpensive substitute for the anthracite coal that households and commercial firms along the East Coast used for domestic heating. They had considerable success, and the anthracite-coal industry consequently fell into a decline from which it never recovered. Fuel oil also found buyers among manufacturing industries and steamship operators.

To the federal government, fuel oil had strategic importance as a source of energy for the U.S. Navy. Many warships and auxiliary naval vessels still used coal, but the process of converting the fleet to run on petroleum was well advanced. Under the Pickett Act of 1910, the government had the authority to guarantee the Navy a supply of petroleum by setting aside public lands in several Western states as naval petroleum reserves. This policy resulted in the designation of large reserve sites under Department of the Interior control during the 1910s and the 1920s. It briefly affected the Bureau of Mines after Congress decided in 1920 to allow private oil drilling on these lands and put the Bureau in charge of managing the leases. The sale of leases for commercial petroleum development on a Wyoming naval petroleum reserve in 1922 touched off the Teapot Dome corruption scandal. Although the Bureau was not implicated in that scandal, the episode resulted in the transfer of the reserve lands to the Navy Department.

The naval petroleum reserves reflected concerns about whether the nation's growing reliance on petroleum for vital military and civilian purposes was sustainable. Domestic petroleum consumption exceeded domestic production from 1915 through 1924. Stockpiles dwindled during World War I, and U.S. refineries began importing crude petroleum from Mexico. In 1919, Van H. Manning, the director of the Bureau of Mines, advised that petroleum shortages were on the horizon. The Bureau's chief petroleum technologist, J. O. Lewis, agreed with the Geological Survey that U.S. petroleum reserves would last less than twenty years at then-current rates of consumption. Similar dire prognostications came from other federal officials, state geologists, and even a few oil-industry executives.

President Coolidge, who accepted the theory that petroleum shortages were likely in the foreseeable future, created the Federal Oil Conservation Board in 1924.

With the long-term supply of petroleum in doubt and the near-term supply of coal subject to chaotic swings and interruptions, the idea that there should be some sort of planning for the fossil-fuel industries took hold during the early 1920s. In 1922, Congress established an independent U.S. Coal Commission to investigate the causes of disorder in the coal markets. President Calvin Coolidge, who accepted the theory that petroleum shortages were likely in the foreseeable future, created the Federal Oil Conservation Board (FOCB) in 1924. Chaired by the Secretary of the Interior and including the secretaries of the Commerce, War, and Navy departments, the FOCB Board members envisioned a conservation strategy based on identifying the purposes that energy served in the U.S. economy and determining the most appropriate energy sources for each purpose. Only such an integrated approach, they argued, could balance current needs with the imperative to safeguard scarce petroleum resources for future generations.

From this perspective, the FOCB concluded that excessively low prices for petroleum had locked in a vicious cycle of inefficient consumption and inefficient production. It specifically criticized the substitution of fuel oil for coal. Coal, the board argued, was adequate for the purpose of heating boilers and furnaces; petroleum should be channeled into more valuable refined products, especially gasoline. To correct what it saw as market distortions, the FOCB recommended that the federal government seek to raise the price of crude petroleum, discourage coal-to-oil end use conversions, and regulate petroleum production to stop unscientific drilling practices that prematurely depleted U.S. reserves. It also favored expanding American access to foreign petroleum fields and developing synthetic liquid fuels.

These ideas, especially the call for more government intervention in the energy industries, constituted a minority view that was out of step with the conservative political atmosphere of the 1920s and had little impact on public policy. Likewise, the findings of the U.S. Coal Commission, completed in 1923 and published in 1925, met with rejection. Critics denounced the commission's tentative proposal for federal licensing of coal companies that shipped coal across state lines, calling it an unjustifiable interference with free enterprise. Faced with strong opposition and lacking a supportive constituency, comprehensive energy planning appeared to be going nowhere.

The Bureau stepped up its research on synthetic liquid fuels and new uses for coal that might eventually supplement or replace petroleum.

However, the planning impulse did gain a foothold within the Bureau of Mines. Bureau documents contained language that echoed the FOCB's depictions of misallocated resources. For example, the 1924 annual report deplored the incursions of petroleum "into fields of use where much lower grade and more abundant fuels should be employed." The Bureau affirmed the need for action to head off petroleum shortages. In addition to its conservation work, it stepped up its research on synthetic liquid fuels and new uses for coal that might eventually supplement or replace petroleum.

Experiments With Oil Shale

The earliest research that the Bureau of Mines conducted on synthetic liquid fuels involved oil shale, which appeared to be the most promising substitute for petroleum during the first third of the twentieth century. "Oil shale" is a generic term for various types of layered sedimentary rock that contain *kerogen*, a solid material made from a complex mixture of organic chemical compounds. Kerogen, like coal or petroleum, is primarily of fossil origin. When heated, it decomposes to release liquid hydrocarbons (shale oil) and gases that can be captured and refined to make useful products.

Oil shale had a long history of industrial significance. It had been known since prehistoric times as the stone that burns, since even in its raw form it was easily combustible and hence could serve as fuel.

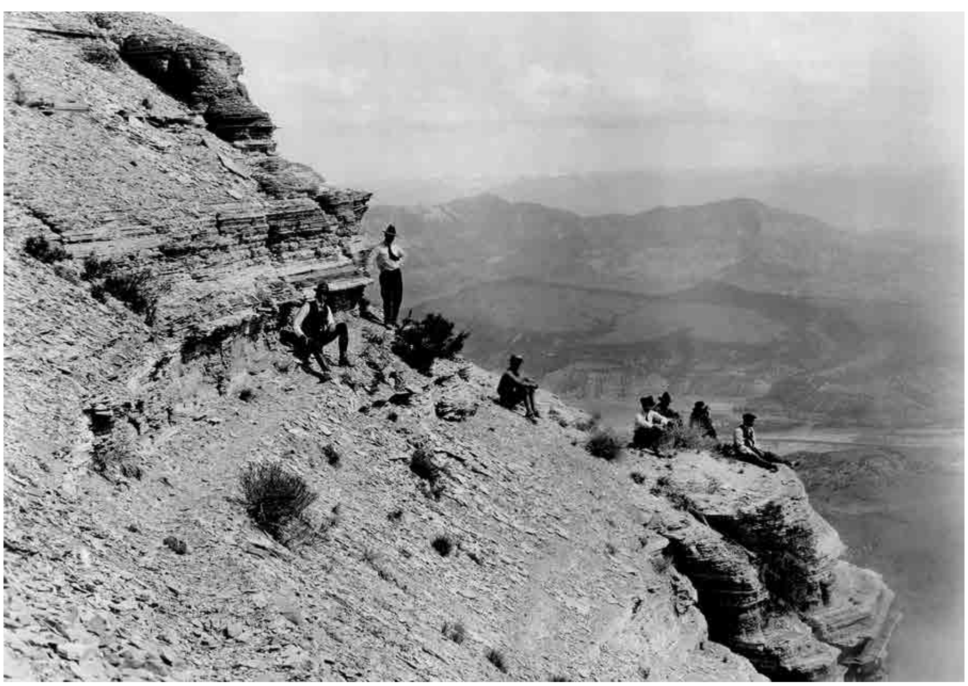
Oil shale had a long history of industrial significance. It had been known since prehistoric times as the stone that burns, since even in its raw form it was easily combustible and hence could serve as fuel. Before the modern petroleum industry existed, oil-shale deposits were important sources of oil for lighting and lubrication. French, Scottish, and American engineers had devised methods for the large-scale production of paraffin wax and kerosene from shale oil in the mid-nineteenth century. Rendered uncompetitive by inexpensive petroleum, most of this activity had vanished by 1900, but in some countries it persisted. The most notable example was Scotland, where a cluster of firms near Edinburgh turned oil shale into paraffin wax, lubricating oils, and ammonium sulfate (an ingredient in fertilizer), as well as gasoline and diesel fuel.

Interest in oil shale revived during the 1910s due to soaring demand for motor fuels, the impact of World War I, and new geological information. In 1913, the U.S. Geological Survey launched an investigation of the country's largest concentration of oil-shale resources: the Green River Formation, covering over 17,000 square miles in Colorado, Utah, and Wyoming. The Survey published its initial report on Green River shales one year later and followed up with additional studies, including a nationwide inventory of oil-shale deposits in 1915. These accounts stoked anticipation that oil shale would become the next great energy bonanza. In a speculative boom that peaked between 1919 and 1921, private investors rushed to acquire shale-bearing land and to build prototype shale-oil manufacturing plants. Government officials and oil companies began exploring the feasibility of reestablishing an American oil-shale industry.

In 1916, the Bureau of Mines responded to this growing enthusiasm by assigning several petroleum specialists to oil-shale investigations. It used its existing laboratories, especially the Pittsburgh Experiment Station, and cooperative agreements with state governments and universities to increase reliable scientific knowledge of the subject. The Bureau's most important partners in this work were the University of Utah in Salt Lake City, where oil-shale research began in 1919, and the State of Colorado, which in January 1920 authorized the establishment of a small federal laboratory at the University of Colorado at Boulder. In 1922, the Bureau also agreed to collaborate with the State of Indiana on an evaluation of shale deposits there.

The Bureau reported that, contrary to popular rumors, oil shale did not contain significant quantities of gold or other precious metals.

This program of laboratory research soon yielded results. Scientists measured physical characteristics of domestic and foreign oil shales, studied the chemical structure of kerogen (about which little was known), and improved the assaying procedure that was used to determine the potential yield of liquid oil from any given sample of shale. As a caution to miners, researchers at the Pittsburgh station established that although oil-shale dust was unlikely to cause underground mine explosions, it was flammable enough to sustain an explosive reaction that had started from another source. Some myths were debunked; for example, in 1922 the Bureau reported that, contrary to popular rumors, oil shale did not contain significant quantities of gold or other precious metals.



Prospecting for oil shale in the rugged Green River Formation area of western Colorado during the mid-1920s. (photo credit: National Archives and Records Administration)

Construction of an oil-shale mine and a shale-oil manufacturing plant marked the federal government's first specific commitment to developing a petroleum substitute. It moved the Bureau's oil-shale research out of the laboratories and into the field.

Most initial oil-shale studies that the Bureau of Mines conducted or sponsored dealt with retorting—the process of heating oil shale to convert the solid kerogen into oil and gases—and refining. During the late 1910s and the early 1920s, inventors developed and patented scores of different retorting methods. Uncertainties about how the conversion of kerogen worked and what variables affected it made assessing the worth of these schemes difficult. The Bureau set out to identify, in the words of one 1923 summary, "the conditions of retorting that produce the highest yields of the best oil from various shales." Several experimental retorts were set up at the Boulder station. Samples of oil were distilled, via refining techniques similar to those used in the petroleum industry, to produce small amounts of gasoline and other liquid fuels. According to Martin J. Gavin, one of the engineers most deeply involved in the program, the tests confirmed that shale oil varied greatly in composition and that its refining costs exceeded those of petroleum.

Having made itself the country's principal storehouse of expertise on oil shale, the Bureau was well positioned to respond when senior officers of the Navy Department requested its assistance in 1924. The Navy viewed oil shale as a possible backup source of fuel oil. Since 1916, the federal government had designated portions of the Green River Formation as naval oil-shale reserves. But the term "reserves," as conventionally understood in the mining industries, meant that the extraction of these resources was practical with available technologies. No one was sure whether Green River oil shales actually met that definition, since there was as yet no evidence that industrial-scale mining, retorting, and refining were possible there. So the Navy wanted to know whether its Green River properties constituted true reserves that could yield large amounts of fuel oil and other useful products.

President Coolidge established a naval petroleum commission to look into the matter. After inspecting the oil-shale reserve lands and conferring with engineers at the Bureau of Mines, the commission recommended in 1924 that the Bureau be authorized to establish an oil-shale demonstration plant somewhere in the Green River Formation. Congress endorsed the recommendation by appropriating $90,000 in March 1925 for the construction of an oil-shale mine and a shale-oil manufacturing plant. This step marked the federal government's first specific commitment to developing a petroleum substitute. It moved the Bureau's oil-shale research out of the laboratories and into the field.

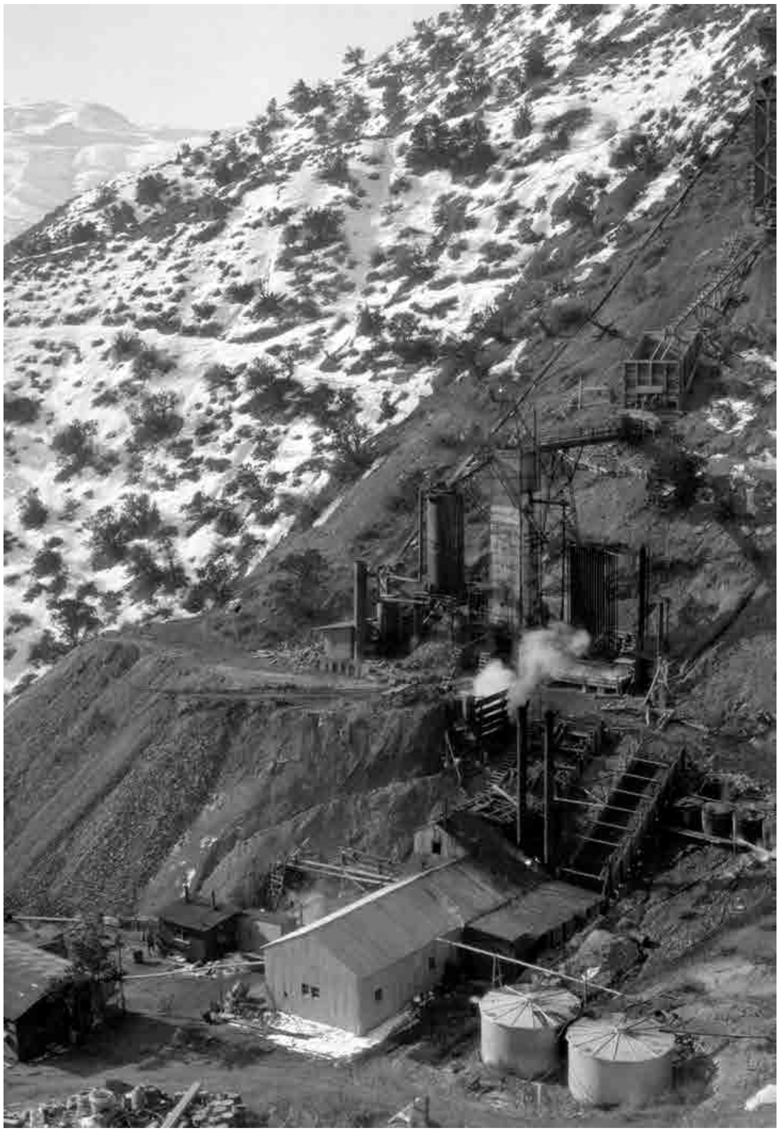
A team led by F. B. Tough, the Bureau's chief petroleum engineer, selected a site for the new venture on the border between Naval Oil-Shale Reserve No. 1 and Naval Oil-Shale Reserve No. 3, near the small town of Rulison in western Colorado. All around this site rose a stark landscape of high plateaus that dropped off into cliffs and canyons. The oil-shale beds that the Bureau proposed to mine formed horizontal bands near the top of the cliffs, at elevations of almost 8,000 feet above sea level and 2,100 feet above where the processing plant would stand. One of the problems that the engineers had to solve was therefore how to connect the plant and the mine. After considering the relative merits of relying on pack animals or building a gasoline-powered cable tramway, they decided to go with the tramway, which was installed during the summer of 1926.

The mine used traditional open quarrying methods to remove oil shale from a seam that outcropped on the face of the cliff. Miners loaded broken shale onto the tram, which carried it down to a point just above the plant site and dumped it into storage bins that fed into a mechanical stone crusher. After being cut into pieces not more than two inches in width, the shale fell by gravity along a chute leading to the plant.

Two distinct types of retort, both derived from existing commercial practice, formed the core of the manufacturing operation. One was a Pumpherston retort, the standard design that the Scottish oil-shale industry had used for decades. Known worldwide for their simplicity and durability, Pumpherston retorts had recently been introduced in the United States, to mixed reviews. Suspicion of foreign innovations, coupled with some disappointing early results, had given rise to claims that the Scottish technology could not work on American oil shales. However, the Bureau of Mines had done well with an experimental retort at Boulder that closely resembled a Pumpherston, and the Bureau's engineers believed that the Scottish industry, with its long experience, offered the best starting point for their own endeavors. Martin Gavin accordingly went to Scotland in 1925 to confer with local experts and purchase the components of a single Pumpherston retort from the Scottish firm of A. F. Craig & Company. In return, James Shaw, the director of construction for A. F. Craig, traveled to Colorado to oversee the installation of the retort at Rulison.

The Pumpherston retort was a vertical cylindrical vessel composed of two connected parts: an upper portion made of cast iron and a lower portion made of firebrick. Heat was transferred through the firebrick walls from burning gas in external combustion chambers. Crushed shale entered continuously through a hopper at the top and was heated as it descended, giving off oil vapor and gases that flowed out through offtake pipes in the cast-iron section. Steam, coming up from an intake at the bottom of the retort, helped to maintain even temperatures within the retort and to increase the output of valuable chemical byproducts. At the end of the process, depleted shale exited through a hopper at the base, and the gases and liquids were separated in condensers, scrubbers, and settling tanks.

The other retort that the Bureau employed at Rulison, called a Dundas-Howe or N-T-U (Nevada-Texas-Utah) retort, operated on very different principles. It was an internal-combustion type, in which the heat needed to decompose kerogen came from burning flammable gases and leftover carbon from the depleted shale inside the retort. A firebrick-lined steel cylinder was charged with crushed shale and sealed with a domed lid. Air was injected, a fire was lit at the top, and heat gradually migrated downward through the shale, releasing oil and then burning the remaining carbon. Waste shale amassed at the bottom and had to be removed manually by sliding a moveable panel. Judging when a



Oil-shale processing plant at Rulison, 1927. The rectangular structure at the center-right housed the Pumpherston retort, while the dark-colored cylinder immediately to its left was the N-T-U retort. (photo credit: National Archives and Records Administration)

Oil-shale quarry near the top of a cliff overlooking the Rulison test. site (photo credit: Bureau of Mines publication) reaction had ended and the N-T-U retort could be safely emptied and reloaded took considerable skill. "Dumping the charge was often spectacular, especially at night," Martin Gavin noted. "If the shale was not completely spent or if it remained gassy, flames shot high into the air, and there was much dust and clouds of steam" as workers sprayed cooling water over the hot rock.

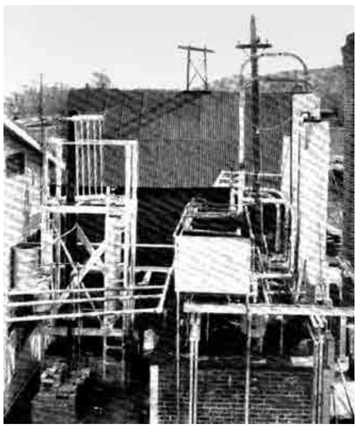
Bureau of Mines officials were impressed with the progress of the N-T-U Company, a private firm, in using this technology to retrieve usable oil from shales in southern California. Of the myriad retort designs that American inventors had proposed, only a handful had demonstrated serious commercial potential, so the N-T-U retort stood out for its relative success. The Bureau's engineers believed that such internal-combustion retorts offered the best alternatives for future development if Scottish methods did prove to be inappropriate for American conditions.

Getting the site into shape took more time than the Bureau had originally anticipated. Everything necessary to support an isolated mining camp had to be provided: an access road, a well and a water-supply system, coal-fired boilers, a generator for electricity, and buildings to house the staff. The Pumpherston retort did not have its first test run until September 17, 1926; the N-T-U retort entered service still later, beginning on January 17, 1927. Even after the plant was in operation, political constraints affected the work schedule. Congress made no further appropriations for oil-shale demonstrations in 1927, thus forcing all activities at Rulison to halt on July 1 of that year. Work did not resume until funds became available once more in January 1928.

The experimental program consisted of numerous test runs, using different grades of oil shale and varying the conditions in the retorts. Careful day-by-day logs of the tests allowed Gavin and his colleague John S. Desmond to reconstruct the history of the Rulison works in Bureau of Mines Bulletin 315, which was published in 1930. Their account vividly illustrated the trials of pursuing scientific knowledge in a remote place. Equipment broke frequently, as when the stone crusher was idled for almost a month after it lost a gear on November 14, 1926. During the last week of January 1927, Gavin and Desmond wrote, "heavy snows at the quarry" made the shale samples too "wet, dirty, and variable in quality" for the retorts to operate correctly. The Pumpherston retort experienced a buildup of coke (carbon residues) on its inner walls in mid-March 1927 that caused it to become clogged with oil shale. After this trouble was corrected, the retort ran smoothly again.

A persistent problem with the N-T-U retort was oil vapor that escaped through the exhaust stack and created a noxious fog. "The fog drifted down to the plant and camp buildings and for a time was almost intolerable," Gavin and Desmond reported. "It was extremely irritating to the eyes and nose and evidently had to be disposed of in some other manner." After much trial and error, the engineers found a temporary solution: The exhaust from the retort was piped over a nearby hillside and diluted so that it no longer posed an acute health hazard to the workers.

From September 1926 through June 1929, the Rulison works processed roughly 6,000 tons of oil shale and produced 150,000 gallons of shale oil. Shale from the clifftop quarry yielded anywhere from 15 to 52 gallons of oil per ton when retorted, and both retorts were able to capture up to 95 percent of the oil content of the raw shale. Differences in experimental procedures and data collection, especially the fact that the N-T-U retort operated for a shorter duration than did the Pumpherston retort, muddied comparisons between the two technologies. Both retort designs clearly could handle Green River Formation oil shales, although the N-T-U had an advantage in versatility because it was not nearly as susceptible as the Pumpherston was to disruption by particular shales that generated large amounts of coke. This observation led the Bureau of Mines engineers to believe that retorts of the N-T-U type would perform best across the wide range of shale types and grades that existed in the U.S.



The experimental oil-shale refining unit at Boulder, Colorado. (photo credit: Bureau of Mines publication)

An experimental refinery at the Boulder station distilled small amounts of shale oil from Rulison during the first six months of 1927. It also sent samples of the oil to five American petroleum refineries and to Scottish Oils, Ltd. in Scotland for further analysis. Unlike the retorting studies, the refining studies had discouraging results. Researchers at Boulder were unable to make shale gasoline that met the federal government's standards for motor fuel. All six companies that independently evaluated the Colorado shale oil declared it to be inferior to petroleum. Scottish Oils found that by traditional Scottish standards, samples from both retorts at Rulison had unusually low yields of refined products, with the oil from the N-T-U retort being especially difficult to process.

A 1930 review of the Colorado experiments concluded that "the present knowledge of shale oil indicates that it is a raw-material supply for future years rather than the present."

Overall, the Bureau of Mines research indicated that the Navy's oil-shale lands in the Green River Formation could not yet be viewed as true reserves. As the engineer A. J. Kraemer later testified to a U.S. Senate committee, the Bureau had proven "that high yields of oil can be obtained from these shales in large-scale operations." But too many unresolved problems remained with the quality of the oil, the quality of refined products, and the relatively high processing costs. "The present knowledge of shale oil indicates that it is a raw-material supply for future years rather than the present," Gavin and Desmond concluded in their 1930 review of the Colorado experiments.

By the time that the Bureau's oil-shale demonstration program ended in mid-1929, its findings hardly seemed to matter anyway, for the great oil-shale boom had become a bust. Discoveries of large new petroleum fields had eased the fear that the U.S. would soon face shortages of liquid fuels. Private companies such as N-T-U went out of business, and the Bureau abandoned its facilities at Rulison. A few active and former members of the Bureau staff continued to think about oil shale. For example, Lewis C. Karrick, who had spent over seven years working on the federal oil-shale program before moving to the University of Utah, took out several relevant patents during the 1930s—including those for the Karrick process of obtaining liquids from oil shale (or other carbon-bearing materials) through low-temperature carbonization. However, this research received little attention from other scientists or the public. What interest remained in synthetic liquid fuels had shifted to coal-based technologies.

Liquid Fuels From Coal: A Transatlantic Technology Transfer

Like shale oil, liquid fuels drawn from coal had been around long before the modern petroleum industry. Several nineteenth-century American companies distilled paraffin oil—popularly known as kerosene—from certain types of coal. Light oils were also extracted from coal tar, a major byproduct when coal was made into coke for the iron and steel industry or into manufactured gas for lighting and fuel.

Dark, sticky, foul-smelling coal tar was transformed into a rainbow of artificial colored dyes. It became the raw material for perfumes, medicines, and flavorings. It provided ingredients for high explosives and synthetic resins and plastics.

The possibility of large-scale production of motor fuels from coal grew out of a revolution in coal chemistry during the late nineteenth and early twentieth centuries. Scientists discovered that coal was useful not only for burning directly to generate heat and power but also as a source of chemicals for many other purposes. Beginning in 1856, when the English chemist William Perkins synthesized a purple dye from coal tar, coal-based organic-chemical industries proliferated in Europe. Dark, sticky, foul-smelling coal tar was transformed into a rainbow of artificial colored dyes. It became the raw material for perfumes, medicines, and flavorings. It provided ingredients for high explosives and synthetic resins and plastics. And both coal tar and raw coal could be converted into liquid fuels that were suitable for powering internal combustion engines.

At first, the U.S. lagged far behind European nations in developing coal chemicals. Germany was the world leader in this field, and American chemical companies depended on imported German products. When World War I temporarily interrupted trans-Atlantic trade, however, industrialists moved quickly to find or invent homemade substitutes. Spectacular growth in U.S. output of synthetic organic chemicals resulted, and by the mid-1920s the foundations of a sophisticated American coal-chemicals industry were in place.

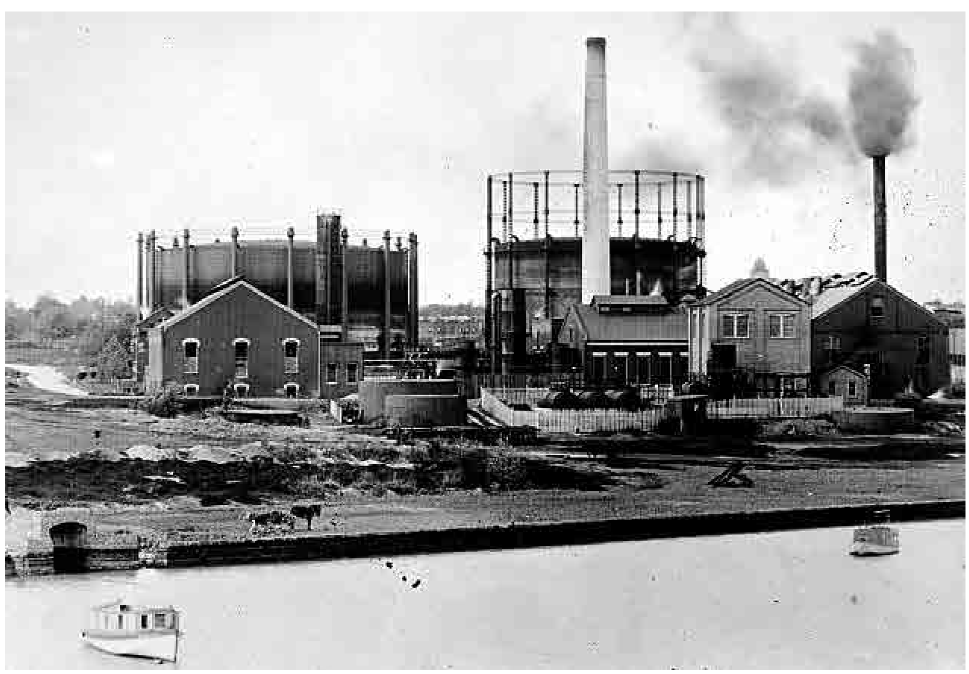
The Bureau of Mines identified four possible options for using this expanding pool of scientific and engineering know-how to develop substitutes for petroleum. One source of feedstock for coal-based liquid fuels was the high-temperature coke industry, which created liquids in the process of carbonizing coal at temperatures between 900 and 1,300 °C. This industry was rapidly adopting a German innovation, the byproduct coke oven, which made the recovery of byproducts easier. Yet it still did not yield enough tar and light oils to make much of a dent in the country's motor-fuel needs.

Manufactured gas production was another potential contributor. In the 1920s, almost every American city had a manufactured-gas works that was essentially a small coal-chemicals factory. Bituminous coal was heated to drive off *coal gas*, a flammable mixture of hydrogen, methane, carbon monoxide, and various other gases, which was then piped to homes and businesses. The process also generated ammonia, phenols, toluene for explosives, and coal tar that could be refined into substances ranging from wood preservatives to gasoline. Again, however, the total volume of liquids that could be obtained from gas works was limited. A further complication was that many gas companies combined coal gas with *water gas*, made by passing steam over red-hot coke or anthracite to create a purer mixture of hydrogen and carbon monoxide. Water gas had a higher heating value than did coal gas and required less capital and labor to produce, but it yielded less tar and other useful byproducts.

To increase the supply of coal tar and light oils, engineers proposed a third approach: low-temperature coal carbonization. This idea created great excitement in the U.S. and Europe during the first third of the twentieth century. As with oil-shale retorts, inventors proposed dozens of schemes for low-temperature carbonization processes—such as the one developed at the Bureau by L. C. Karrick—and by 1924 several of these designs were ready for commercial trials.

Low-temperature carbonization referred to the production of coke at temperatures between 450 and 700 °C, about half as high as in conventional coke making. It promised several advantages. First, it seemed likely to reduce the cost of coke. Second, the coke that resulted was an excellent smokeless solid fuel for use in fireplaces, stoves, and furnaces. This fuel was a potential boon for cities that wanted to reduce air pollution, and for the coal industry's efforts to discourage consumers from switching to fuel oil. Third, low-temperature carbonization yielded two to three times more byproduct coal tar than did high-temperature carbonization, and the chemical composition of its tar more closely resembled that of petroleum.

A final category of processes was more radical, involving the nearly complete transformation of coal into liquids as a primary goal rather than as a secondary offshoot of coke or gas production. Reports were filtering out of Germany



This manufactured gas plant, owned by the Washington Gas Light Company and serving the Washington, D.C., area, was typical of the gasworks that provided American cities and towns with fuel and industrial chemicals in the 1920s.

about amazing new research on the liquefaction of coal. In 1913, a German chemist named Friedrich Bergius had patented a method of combining powdered coal with hydrogen under high pressure to produce synthetic oil. His discovery rested on the insight that a fundamental difference between solid coal and liquid petroleum is the ratio of hydrogen atoms to carbon atoms within each material. Petroleum has about twice as many hydrogen atoms per carbon atom as coal does. Therefore, if coal could be sufficiently *hydrogenated*—forced to absorb additional hydrogen—it would turn into a liquid that closely resembled petroleum. Building upon the expertise that German engineers had gained from the recently invented high-pressure Haber-Bosch process for synthesizing ammonia, Bergius found that many types of coal could be decomposed and hydrogenated at around 200 times normal atmospheric pressure and at temperatures over 300 °C.

Friedrich Bergius (1884–1949) invented the direct coal hydrogenation process. Bergius won the Nobel Prize for Chemistry in 1931 for his revolutionary contributions to coal utilization. (photo credit: Bettman/Corbis)

The Bergius process interested the German government and German industrialists, who were deeply concerned about the strategic problem posed by their country's almost total lack of natural petroleum reserves. Efforts to industrialize coal hydrogenation began during World War I, but encountered many complicated technical problems. Not until the early 1920s did Bergius succeed in bringing his research to the verge of commercial feasibility and begin to draw international attention to it.

One obstacle to implementing coal hydrogenation was the lack of an adequate hydrogen supply. Deriving hydrogen from hydrocarbons, including the ubiquitous water gas that manufactured-gas plants generated, seemed to be the most likely solution. Heretofore largely ignored by chemists outside the manufactured-gas industry because it was a poor source of coal tar, the water-gas process suddenly took on new scientific and commercial significance.

German scientists went on to prove that water gas could do even more than provide hydrogen for the Bergius process. It could itself be turned into liquid fuels. In 1923, the German chemical company BASF developed a process for synthesizing methanol from a purified form of the mixture of hydrogen and carbon monoxide that constitutes water gas. This invention had great importance because methanol, the simplest alcohol, is a fundamental ingredient in the manufacture of numerous other organic chemicals. The new synthetic process allowed BASF to produce methanol on a larger scale and at lower cost than traditional means of distilling methanol from wood could ever achieve. Since methanol could be used as a motor fuel, it offered another possible substitute in the event of a petroleum shortage.

Intriguing hints that synthetic oil could be made from water gas by a similar method also began to surface during the early 1920s. Franz Fischer and Hans Tropsch at the Kaiser Wilhelm Institute for Coal Research reported in 1923 that they had created a complex mixture of alcohols and acids by heating and pressurizing water gas and exposing it to an iron catalyst. They called this concoction "synthol" and suggested that it might form a base for motor fuel. Three years later, Fischer and Tropsch announced the synthesis of gasoline, the most sought-after liquid fuel, indirectly from coal by way of the familiar water-gas process.

In keeping up with the flood of new developments in coal research, Bureau of Mines officials could count on assistance from scientific agencies in Great Britain. The British Department of Mines had approached the Bureau in 1923 with a proposal for cooperation on issues of mine safety. George S. Rice, the Bureau's chief mining engineer, had enthusiastically endorsed the idea, and within a year the American and British governments had arranged for regular exchanges of personnel and test results. Mining was the principal focus; in particular, investigators from both countries wanted to resolve discrepancies in their data on the explosiveness of coal dust. But the transatlantic connection had much to teach the Americans about synthetic liquid fuels as well. Because Great Britain was geographically and economically closer to Germany than the U.S. was, it had better access to technical news from German sources, and British scientists had begun a program of research on coal-to-liquids conversion.

James G. King (left), chief chemist of the British Fuel Research Station, with Arno C. Fieldner (right) in London, 1924. (photo credit: National Archives and Records Administration)

A perfect opportunity to cement a working relationship between the Bureau and its British analogue came in the summer of 1924, when the first World Power Conference convened in London from June 30 to July 12. Arno Fieldner, who was then the superintendent of the Pittsburgh Experiment Station, attended as the Bureau's representative. After the conference, he stayed in Europe for several months to meet with government officials, scientists, and industrialists who were studying coal mining and coal chemistry.

Fieldner began his European tour at the British National Fuel Research Station, located in Greenwich just outside London. He described this agency, established in 1919, as "the largest government-supported experimental station exclusively for fuel research in the world." The staff there was conducting an assay of British coals to determine which coals were best suited for low-temperature carbonization and to estimate likely tar and oil yields. Fundamental research on coal was also in progress at British universities and industrial laboratories. At Sheffield University, Fieldner observed work similar to what his staff in Pittsburgh was doing on the dynamics of flames and coal-dust explosions. He noted "intensive experimentation" on the Bergius coal-hydrogenation process in a joint public-private laboratory at the University of Birmingham.

Across the English Channel, Fieldner visited the mining districts of Belgium and France. He was impressed with the efforts of E. Audibert, the director of the French Coal Dust and Explosives Testing Station, whom the French government had just put in charge of an ambitious research program on synthetic liquid fuels. A laboratory was being set aside for investigations of synthetic methanol and the Bergius process.

Fieldner then proceeded to Germany, where he reported that "one is at once impressed by the close cooperation of the government, the universities, and the industries." He met with Franz Fischer in Fischer's laboratories at Mülheim in the Ruhr, the country's largest mining and industrial district. Fischer came across as an intense, effective leader who was pushing the Kaiser Wilhelm Institute to the frontiers of knowledge about producing liquid fuels "from the interaction of carbon monoxide and hydrogen, in the presence of catalysts at high pressures and temperatures." Toward the end of his trip, Fieldner also visited Friedrich Bergius and examined a Bergius-process demonstration plant—the only functioning one in the world at that time—near Mannheim. This facility, Fieldner later wrote, remained "a long ways from a commercial operation," but it looked promising; it was "a full-scale, single-unit plant" that could produce up to one ton of synthetic crude oil per day. Based on his observations, he concluded "that the hydrogenation process works, although it is still at an experimental stage. Whether it can be carried on at a profit has not yet been demonstrated."

Fieldner returned to Pittsburgh convinced that the Bureau of Mines could and should invest more in research on coal-based synthetic liquid fuels. His international comparisons had increased his confidence in the Bureau and the future of American coal chemistry. In terms of volume and quality, American science on energy and fuels still lagged behind European work, but it was soundly organized. The cooperative relationships that had grown up among the Bureau, universities, and the energy industries more nearly resembled the extraordinarily fruitful German system of support for energy research than did the looser British system, in which Fieldner detected a "well-defined gap" between government and industry.

Fieldner returned to Pittsburgh convinced that the Bureau should invest more in research on coal-based synthetic liquid fuels. His international comparisons had increased his confidence in the Bureau and the future of American coal chemistry.

At the Pittsburgh Experiment Station, Fieldner and several other chemists organized a small group to work on coal-to-liquids conversion. Only a handful of people, probably not more than half a dozen, were deeply involved during its early years. Key participants included David F. Smith, the supervising chemist of the Bureau's Physical Chemistry Section; D. A. Reynolds; J. D. Davis; the laboratory technician Paul Golden; and the catalysis expert Charles O. Hawk. By 1926, two years after its inception, the group had equipped a laboratory with handcrafted apparatus for producing small quantities of water gas and observing how the components of this gas reacted to different catalysts at varying temperatures and pressures. The annual report of the Bureau of Mines for that year noted briefly that this laboratory had been completed.

Work at the new facility got underway just as Pittsburgh was gaining prominence in international coal-chemistry circles. From November 15 to November 18, 1926, the Pittsburgh Experiment Station collaborated with the Carnegie Institute of Technology (CIT), its neighbor and partner, in the First International Conference on Bituminous Coal. Convened at the behest of CIT President Thomas Stockham Baker, the conference attracted over 1,600 delegates. Baker envisioned the gathering as a showcase of the latest science on coal utilization and as a way to promote world peace by building an international community of interest among producers and users of the industrialized world's dominant fuel. "Cheaper power and a wider distribution of power," Baker asserted in his opening address, "may affect not only commerce and industry, but the very form and character of our civilization; and coal will remain the chief source of energy for generations to come. It is the foundation of our industrial life."

"Coal will remain the chief source of energy for generations to come. It is the foundation of our industrial life."
--Thomas Baker, 1926

Both Friedrich Bergius and Franz Fischer attended the conference, riveting the audience with descriptions of their rival methods for producing liquid fuels from coal. "Bergius and Fischer crossed swords at Pittsburgh, each slyly thrusting at the other, each pointing out defects in the other's process," the *New York Times* reported. Championing his coal-hydrogenation process, Bergius stressed its proven reliability as a source of high-grade gasoline and noted that two commercial-scale hydrogenation plants were already under construction in Germany. Fischer conceded that his Fischer-Tropsch synthesis process had not progressed as far toward commercialization, but he emphasized its simpler chemistry, its versatility, and its reliance on abundant water gas. He demonstrated samples of several liquid products and solid paraffin wax obtained from the synthesis. Amid the drama, these two illustrious scientists provided the most complete account that Americans had yet heard of German synthetic-fuels research.

Arno C. Fieldner, in a 1953 portrait. (photo credit: National Archives and Records Administration)

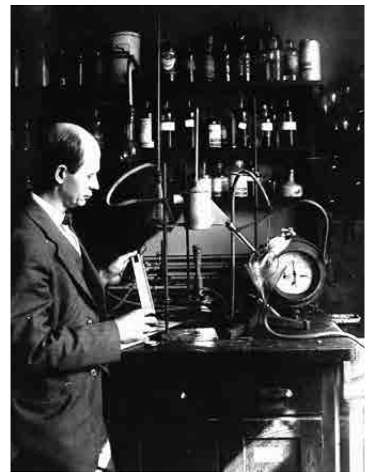
There was news on the low-temperature coal carbonization front as well. Near Fairmont, West Virginia, less than a hundred miles south of Pittsburgh, a subsidiary of the Consolidation Coal Company had built a demonstration plant that was turning out fifty tons of compacted low-temperature coke each day. The company marketed this product as a cheap, clean-burning fuel for home heating. British researchers reported good results from a prototype low-temperature carbonization retort modeled on the Scottish Pumpherston oil-shale retort. Costs were high, however, and some observers warned that demand for coal chemicals was too low to support a large expansion of coal-tar output. If plants such as the one at Fairmont succeeded, most of their byproduct tar would likely just be burned as fuel or discarded, since no market for it existed.

The messages of this event, and of a second coal conference that took place at CIT two years later, were plural and mixed. Optimism about new technologies coexisted with uncertainty about whether synthetic liquid fuels and other triumphs of coal chemistry were economically viable. Despite President Baker's call for international cooperation, an undercurrent of competition was present. Advocates of different methods, companies, industries, and countries were contending to master the chemical mysteries of coal. As it ventured into this thicket of intrigue, the Bureau of Mines synthetic liquid fuels group faced the challenge of drawing its own conclusions.

The synthetic liquid fuels group initially chose to study the synthesis of alcohols and liquid hydrocarbons from water gas. Part of its rationale was the lack of publicly available data about how these processes worked. The Germans, aware of the strategic value of their innovations, were not telling all that they knew. For example, Fischer's earliest published reports on the Fischer-Tropsch process did not detail how he conducted his experiments. Companies that hoped to profit from making synthetic methanol in the U.S. also avoided disclosing information. By doing its own research on the processes and placing its findings in the public domain, the Bureau of Mines could disseminate important scientific knowledge more broadly.

Equally important was the Pittsburgh station's interest in addressing the economic problems of the American manufactured-gas industry. Manufactured-gas production was very seasonal; it peaked during the heating season, which ran from October through March. For the rest of the year, gas companies had to reduce production and idle much of their equipment. If they could keep their plants in continuous, full operation by making synthetic liquid fuels and other organic chemicals during the off-peak periods, then they might achieve cost savings that would cut the price of manufactured gas while still increasing profits.

During 1927 and 1928, the Bureau's synthetic liquid fuels laboratory experimented with the methanol synthesis. Its experiments verified that the process yielded crude methanol of high purity and that this methanol could be converted into dimethyl ether, another industrially valuable chemical that had potential as a motor fuel. At a meeting of the American Chemical Society in September 1927, the researchers reported on their first tests of the Fischer-Tropsch hydrocarbon synthesis, which had generated assorted products including gases, some liquid oils and "a deposit of a substance resembling white vaseline." Trial and error led the group to focus on an iron-and-copper catalyst that was relatively effective in turning water gas to liquids at temperatures between 200 and 300 °C.



J. D. Davis, fuel chemist, studying low-temperature coal carbonization at the Pittsburgh station in 1926. (photo credit: National Archives and Records Administration)

Three major difficulties soon became apparent: heat control, catalyst selection, and sulfur removal. Water-gas synthesis reactions seemed to work best in a narrow range of temperatures, and because these reactions gave off large amounts of heat, staying within that range was not easy. The issue was especially serious with the Fischer-Tropsch synthesis, which, if overheated, produced large amounts of unwanted water, carbon dioxide, and methane gas.

The choice of catalyst was crucial for determining the pace of a reaction and the types of product that resulted, but many catalysts that the Bureau investigated during the late 1920s were unimpressive. Some did not work at all. Others were inefficient, or lost their effectiveness over time. Part of the problem was that sulfur in the water gas seriously damaged catalysts. The researchers tried their best to remove sulfur from the gas supply, but their knowledge of how to do so was limited.

Underlying many of these challenges was the absence of a solid theoretical understanding of the reactions. No one quite knew why and how a simple, lightweight mixture of carbon monoxide and hydrogen could yield complex, heavy liquids. The Bureau of Mines team was convinced that these processes were far more intricate than they seemed to be. There had to be multiple steps involved, beginning with hydrogenation of the carbon monoxide and extending all the way to polymerization—the creation of chains or networks of molecules. In 1930, David Smith, Charles Hawk, and Paul Golden summarized their observations and theories about the Fischer-Tropsch process in an article entitled "The Mechanism of the Formation of Higher Hydrocarbons from Water Gas" for the prestigious *Journal of the American Chemical Society*.

The synthetic liquid fuels group also began investigating the Bergius coal-hydrogenation process in 1928 and did preliminary work on the conversion of water gas into methane, the primary ingredient of natural gas. However, the coming of the Great Depression halted the research program. Some work on low-temperature coal carbonization, synthetic methanol, and the Bergius-I. G. Farben process continued, but a shortage of funding after 1931 obliged the scientists to concentrate on other projects. The economic collapse coincided with the great petroleum discoveries in Oklahoma and East Texas, with the result that energy prices fell and the likelihood of petroleum shortages seemed more remote than ever. Synthetic liquid fuels development in the U.S. went dormant, awaiting a shift in the economic and political climate.

President Roosevelt returned the Bureau to the Interior Department and an exceptional public administrator: Secretary Harold L. Ickes.

New Deal Energy Policies and the Pittsburgh Coal-Hydrogenation Plant

That shift began after President Franklin D. Roosevelt took office in 1933. Energy became an important theme in the New Deal programs that the president and Congress established to combat the Depression. Government-owned, government-operated hydroelectric dams generated inexpensive electricity. The Natural Gas Act of 1938 authorized the Federal Power Commission to set prices for interstate shipments of gas and to approve or veto new interstate gas pipelines. Revisiting earlier concepts for regulating petroleum output, the administration orchestrated a partially effective scheme of production quotas in the Mid-Continent petroleum fields. Interest in synthetic liquid fuels revived as this activist stance toward energy and the economy intersected with the rising threat of international conflict against Nazi Germany and Imperial Japan.

When President Roosevelt returned the Bureau of Mines to Interior Department control in 1934, the Bureau came under the authority of an exceptional public administrator who was at the forefront of the New Deal: Secretary of the Interior Harold L. Ickes. Temperamental, incorruptible, and politically astute, Ickes held his position from 1933 to 1946, making him the longest-serving Cabinet officer in American history. He directed highly visible programs that had lasting impacts on the physical landscape and the relationship of American citizens to the federal government. For example, Ickes headed the Public Works Administration, an Interior Department agency that stimulated the economy by building bridges, schools, and other infrastructure projects. He supervised the Civilian Conservation Corps and the operations of the Bonneville Power Administration, which in 1938 began distributing hydroelectric power from the new Bonneville Dam throughout the Pacific Northwest.

Ickes had definite ideas about energy policy. Like many other Roosevelt administration officials, he believed that the energy industries had such far-reaching impacts on American society that they merited an unusual degree of governmental oversight. He regarded plentiful, affordable energy as vital for restoring national economic growth and extending that growth to poorer regions, especially rural areas of the South and the West. Informed by his lifelong concern for environmental issues and his experience as a political reformer in Chicago, Ickes thought that public regulation and public investment were necessary to provide an adequate energy supply while conserving nonrenewable natural resources.

Under Secretary Ickes and Director John W. Finch, the Bureau of Mines prospered during the late 1930s as demand for its expert knowledge of fossil fuels and other minerals grew. It received annual budget increases beginning in the 1935–1936 fiscal year. Research laboratories at the experiment stations were modernized and expanded. The Economics and Statistics Branch compiled data that assisted the Interior Department and other agencies in implementing New Deal energy initiatives, such as the petroleum-production quotas and laws that Congress passed to stabilize coal prices. Toward the close of the decade, the Bureau turned its attention to the problem of strategic minerals—industrially critical substances that the U.S. had to import due to lack of domestic reserves—and possible substitutes for them.

Secretary of the Interior Harold L. Ickes. (photo credit: Library of Congress)

Whether substitutes for petroleum would also become necessary was a question that greatly interested Ickes, who referred to petroleum as "the life blood of the nation." By the mid-1930s, the national-security implications of petroleum extended far beyond the narrow issue of provisioning the Navy with fuel oil. Land warfare had become highly mechanized and dependent on liquid fuels. Military aircraft, which required special high-octane gasoline, seemed certain to play a large and even decisive role in any future conflict. Interior Department geologists and economists fretted that the current abundance of petroleum would give way to shortages in the event of a protracted war.

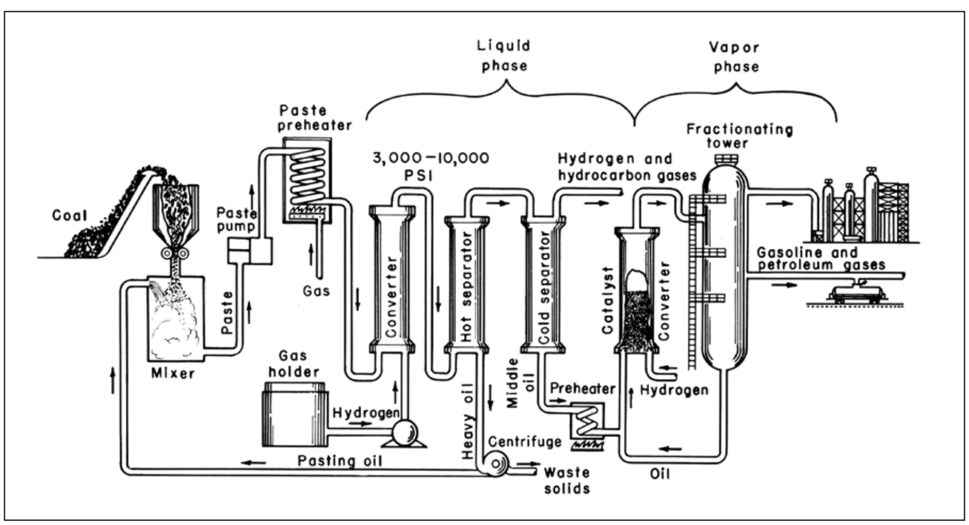
Ominous events in Germany made the threat of war credible and dramatized the connections between energy resources and military strategy. Adolph Hitler's Nazi dictatorship had embarked on a massive synthetic liquid fuels program to aid German rearmament and free the country from reliance on imported petroleum. German innovations in coal-to-liquids chemistry, which Americans had admired during the 1920s, suddenly became more than an intriguing scientific puzzle. Now linked to an oppressive and powerful regime that was hostile to American interests, these technologies had acquired menacing overtones.

The foundations of the Nazi commitment to coal-based synthetic fuels lay in commercial advances that German industry had made over the previous decade. I. G. Farben, a German chemical conglomerate that formed in 1926 when BASF merged with several other firms, had greatly improved the Bergius coal-hydrogenation process by subdividing it into two steps—a liquid phase and a vapor phase—and adding catalysts that accelerated the conversion of coal to oil. This revamped method had entered full-scale production in an I. G. Farben plant near the town of Leuna in 1927. To aid the Leuna venture, the German government used public subsidies that included tax exemptions and the extension of a tariff on imported petroleum. I. G. Farben licensed its patent rights in the hydrogenation process to other companies around the world; among the licensees was Standard Oil of New Jersey, which used hydrogenation to turn heavy petroleum into aviation gasoline, lubricants, and other products.

When the Nazis came to power, they redirected the Bergius-I. G. Farben technology and the highly centralized structure of the German coal-chemicals industries toward the goal of national self-sufficiency in liquid fuels. An agreement between the new government and I. G. Farben in December 1933 bound the government to subsidize synthetic liquid fuels production and to be the buyer of last resort for any synthetic oil that the company could not otherwise sell. The government extended assistance to other companies in 1934 and ordered German coal producers to set up a consortium for the sole purpose of building hydrogenation plants. By the end of 1936, the country had six such plants in operation or under construction.

The Nazis also speeded up the commercialization of the Fischer-Tropsch process for obtaining liquid fuels from water gas. Franz Fischer had established a small pilot plant at his Kaiser Wilhelm Institute laboratories in 1932, and in 1934 a private company backed by a German coal cartel built a larger version nearby at Oberhausen-Holten to produce motor fuels and lubricants. Government subsidies induced other companies to participate, with the result that five additional Fischer-Tropsch plants were completed or under construction in 1936.

These developments alarmed the governments of Western Europe, which feared that synthetic liquid fuels would give Germany additional leverage in its increasingly overt drive to dominate Europe. Also disturbing was evidence that the Germans were sharing coal-to-liquids technology with Imperial Japan, which was similarly trying to overcome the constraint of limited petroleum supplies as it expanded its military power in the Pacific. France and Great Britain responded by intensifying their research on and development of synthetic liquid fuels. At Billingham in northeastern England, the British government collaborated with Imperial Chemical Industries—a Bergius-I. G. Farben patent licensee—to set up a commercial-scale coal-hydrogenation demonstration plant in 1935. The British echoed the German practice of offering public subsidies, in the form of tax exemptions for synthetic oil, to encourage private investment.



Bureau of Mines diagram of the Bergius-I.G. Farben coal hydrogenation process.

In 1935, Secretary Ickes identified coal hydrogenation as a top research priority for the Bureau of Mines and asked Congress to fund a hydrogenation pilot plant at the Pittsburgh Experiment Station. His logic was twofold, merging national-security and economic-development rationales. Information from the pilot plant would help Americans understand what the Germans were doing with synthetic liquid fuels and design a comparable U.S. program if the need arose. And the research might assist the faltering coal industry. Bituminous coal output in the mid-1930s was less than 80 percent of its 1929 level and showed little sign of a rebound. It had become clear that price was not the only reason for the ongoing switch from coal to petroleum and natural gas; consumers preferred cleaner, more convenient fuels. Manufacturing high-value liquids and gases from coal seemed to be one of the few options left for increasing demand and brightening the economic outlook for coal-mining districts.

In 1935, Secretary Ickes identified coal hydrogenation as a top research priority for the Bureau and asked Congress to fund a hydrogenation pilot plant at the Pittsburgh Station.

Henry H. Storch, the Bureau's principal physical chemist, headed the pilot-plant initiative after Congress approved the necessary funding in 1935. Storch had been with the Bureau since 1928 and had participated in the synthetic liquid fuels group at Pittsburgh since 1931. Under his direction, engineers erected a small hydrogenation plant that could process up to 100 pounds of coal per day in a separate building—which they proclaimed to be "bombproof"—at the Pittsburgh station. The ties that the Bureau had forged with British scientists and engineers paid off; the plant was modeled on one that the British were using at Billingham, and the directors of fuel research in Great Britain and Canada provided invaluable technical advice on its design. It was ready for operation in September 1936. A distillation laboratory, equipped with instruments for analyzing synthetic oil and byproducts, reached completion in 1937.

The first experiments used local raw materials. Bituminous coal from the Experimental Mine at Bruceton was powdered and mixed with heavy oil and a tin-sulfide catalyst to form a thick paste. At first, the oil came from coal tar made at Pittsburgh's only low-temperature coal carbonization plant, which had opened in 1934; later, the tar gave way to recycled heavy oil from the hydrogenation process itself. Hydrogen was obtained by combining steam with local natural gas to form water gas, which was then transformed by another chemical reaction into pure hydrogen and carbon dioxide.

In the first phase of the Bergius-I. G. Farben process, the liquid phase, the coal-and-oil paste was pumped into a converter that took the form of a thick alloy-steel tube eight feet tall and three inches in internal diameter. Preheated hydrogen gas entered at the top of the converter. Inside, the hydrogen combined with the paste at temperatures between 410 and 480 °C and pressure of 3,200 pounds per square inch. The reaction converted the original coal into hydrocarbon gases and liquids, with the liquids divided about equally between heavy oil and light- and middle-grade oil. Heavy oil was stripped of ash and other wastes and prepared for recycling into more coal-and-oil paste. Lighter oils were collected in a condenser and saved for further investigation.

The coal-to-liquids converter for the Pittsburgh coal hydrogenation plant. (photo credit: National Archives and Records Administration)

Preparing a mixture of powdered coal and heavy oil for the experimental coal hydrogenation plant at Pittsburgh. (photo credit: National Archives and Records Administration)

A Bureau of Mines truck equipped to run on synthetic gasoline derived from coal, 1941. (photo credit: National Archives and Records Administration)

The pilot plant initially was not equipped to perform the vapor phase, the second stage of the process. In a typical Bergius-I. G. Farben plant, this phase involved further hydrogenating middle-grade synthetic oil by vaporizing the oil, combining the vapor with pressurized hydrogen, and injecting the mix into a reactor that contained catalysts. It increased the yield of lighter oils such as gasoline. However, Storch and his associates were primarily interested in mastering the basic technique of turning coal to synthetic crude oil, so they were content to distill the oil in smaller, laboratory-scale apparatus. Crude oil from the pilot plant yielded up to seven gallons per day of gasoline, some of which fueled vehicles in the Pittsburgh station's motor pool. A vapor-phase unit was constructed later, in 1939, and used for experiments during World War II.

A key task of the Pittsburgh pilot plant during the late 1930s was to begin a hydrogenation assay of American coals.

One of the greatest challenges in adapting the Bergius-I. G. Farben process for American use was the sheer variety of coals that existed in the U.S. Coals differed in terms of rank—the percentage of carbon they contained—and in other aspects of their chemical makeup and physical structure. Storch's team, like their mentors in Great Britain, wanted to know which types of coal worked best for hydrogenation and how much crude oil each type yielded. Thus a key task of the Pittsburgh pilot plant during the late 1930s was to begin a hydrogenation assay of American coals. The researchers compared the results of tests on Bruceton bituminous coal to the results of tests on representative samples of coal from other regions. Their findings showed that low-ranked (low-carbon)

Delivery of coal samples from various regions of the United States to the coal hydrogenation section of the Pittsburgh station. (photo credit: National Archives and Records Administration) coals, such as lignite, liquefied easily but produced relatively little oil. Higher-ranked, carbon-rich coals were harder to work with but tended to be better oil sources. For example, North Dakota lignite had an oil yield of about 30 percent, while Bruceton bituminous could yield over 60 percent.

By conducting these systematic tests, which kept the plant running continuously around the clock for weeks at a time, the Pittsburgh group also learned about the characteristic problems of coal hydrogenation. Pumps and valves that encountered the thick, hot, abrasive coal-and-oil paste quickly clogged or wore out. Appropriate parts and instruments were often not commercially manufactured, so the Bureau's engineers and highly skilled laboratory technicians had to make their own.

The hydrogenation assay confirmed that hydrogenation could work across a wide range of American coals, indicating that most of the country's vast coal reserves qualified as usable raw material for synthetic liquid fuel production. Outside the Bureau, the Interior Department, and some corners of the U.S. military, however, this potential was still not taken very seriously. Coal liquefaction, like oil shale, seemed no more than a possibility for the distant future. When World War II began on September 3, 1939, the little coal-hydrogenation plant at the Pittsburgh station was the only tangible sign of over two decades of synthetic liquid fuels research at the Bureau of Mines.

A Century of Innovation

From the U.S. Bureau of Mines to the National Energy Technology Laboratory

Chapter Five: World War II and Its Aftermath

The official seal of the Bureau of Mines.

Chapter Five:

World War II and Its Aftermath

Inasmuch as any program of military preparedness depends on an unobstructed flow of minerals, the Bureau of Mines, by virtue of the duties specified in congressional acts, is in reality an important defense agency of the United States Government. . . .
--Royd R. Sayers, Director, Bureau of Mines, 1940

Although the United States did not officially enter World War II until December 1941, government preparation for the country's possible entry into the fray had begun long before. A key ingredient was planning to ensure the energy security of the United States for the duration of a long war. Bureau of Mines personnel at Pittsburgh and Bartlesville were put to work surveying all the coal, oil, natural gas, and mineral resources available, and finding ways to extend these resources through conservation, improved production methods, discovery of new deposits, and recycling. Research efforts for improving the ability of American forces to fight the enemy focused on each research center's strengths: Pittsburgh's experience with explosives and coal and Bartlesville's knowledge of blending fuels to produce the best aviation fuels possible.

At Bruceton, the Experimental Mine aided the War Department in testing munitions and improving the safety of explosives handling and storage.

The Wartime Uses of Explosives Research

Many wartime issues related to explosives were logical extensions of the Bureau's peacetime activities. At Bruceton, the Experimental Mine and its associated laboratories aided the War Department and the Navy Department in testing munitions, improving the safety of explosives handling and storage, and evaluating factors that affected the use of high explosives for demolition work. Much of the research that the Bureau did for the military was classified, but hints of its content peeked through the dry language of Interior Department annual reports: appraisals of captured German and Japanese weaponry; studies of how sensitive various explosives were to friction, impact, heat, and electricity; and analysis of the shock waves that explosions produced.

The Explosives Division also continued to investigate explosion hazards in vital manufacturing industries. It inventoried the fire and explosion dangers created by metallic dusts in factories and studied methods of preventing the butadiene used in synthetic-rubber plants from blowing up. When a wave of explosions in the acetylene generators that West Coast shipyards used for welding threatened to delay the U.S. shipbuilding program in 1944, Bureau experts traced the causes to inferior materials and improper operation. Investigators from the Pittsburgh station probed one of the worst home-front disasters of World War II: the explosion of two large tanks containing liquefied natural gas (LNG) at Cleveland, Ohio, on October 20, 1944, an event that killed 130 people and wrecked one square mile of a densely built urban neighborhood. LNG—produced by cooling natural gas to very low temperatures of around -160°C—was a novel energy technology in the United States at that time, and the Bureau developed recommendations for storing and transporting it safely.

The M1 bazooka wielded by this American soldier in 1943 resulted from years of research on explosives, rockets, and propellants. The Bureau of Mines was one of several federal agencies that participated in the further development of these weapons during World War II. (photo credit: Library of Congress).

However, some types of research on explosions and explosives that were valuable to the military had no direct counterparts or applications in civilian life. The National Defense Research Committee (NDRC) observed in 1941 that "there were very few chemists indeed in this country having a knowledge of military explosives" and that the importance of developing new high explosives and weapons had made it "necessary for organic chemists to learn a somewhat new art." To cultivate that art and other specialized forms of scientific knowledge, the Roosevelt administration relied on the NDRC during 1940–1941 and the Office of Scientific Research and Development (OSRD) for the remainder of the war. These agencies were the federal government's instruments for coordinating civilian scientific research and focusing it on key military problems. They designated universities and government research facilities around the country as host sites for special-purpose laboratories.

One of these sites was Bruceton, where the NDRC began to contract with the Bureau of Mines in 1940 and formally established an Explosives Research Laboratory in early 1941. Although it was administratively separate from the Bureau of Mines, this new organization piggybacked on the Bureau's existing physical facilities and staff. It attracted outstanding scientific talent, including scholars from the country's top research universities. George B. Kistiakowski, its director from 1940 to 1943, was a noted professor of chemistry at Harvard University. After volunteering for service with the NDRC, he focused on the study of explosives and subsequently became the chief of the OSRD Explosives Division in 1942. The associate director was Louis Plack Hammett, a prominent American physical organic chemist. A professor at Columbia University, he had devised several important concepts and mathematical descriptions of organic-chemical reactions and had written the leading textbook in his field.

Relations between the academic newcomers, the federal civil-service employees on the Bureau of Mines staff, and representatives of the military were sometimes prickly, especially at the beginning. According to a biographer of Hammett, "one industrial chemist predicted that a group of college professors would blow their own heads off and one admiral announced that he already knew what there was to know about explosives." The Bureau staff "taught many of the academics some extraordinary and unwelcome lessons about the civil service." However, the diverse wartime inhabitants of the Bruceton site managed to collaborate productively on their shared mission of moving new explosives technologies quickly through the stages of research and development to deployment on the battlefields.

The Explosives Research Laboratory concentrated on two areas: high explosives and rocket propellants. It worked with substances such as RDX, a powerful solid explosive made from nitric acid and hexamine. RDX, usually in combination with TNT or other materials, became the standard American military explosive during World War II and was also a basis for innovations such as new types of plastic explosives. Often the researchers at Bruceton developed explosive materials that were carefully tailored to accomplish specific tasks, reflecting Kistiakowsky's guiding philosophy that, as he later summarized, explosives "could be made into precision instruments."

The most far-reaching contribution of the Explosives Research Laboratory was its participation in the design of a trigger for the atomic bomb.

Improved rocket propellants were in great demand. When Henry Linschitz, a graduate student from New York City, arrived at Bruceton in 1943, he found the Explosives Research Laboratory busy testing a weapon called the bazooka that individual soldiers could use to hurl small rockets against tanks or gun emplacements. The basics of this technology had been known for some time, but the U.S. Army was just beginning to adopt bazookas in large numbers. A Bruceton specialty was solid rocket propellants made with ammonium perchlorate, which was initially used in boosters to assist heavily loaded military aircraft at takeoff. This wartime research on propellants contributed to the postwar American long-range missile and space exploration programs.

The most far-reaching contribution of the Explosives Research Laboratory was its participation in the design of a trigger for the atomic bomb. No nuclear research took place at Bruceton; the main work of the Manhattan Project was done elsewhere, under the authority of another OSRD division and the U.S. Army. What the Bruceton laboratory did was use its expertise in conventional high explosives to help solve the crucial engineering problem of how to start the chain reaction that would cause a fission-type atomic bomb to explode.

Manhattan Project scientists and engineers identified two possible designs for a trigger. The first method would ram one piece of radioactive material (either uranium or plutonium) into another piece of the same type of material at high velocity, forcing the material to organize itself into a critical mass that would sustain an explosive reaction. Known as the gun model, this approach was initially thought to be most likely to succeed. A rival approach, the implosion model, envisioned covering a hollow sphere of radioactive material with a shell made of high explosives. The shell would be detonated from multiple points simultaneously, directing the blast energy inward and crushing the sphere to such a high density that critical mass would be reached. This method gradually gained favor as problems with the gun model emerged.

Seth Neddermeyer, the physicist who headed the Ordnance Engineering Group at the Los Alamos, New Mexico, headquarters of the bomb project, was an early proponent of the implosion model. He traveled to Pittsburgh in mid-1943 to enlist the help of the Explosives Research Laboratory in demonstrating that a device based on this concept could work. The first experiments with implosion charges were performed at Bruceton, using lengths of ordinary iron pipe wrapped in explosive materials. These tests showed that the concept was valid; when the explosives were detonated, the pipe segments collapsed in on themselves to resemble solid bars. Returning to Los Alamos, Neddermeyer and his colleagues continued similar experimentation there.

The difficulties of perfecting implosion charges were immense. To perform effectively, the researchers had to figure out how to coordinate multiple explosive detonations so that the shock waves emanating from different points on the shell were synchronized instead of interfering with one another. An explosive lens was required in order to focus the blast energy, similar to the way that an optical lens focused light. George Kistiakowsky became a key participant in organizing the design process, making frequent visits to Los Alamos as a consultant. In January 1944, he agreed to leave the Bruceton laboratory in Hammett's capable hands and join the Los Alamos staff, where he officially started on February 16 and succeeded Neddermeyer as the chief of implosion research four months later. Several other researchers from Bruceton also moved to Los Alamos, and the two laboratories cooperated closely in the final stages of the program. The judgment and hard work of the implosion advocates was vindicated when the first successful test explosion of an atomic bomb using the implosion model took place in the New Mexico desert on July 16, 1945.

Toward the end of the war, the extraordinary gathering of scientific talent at Bruceton dissipated as scientists and engineers moved on to other jobs. But the temporary presence of the Explosives Research Laboratory left its mark on the development of the Pittsburgh station. The station's explosives research had already been moving toward more rigorous integration of theory and practice, and the wartime experience accelerated this trend. Under the direction of Bernard Lewis, the Explosives Division of the Fuels and Explosives Branch was renamed the Explosives and Physical Sciences Division in 1946, and greater emphasis was placed on cutting-edge inquiry into the structure and propagation of flames and explosions. One legacy of the wartime explosives work was the so-called "Bruceton test" or "Bruceton up-and-down method" of statistical analysis, which subsequently gained wide usage in sensitivity testing for explosives and other hazardous materials. The connections that the Bureau had developed with the military and the nascent nuclear program during the war would also continue to ramify during the postwar era.

Supplying Coal to a Nation at War

On January 10, 1940, an explosion triggered by an electric spark killed 91 people at Pond Creek Mine No. 1 in Bartley, West Virginia. The blast was the first of several disasters that roiled the American coal industry as rising economic activity, driven by military-related demand, finally began to lift the country out of the Great Depression. Pond Creek and five other mine explosions during 1940 claimed a total of 276 lives, the worst annual tally since the Bureau of Mines had launched its rock-dusting campaign in 1924. Coming as a shock after several years of calm, the tragedies were perceived as evidence that voluntary cooperation between mining companies and government had reached its limits of effectiveness. For example, the Pond Creek mine had used permissible explosives and permissible electrical equipment but had not followed Bureau guidelines on ventilation and rock dusting. Stricter oversight was apparently necessary to ensure that mines operated safely.

The Federal Coal Mine Inspection Act, which President Roosevelt signed into law on May 7, 1941, responded by granting the Bureau the power to conduct mandatory mine inspections. For the first time, Bureau employees could enter privately owned mines without notice or permission, at least once a year and more often at need, to examine health and safety conditions. They still could not order mine operators to correct any hazards that were discovered. But they could apply pressure by recording and publicizing their findings—in contrast to the confidential, informal safety evaluations that the Bureau had been providing at the request of individual companies since 1923.

To implement the Coal Mine Inspection Act, the Bureau had to make substantial organizational changes. It formed a Coal Mine Inspection Division, headquartered at Pittsburgh, within the Health and Safety Branch. Edward H. Denny, a mining engineer who had worked for the Bureau since 1912, headed the new division; John J. Forbes, who had supervised the agency's safety activities in the Pittsburgh region since 1925, became its chief engineer. During 1941, 107 mine inspectors—the number eventually grew to 137—were hired, trained, and assigned to eight safety districts that the Safety Division had already established. The Pittsburgh station created additional laboratory space to handle an increased volume of gas and dust samples. An occupational-health unit was set up to fulfill a legal requirement that the Bureau use mine

Bureau of Mines inspectors entering a coal mine in West Virginia.

inspections to develop knowledge about the causes of occupational diseases in the coal-mining industry.

In 1945, the Bureau estimated that "nearly 4,000 coal miners are alive today who might have perished during the last 3 ½ war years had coal-mine fatality rates remained at the levels of World War I."

Federal mine inspections began on December 1, 1941, just six days before the Japanese attack on Pearl Harbor brought the United States fully into World War II. The Bureau did not have enough resources to examine every one of the approximately 14,000 coal mines in the United States, so the program focused on some 2,500 large mines that accounted for over 90 percent of American coal production. By June 1944, the inspectors had visited almost all of these large mines at least once and had re-inspected more than half. Company managers, labor unions, and state mining regulators received copies of the inspection results, which were also available to the general public.

Not all mining companies followed the inspectors' recommendations, but many apparently did, and the inspection program contributed to the respectable safety record of American coal mining during the war. Despite occasional disasters and a rise in the number of accidents and casualties as mine output expanded, the overall casualty rate did not spike upward. One Bureau report noted that coal-mining fatalities actually hit a record low in early 1944 "in the face of numerous handicaps," including an inexperienced workforce, "greater effort by workers resulting in physical and mental fatigue," and difficulties with keeping machinery in repair. In 1945, the Bureau estimated that "nearly 4,000 coal miners are alive today who might have perished during the last 3 ½ war years had coal-mine fatality rates remained at the levels of World War I."

The reorganization of the Bureau's Health and Safety Branch during the 1941–1942 fiscal year included two other new units that handled special wartime duties. One was the Explosives Control Division. In December 1941, Congress reactivated the Federal Explosives Act of 1917, which authorized the Bureau to regulate civilians' possession of explosives. The agency carried out this responsibility by granting explosives licenses to individuals and organizations that could demonstrate a valid need for them. Manufacturers, educational institutions, and research laboratories could obtain licenses directly from the Bureau. To handle other requests, over 4,000 local licensing agents were deputized to issue licenses in exchange for a 25-cent-per-application fee. Federal explosives investigators supervised these agents and could suspend, fine, and recommend for prosecution any who engaged in misconduct.

The other emergency innovation was the Mineral Production Security Division, which worked closely with industry, law enforcement, and the armed services to defend mines and processing plants against sabotage. "Engineer-investigators" studied security conditions at ordnance plants on behalf of the Army and monitored protective measures at certain mines that the government had identified as essential to the war effort. However, the distinct absence of subversive activity eventually convinced all involved that the division's resources would be better used elsewhere. Security inspections at coal mines ceased after June 1944, and the entire program ended when Germany surrendered to the Allies in May 1945.

Routine health and safety work continued at the Pittsburgh station during the war under Superintendent Harold P. Greenwald. The list of permissible explosives and equipment received frequent updates, and Bureau engineers further improved methods of detecting and measuring dust and harmful gases. A problem that received much careful thought was the question—raised by the coal-mining industry—of whether a charge of permissible explosives could safely be increased from the standard 1.5 pounds to 3 pounds in order to accelerate coal production. Experimentation at Bruceton concluded that the answer was generally yes. This research culminated in 1948 when the Bureau issued an official standard that allowed the larger charge size.

Harold P. Greenwald, superintendent of the Pittsburgh station during the war years. (photo credit: National Archives and Records Administration)

The Bureau's first permissibility schedule for the use of diesel engines in mines emerged in 1944 after years of thorough research. Diesels, which the Bureau had been studying since the 1910s, were gaining popularity in the railroad and construction industries. They had advantages for underground work, since they produced much less carbon monoxide than gasoline engines did and could replace dangerous electrical devices. But they also created the new hazard of toxic nitrogen-oxide emissions. In a process reminiscent of the Holland Tunnel ventilation studies, Bureau of Mines engineers identified the chemical composition of diesel exhaust, studied human reactions to it, and constructed an underground gallery at Bruceton that was large enough to accommodate a mine locomotive. The investigations found that diesel engines were safe to use in well-ventilated mines if such engines were adjusted to minimize poisonous gas emissions, and if they were equipped with flame arresters to limit the risk of explosion.

Safe, efficient mining was only the first stage in the process of meeting the immense wartime demand for coal. As it had been since its creation, the Bureau was responsible for ensuring that all agencies of the federal government—the single largest buyer and consumer of coal in the United States—received adequate, high-quality coal supplies. Engineers with the Bureau's fuel advisory service consulted with the Army, the Navy, and civilian departments to determine what types of coal and coal-burning equipment best fit the needs of each agency. Then the Bureau policed the government's coal purchases by checking samples of coal against the specifications that the purchase contracts required. During the 1943 fiscal year, almost 23,000 such inspections were made. Bureau trucks bearing portable analytical equipment roamed the land, collecting samples of coal from hundreds of mines.

The war brought unusual coal-handling problems to the armed services and to industry. As military bases and training camps multiplied in isolated rural areas of the country and in overseas combat zones, getting coal to these destinations and storing it after it arrived became major logistical issues. Arsenals and other crucial manufacturing plants stockpiled coal so that strikes or natural disasters that interrupted fuel delivery would not also interrupt industrial production. Because coal gradually oxidizes and deteriorates when exposed to air, causing it to lose heating value and even spontaneously catch fire, faulty transport and storage practices could lead to big economic losses and endanger local communities. The Bureau advised military officers and plant managers, training them to store coal properly and monitor it to avoid accidental fires.

Coal samples from around the country arriving at the Pittsburgh station for testing to determine whether they met the federal government's specifications.

Spontaneous combustion of improperly stored coal caused this fire at the Nonconnah Yards of the Illinois Central Railroad near Memphis, Tennessee. Preventing such dangerous and wasteful fires and improving methods of extinguishing them were important missions of the Bureau of Mines during World War II. (photo credit: National Archives and Records Administration)

Another way in which the Bureau used its expertise to protect government buildings, ships, and industrial facilities was boiler-water conditioning. Since water is never entirely pure, it forms mineral deposits inside steam-generating boilers, resulting in damage that can cause boilers to fail. Boiler outages could snarl critical industries and hinder military operations, especially when wartime shortages of steel meant months-long waits for repairs. The Bureau instructed power-plant operators in how to prevent or reduce this harm by adding conditioning chemicals to boiler water. To deal with the problem of embrittlement, in which waterborne caustic minerals trigger cracks in steel boiler components, Bureau engineers at Pittsburgh and at the College Park station developed an embrittlement detector that gave advance warning of hazardous mineral concentrations.

Wilburn C. Schroeder displaying the embrittlement detector that the Bureau of Mines invented to help protect against boiler failures. The Bureau received a patent for this device in July 1943. (photo credit: National Archives and Records Administration)

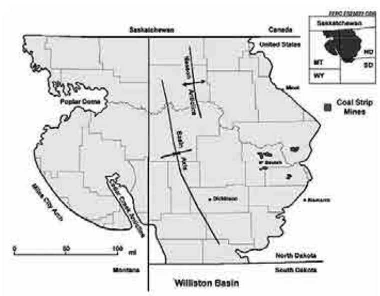
Expanding U.S. coal supplies by locating new deposits and making better use of coal from known fields was a major task of the Coal Division. Particularly worrisome were strains on the available sources of high-grade coking coal for the iron and steel industry. The Pittsburgh coal seam, which had for decades provided excellent coke and anchored the concentration of metallurgical industries in the Upper Ohio Valley, was showing signs of exhaustion by the early 1940s. Concurrently, new blast furnaces to serve wartime industrial growth in the Rocky Mountain and Pacific Coast states created an urgent need to find more coking coal for the West.

The Pittsburgh coal seam was showing signs of exhaustion by the early 1940s.

Here the Pittsburgh station's deep knowledge of American coals proved useful. Since 1927, the coal-carbonization laboratory at Pittsburgh had been systematically surveying the coking and gas-making properties of coals from all regions of the country. Data from this ongoing project aided mining and metallurgical engineers in identifying new reserves of coking coal in Washington State, the Rockies, Oklahoma, and Arkansas. The station also studied methods of improving lower-quality coals, such as removing impurities and blending output from several different mines, so that they could be used for making high-grade coke.

At Pittsburgh and several other experiment stations, Bureau scientists and engineers sought to make low-rank coals—coals that contained relatively little carbon—more useful to industry. Many American states, especially those on the Great Plains and along the northern tier from New England to Washington State, harbored large deposits of subbituminous coal, lignite coal, and peat that had considerable potential as fuel sources. Lignite held particular economic significance. This moisture-rich, soft coal had a carbon content of 35 percent or less; thus it yielded much less thermal energy than did standard bituminous coals, which were typically 60 to 80 percent carbon. But it was plentiful, cheap, and often vital to remote areas that lacked other fuels. Settlers on the prairies of the Upper Midwest had long used lignite, mined from the vast deposits of the Williston Basin in Montana and the Dakotas, to generate heat and power.

Due to technical and economic limitations, lignite had remained a matter of regional rather than national interest before the 1940s. It disintegrated easily and was prone to spontaneous combustion, making it difficult to handle and store. It did not perform well in conventional boilers or manufactured-gas equipment that had been designed for bituminous coal. Bulky yet relatively low in heating value, it was awkward to transport far from where it was mined. These realities confined lignite to a few local markets in the Upper Midwest and Gulf Coast, and even where it abounded many consumers preferred to import higher-quality coals from distant sources.



The Williston Basin region of the Upper Midwest, a major source of lignite. (photo credit: United States Geological Survey)

World War II changed the economic calculus as industrial mobilization created immense pressure to use all available fuels, including lignite and other low-rank coals. The Bureau helped to develop techniques for burning lignite or subbituminous coal instead of standard bituminous coal in power plants. Among the methods that it demonstrated were drying lignite to remove excess moisture, using mechanical stokers to feed low-rank coals evenly and efficiently into furnaces, and protecting these coals against oxidation in storage.

As well as encouraging coal users to switch to lower-rank, lower-quality coals, the Bureau encouraged fuel conservation and the substitution of coal for petroleum and natural gas, which were both in increasingly tight supply. Some industrial and commercial establishments that had turned to fuel oil or natural gas reverted to coal temporarily during the war years. Others experimented with burning a mixture of pulverized coal and fuel oil. Looking ahead, Bureau officials cited the wartime drawdown of American natural-gas and petroleum reserves as a reason for making research and development on synthetic liquid fuels an urgent national priority. Coal could always be a backstop whenever other domestic sources of fossil energy faltered. The example of Germany offered a stark reminder of how strategically important a country's coal reserves could be.

Synthetic Liquid Fuels in Wartime

Americans knew that Nazi Germany's war effort depended on coal-to-liquids technologies. They did not know exactly how large the German synthetic liquid fuels program had become, or whether it had resulted in any major technological advances since the outbreak of the war. In 1943, Bureau of Mines Director Royd R. Sayers offered an informed guess that the program supplied "at least a half to two-thirds of the gasoline, oils, and waxes" for German-dominated Europe. He and other energy analysts voiced grudging admiration for the Germans' skill and foresight in parlaying the technical achievements of coal hydrogenation and the Fischer-Tropsch water-gas synthesis into an industry that had enabled their country to attain great international power.

By the fall of 1943, the Bureau had two distinct lines of investigation underway on synthetic liquid fuels. One grew out of studies aimed at converting lignite into higher-value gas and liquid products. The original impulse for this research was an emerging raw-materials problem: depletion of the nation's iron-ore reserves, which, like coking coal, were essential for steel production. Wartime demand rapidly diminished the best natural iron-ore deposits in the Iron Ranges of Minnesota and elsewhere around the Great Lakes. Midwestern mining companies turned to the alternative of taconite, a hard rock in which layers of iron ore intertwined with layers of other minerals. Processing taconite was a complex, energy-intensive business that involved pulverizing the rock, separating the iron ore from other substances, and forming iron pellets that could be easily shipped. It required fuel. It needed industrial gases, especially carbon monoxide, for the chemical reactions that extracted metallic iron from iron ore. A potential source of these inputs was water gas made from the lignite of the nearby Williston Basin.

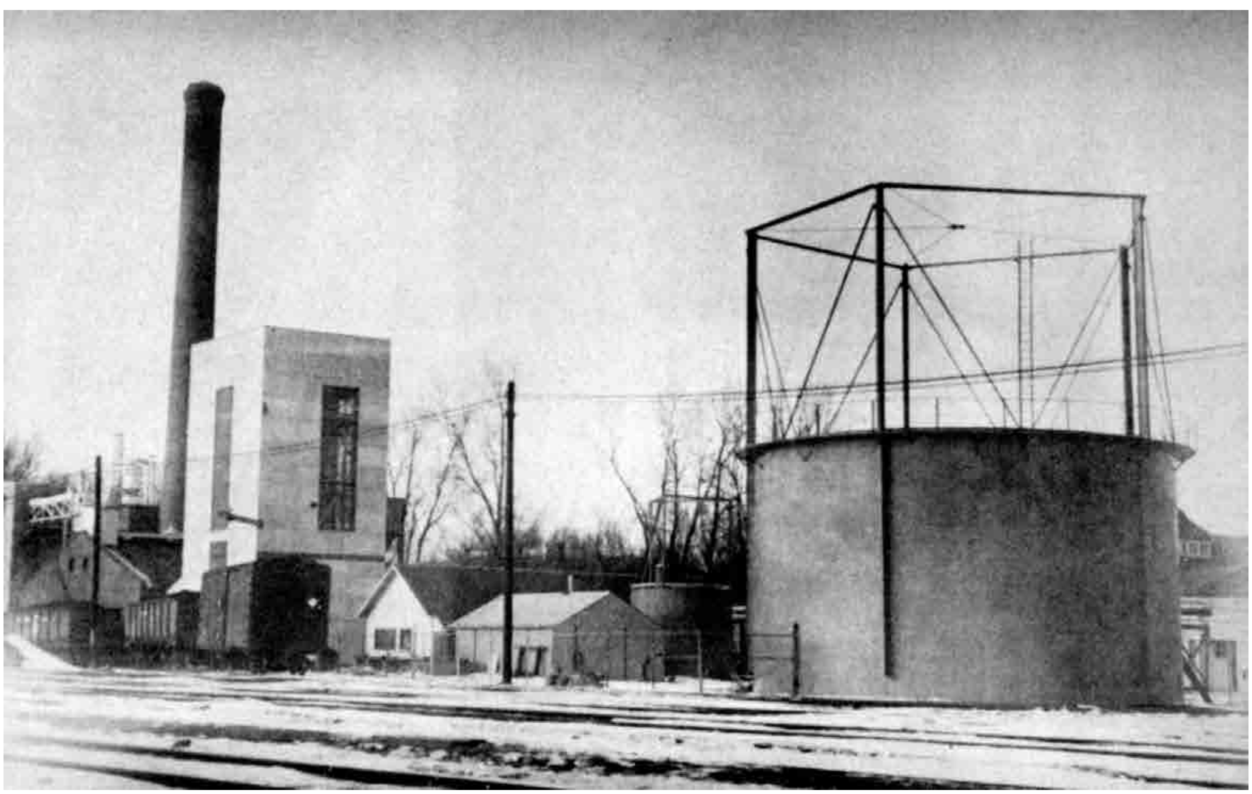
Between June 1945 and June 1946, the Grand Forks plant turned 381 tons of lignite into 16 million cubic feet of water gas.

The Bureau of Mines began studying the gasification of Williston Basin lignite in August 1943. Earlier studies had verified that this type of coal did not work well in conventional water-gas generators, but engineers at the University of Minnesota had developed a new approach called the Reyerson-Gernes process that looked promising. In a Reyerson-Gernes generator, two concentric alloy-steel pipes of differing diameters framed a narrow, ring-shaped space—in mathematical terms, an annulus—into which lignite and steam were continuously fed from the top. The annulus was externally heated by surrounding the pipes with a cylindrical furnace. Temperatures of around 900°C converted the lignite and steam into the familiar water-gas mixture of carbon monoxide and hydrogen. Any remaining solid matter that did not react was automatically discharged from the bottom of the generator.

In February 1944, a small prototype Reyerson-Gernes generator designed by the Bureau of Mines engineer V. F. Parry was completed in a laboratory that the Bureau operated at the Colorado School of Mines in Golden, Colorado. This first pilot plant underwent several trial runs over the next nine months. Concurrently, the Bureau proceeded with the planning and construction of a larger version on the University of North Dakota (UND) campus at Grand Forks, North Dakota. The Grand Forks pilot plant, finished in February 1945, had a capacity six times greater than that of its predecessor at Golden and was meant to demonstrate the feasibility of lignite gasification on a commercial scale. UND donated the site and allowed the Bureau to use existing buildings and tap into the university's power and steam facilities to keep costs down.

Between June 1945 and June 1946, the Grand Forks plant turned 381 tons of lignite into 16 million cubic feet of water gas. It operated smoothly; the greatest challenges were controlling dust and maximizing the life of the steel components under the stress of prolonged heat. Lignite's distinctive texture created large surface areas that made the coal highly reactive and quick to gasify. The ratio of hydrogen to carbon monoxide in the water-gas output could be varied readily in order to tailor the gas to the needs of specific industrial processes. Moreover, Williston Basin lignite was low in sulfur, thus limiting the problem of sulfur damage to equipment and catalysts.

Interior view of the retort building at the Grand Forks gasification plant, showing the hopper and charging valves that fed lignite into the top of the Reyerson-Gernes water-gas generator. (photo credit: Bureau of Mines publication)



Exterior view of the large pilot plant for lignite gasification at Grand Forks, North Dakota, completed in 1945. (photo credit: Bureau of Mines publication)

The results of the tests at Golden and Grand Forks suggested that the lignite reserves of the Upper Midwest had value not only for upgrading poor-quality iron ore but also for manufacturing industrial organic chemicals, including synthetic liquid fuels. Gasifying lignite was apparently a good method of obtaining what chemical engineers increasingly termed *synthesis gas*: water gas with few impurities and a controlled ratio of hydrogen to carbon monoxide so that it could be used as a base, or feedstock, for synthesizing other organic chemicals. Work on gasification and industrial uses of lignite products continued after World War II at the UND facility, which developed into the Charles Robertson Lignite Research Laboratory (completed in 1951) and became an important center of federally sponsored applied research on energy.

Lignite and other low-rank coals also figured prominently in the coal-hydrogenation assay that the Pittsburgh Experiment Station had begun in 1937 and continued throughout World War II. By mid-1943, the staff of the experimental hydrogenation plant at Pittsburgh had tested fourteen different American coals to evaluate how readily they could be converted to liquid oil in the Bergius-I.G. Farben process. The assay paid special attention to subbituminous and lignite coals, for two reasons. One was the lack of existing information; low-rank coals in European countries differed significantly from the American varieties, so prewar data from European coal-hydrogenation plants offered little guidance. The other was the belief, held as strongly at the Pittsburgh station as it was at Bureau experiment stations in the West, that low-rank coals were underdeveloped economic resources.

The coal-hydrogenation group continued to find that low-rank coals liquefied most easily and completely, while bituminous coals gave higher yields of synthetic oil. Henry Storch, the supervising chemist for physical chemistry and coal hydrogenation at Pittsburgh, thought that subbituminous coals from the Monarch seam in Wyoming struck the best balance between yield and ease of use. But he and other Bureau officials stressed that most coal found in the U.S. was acceptable for hydrogenation. They also noted that changes in pressure, temperature, and other variables in the operation of the hydrogenation pilot plant frequently affected oil output more than the type of coal did.

During the war years, the staff of the Bureau's synthetic liquid fuels program was exceedingly industrious. Storch and his superior Wilburn C. Schroeder, the assistant chief of the Fuels and Explosives Service, put themselves at personal risk by crossing the Atlantic in 1943 to touch base with British fuel researchers—who had established good rapport with exiled German engineers—and gather information about the large British coal-hydrogenation plant at Billingham. The Pittsburgh laboratories developed a modified form of coal hydrogenation that could produce heavy fuel oil at lower pressures than were customary in the Bergius-I. G. Farben process. Samples of synthetic gasoline underwent further tests in automobiles and aircraft, and Bureau reports made the findings of the hydrogenation research program publicly available.

Most importantly, the Bureau persuaded Congress to resume funding for studies of the Fischer-Tropsch process in 1942, allowing the Pittsburgh station to take up this subject for the first time since 1930. Storch and his colleagues began equipping a chemical-engineering laboratory for Fischer-Tropsch investigations in 1943. They first resumed the tedious but essential work of testing catalysts and methods of preparing catalysts. In November 1943, they built a small laboratory-scale reactor. A second, larger version followed in 1944, and in March 1945 the Bureau's first Fischer-Tropsch pilot plant was ready. This plant could convert synthesis gas, made from local natural gas and steam, into three gallons of liquid products per day. By then, the researchers were once again pursuing theoretical questions about how carbon monoxide and hydrogen gases reacted to produce liquid oils and alcohols—the topic that had inspired the beginnings of synthetic liquid fuels research at Pittsburgh in the mid-1920s.

Bartlesville's Contribution to the War Effort

"Do not forget that petroleum is an exhaustible and irreplaceable natural resource," Secretary of the Interior Harold Ickes—who was also the director of the newly established Office of Petroleum Coordinator—said in a speech to the American Petroleum Institute on November 5, 1941. "Not only does our commerce and our industry and our husbandry and our pleasure depend upon it, this war demonstrates that the possession of an abundance of petroleum and its products is a matter of life and death to a nation. And our own nation would

The Fischer-Tropsch laboratory at the Pittsburgh station in 1946. (photo credit: National Archives and Records Administration) be negligent of its duty, recreant to its trust, if it permitted any industry to waste such a valuable natural resource."

The Secretary's profound statement was well received in Bartlesville, where the researchers were already on the job. In his 1940 annual report to the Bureau of Mines, N. A. C. Smith wrote that his staff had supplied four manuscripts on the history and trends of technological development in the petroleum industry for the National Resources Planning Board; other reports had been prepared relating to national defense and conservation. This work signaled the beginning of heightened activity at Bartlesville as the United States prepared for possible involvement in World War II. Much depended on the availability of high-quality, high-octane aviation fuels, on other petroleum products to lubricate engines, turbines, and other machinery for the war effort, and on asphalt for use in military construction projects.

Smith emphasized the need for petroleum products more dramatically in 1941:

> *The international importance of petroleum and its products, even to the extent of controlling a nation's destiny, has prompted a reappraisal of each technical problem in the Petroleum and Natural Gas Division to determine its bearing on (1) availability and conservation of petroleum needed in a national emergency, (2) production, manufacture, and use without waste, and (3) means of safeguarding physical equipment used by all branches of the industry. Long-term research judged to be of secondary importance was suspended, and each active study was oriented to advance in step with rapidly changing conditions.*

Smith also wrote that the Advisory Commission to the Council of National Defense had requested that Bartlesville's refinery group dedicate its efforts to a survey of the quantity and geographic distribution of crude oils suitable for the manufacture of aviation gasoline. About 250 from selected oil fields around the United States were analyzed, revealing that a few fields that had not been large producers to date had the potential to supply crude for aviation-grade gasoline. The group also made a survey of the location, capacity, and type of refineries available in relation to national defense requirements for manufactured petroleum products.

The black oils of the Rocky Mountains were found to be suitable for producing the asphalts the military required, and the semi-annual motor-gasoline surveys that had begun in 1915 "proved especially valuable in defense planning because they give a cross-section of the characteristics of present-day motor fuels available throughout the country for motorized equipment," according to Smith.

Activity and funding picked up after the Pearl Harbor attack on December 7, 1941. Total funding for Bartlesville climbed from $260,000 annually before the war to over $650,000 in 1945. Congress provided additional support for aviation fuel investigations, which, under the leadership of Senior Chemist Harold Smith, blended various petrochemicals to produce 100-octane aviation fuel. "The Bureau turned the whole chemistry and refining program of the Petroleum Experiment Stations at Bartlesville, Okla., and Laramie, Wyo., to search for technical answers to current practical questions regarding the essential nature of crude oils, natural gas, condensates, and their components," Smith wrote in 1942. "High-efficiency fractionating towers were designed and built; work progressed on desulfurization of marginal aviation-gasoline base stocks to improve their response to tetraethyl lead; and reports gave valuable information on volume and types of asphalts needed for military airport runways and roads."

In 1943, the government and the war industries turned to Bartlesville scientists even more for help in improving aviation fuels and producing large volumes of toluene from petroleum for use in explosives.

In 1943, the government and the war industries turned to Bartlesville scientists even more for help in improving aviation fuels and producing large volumes of toluene from petroleum for use in explosives. Secondary oil recovery efforts using compressed air, natural gas, and waterflooding were increased to improve petroleum yields in old fields. The Bureau's long-term study of the effect of well spacing on the amount of oil extracted was given high priority as steel for oil drilling bits became a scarce commodity. If these well-spacing studies showed that fewer wells could be drilled without diminishing oil production, then the steel used in drill bits could be diverted to other wartime uses. Thermodynamics studies of hydrocarbons began to aid in the production of synthetic rubber. In 1943 alone, 132 special reports were prepared on the properties of crude oils and distillates for war uses. This scientific work contributed greatly to the Allied victory in 1945.

The shortage of natural rubber during the war gave the Bartlesville staff a challenging problem that would eventually lead to the station's recognition as an elite institution for the determination of thermodynamic properties of chemicals and materials. To make synthetic rubber, scientists needed to know the fundamental energetic properties—the thermodynamics— of butane, butene, and butadiene (rubber), in order to perform reactions that would lead from butane as a raw material to butadiene as a final product. That is, they had to

Bartlesville employee logs incoming barrels of crude oil for the aviation gasoline survey.

know the amount of energy contained in the chemical bonds of these various compounds. This information did not exist in handbooks; it would have to be obtained through painstaking laboratory experiments.

Fortunately, Bartlesville had the services of Dr. H. M Huffman, who was considered to be one of the world's leading thermodynamics experts. "Dr. Huffman, and other Bureau scientists, began investigating the thermal energy possessed by molecular crystals in different lattice patterns and in different molecular structural conformations," the *Bartlesville Examiner-Enterprise* reported in its 1968 issue celebrating the fiftieth anniversary of the Bartlesville Station. "Petroleum hydrocarbon samples were confined in cryostats at temperatures as low as -440 degrees F, reached by using liquefied hydrogen refrigerant. Other studies of the heat released upon combustion of petroleum hydrocarbons under controlled conditions formed the experimental basis for relating the heat of combustion to the energy in the atomic bonds which constitute molecular structure…." So by cooling the compounds down or burning them up, the scientists were able to determine thermodynamic properties such as the heat of formation, the heat of combustion, the Gibbs free energy, and the entropy of the compounds of interest. With these values in hand, organic chemists could then perform calculations and devise reaction pathways to convert butane to butane to butadiene. This effort led to the successful synthesis of synthetic rubber in large quantities.

The shortage of natural rubber during the war gave the Bartlesville staff a challenging problem that would eventually lead to the station's recognition as an elite institution for the determination of thermodynamic properties of chemicals and materials.

When the war was over, a great need still existed for thermodynamic studies in petroleum research, which Bartlesville was well equipped to perform. Petroleum is a complex mixture of many hydrocarbons, other organic compounds, and contaminants such as sulfur. To optimize the refining of fuels from crude petroleum required knowledge of thermodynamic properties of many of these components. That knowledge then allowed chemists to make reliable predictions about the properties of other compounds.

The American Petroleum Institute (API), composed of the nation's leading petroleum companies, had both a natural interest in such studies and the money to fund the research. Of particular interest to the industry were the contaminating compounds of sulfur, which smelled terrible and corroded metal engine parts. The *Bartlesville Examiner-Enterprise* reported that the Executive Committee of the API's Advisory Committee on Fundamental Research on Composition and Properties of Petroleum, meeting in 1947, "concluded that the deleterious effects of sulfur compounds in the petroleum industry and the dearth of knowledge of them justified the establishment of a research project to study their occurrence and nature in petroleum." In 1948, the institute established API Project 48 in collaboration with the Bartlesville station to determine the identity and properties of the numerous sulfur compounds in crude oils. At the time, fewer than 25 of these compounds had been identified, and the data on them were sparse.

The project was divided into two sections: 48A and 48B. Project 48A was under the direction of Harold M. Smith of the Bartlesville Petroleum Research Center.

Huffman and his colleagues invented a "rotating bomb calorimeter" that would revolutionize thermodynamics work.

It was during the late 1940s that petroleum finally surpassed coal in providing for the nation's energy needs.

Smith coordinated the work done by John S. Ball at the Laramie Center, who was charged with producing and purifying sulfur compounds, and Huffman at Bartlesville, who measured the thermodynamic properties of the sulfur compounds. Smith himself identified the compounds that Ball and Huffman isolated and studied. Project 48B, performed by F. G. Bordwell of Northwestern University, involved synthesis and reaction studies of sulfur compounds.

To perform the thermodynamics measurements with the utmost accuracy and precision, Huffman and his colleagues, in cooperation with researchers at the University of Lund, Sweden, invented a "rotating bomb calorimeter" that would revolutionize thermodynamics work. For a few years it was the only one

Bartlesville scientists invented the rotating bomb calorimeter to obtain precise measurements of thermodynamic properties.

of its kind in the world. Explaining its operation, a reporter from the *Bartlesville Examiner-Enterprise* wrote: "Bomb calorimeters consist of a well-insulated pot with a small container suspended inside. The pot is filled with water and a chemical reaction is started inside the container. The inner container is called a bomb because the reactions in it are generally rapid and almost explosive. The reaction of the substances increases the temperature of the water and the change is recorded on a thermometer." The thermodynamic heat of reaction can be determined from the temperature increase of the surrounding water. Rotation of the bomb ensures thorough mixing, leading to a thermodynamically defined final state for the combustion process.

API Project 48 would last for 18 years. It provided continuous funding for significant research at Bartlesville, and resulted in extensive contributions to the thermodynamics literature. By the mid-1950s, the thermodynamics researchers were considered the elite of the laboratory, and the Bartlesville station had gained international renown for its work on the thermodynamics of sulfur, nitrogen, and hydrocarbon compounds.

Harry C. Fowler, Superintendent of the Bartlesville station, 1945-1963.

Smith stepped down as superintendent of the Bartlesville Petroleum Experiment Station in 1945, but stayed on for a few years to polish the prose of any report that was issued; his reputation as an impeccable editor had grown during his years leading the station. His talents were especially needed in 1946, as every researcher at Bartlesville spent the first six months of that year writing reports about research done between 1940 and 1946 (nothing had been published during the war, for security reasons). Harry C. Fowler became Smith's successor.

The years immediately following World War II witnessed an important and lasting shift in the fortunes of the petroleum industry. It was during the late 1940s that petroleum finally surpassed coal in providing for the nation's energy needs. In 1945, as the war came to an end and the transition to a peacetime economy began, coal still accounted for almost half—about 49 percent—of American energy usage as measured in terms of BTUs. By 1950, its share had plummeted to less than 35 percent, while petroleum supplied 38.5 percent of domestic energy consumption and had become the single largest source of energy in the country. Petroleum's crucial role in winning the war and in powering postwar economic growth created a new set of economic and political challenges for energy researchers at the Bureau of Mines to address.

N.A.C. Smith

N.A.C. Smith died on May 19, 1952. On December 31 of that year, the Department of the Interior honored him with a posthumous Distinguished Service Award, the highest honor in the department. Smith had spent nearly 37 years in government service, 19 of them as Superintendent of the Bartlesville Station. His son Arthur C. Smith gathered with some of his father's friends and colleagues to accept the citation in the station's library. The January 1, 1953 edition of the *Bartlesville Examiner-Enterprise* reported, "The Citation points out that N.A.C. Smith was a pioneer in developing methods of analytical distillation of petroleum and its products, and in interpreting crude oil analyses, and that he added greatly to the fund of human knowledge regarding the chemistry of petroleum. The Citation reads in part: 'Mr. Smith established the main working principles of the petroleum-chemical activities of the Bureau of Mines, organized and directed the group engaged in that work, and developed a philosophy of research in this field that has endured for many years. His writings have served as guideposts to others in their development of a broader knowledge of the characteristics of crude petroleum.'"

Learning from German Synthetic-Fuels Scientists

The oldest commercial coal-hydrogenation facility in the world was barely operational when Lester L. Hirst and W. W. Odell of the Bureau of Mines reached it on April 21, 1945, just before World War II ended in Europe. Like many other German synthetic liquid fuels plants, the giant I. G. Farben works at Leuna had sustained massive damage from Allied bombing raids. Only one of its original ten liquid-phase hydrogenation reactors still functioned. Over several days, the American investigators toured the shattered Leuna works and interviewed the German engineers and chemists in charge. The Germans explained the details of how the plant converted local brown coal (a fuel similar to lignite) to synthetic oils and water gas that supplied raw materials for making aviation fuel, synthetic ammonia, and other industrial chemicals.

Hirst and Odell were part of the Technical Oil Mission (TOM), the American side of a joint American and British effort to ferret out and publicize the secrets of the German synthetic liquid fuels industry. The TOM began a new phase in the transfer of coal-chemistry expertise from Germany to the rest of the world. With the collapse of the German economy and government, culminating in unconditional military surrender on May 8, 1945, the country's industries and laboratories could no longer shield themselves from foreign eyes. Sometimes reluctantly, sometimes willingly, German scientists and technicians shared their knowledge with Allied investigators and traveled to the United States to participate in synthetic-fuels development there.

The idea for the TOM had originated during 1943 in discussions between the Petroleum Administration for War—the federal government's wartime coordinating agency for petroleum, headed by Secretary of the Interior Harold Ickes—and representatives of the petroleum industry. A year later, as Allied forces moved into Nazi-occupied Europe, the TOM proposal acquired greater military significance. American and British commanders established the Combined Intelligence Objectives Subcommittee (CIOS) in August 1944 to identify European targets about which the Allies needed technical information. Having a contingent of oil and gas experts ready to assist with this intelligence-gathering endeavor suddenly made great sense.

In October 1944, the Joint Chiefs of Staff created a Technical Industrial Intelligence Committee to advise CIOS on target selection and to begin choosing American civilians for membership in field teams that CIOS planned to dispatch into Europe as soon as possible. The TOM was organized under the Fuels and Lubricants Subcommittee of this body. Of the 26 TOM members, 18 were nominated by a petroleum-industry advisory council, two by the Petroleum Administration for War, and six by the Bureau of Mines. Besides Hirst and Odell, the Bureau delegation included L. L. Newman, Edward Rogers, Wilburn C. Schroeder, and Guenther von Elbe.

Every TOM member was temporarily assigned to the United States Army as a technical consultant and given the rank of colonel, with an Army uniform to match. After briefings in Washington, D. C. during the winter of 1944–1945, the group traveled to London to meet its British counterpart and form official CIOS field teams. These field teams began arriving in German territory in March 1945, following or even accompanying the Allied combat units that had swept across the Rhine River.

The work was dangerous. Much of Germany was in chaos, hazardous debris and unexploded ordnance lurked about, and the speed of the Allied advance obliged the field teams to shift their attention rapidly from one target to another. Once at a German industrial site, each field team had full military powers to secure the facility and to detain and question any Germans who might possess valuable information about it. German plant managers and employees surrendered voluminous files of technical documents and drawings, which field teams sent back to London for microfilming and distribution to British and American government agencies.

The TOM gave the Bureau of Mines and other interested Americans many insights into German coal chemistry. Wartime Germany had synthesized roughly 85 percent of its aviation fuel from coal, primarily from Bergius-I.G. Farben hydrogenation plants. Almost all its rubber, nitrogen and methanol for military explosives, and other vital industrial chemicals were also coal derivatives. To achieve these feats of production, scientist and engineers had made many process innovations. German synthesis-gas reactors differed from American ones, Odell reported, particularly in the use of pure oxygen rather than air. Hirst found that engineers at Leuna "had made some progress in instrumenting the plant and this had resulted in much smoother operation, which had in turn permitted them to operate the plant at considerably higher temperatures" and thus increase oil output. The investigators were intrigued by German successes in using carbides obtained from coal to develop acetylene chemistry, a specialty that had not taken hold in the United States.

After hostilities ended in the Pacific theater on 15 August 1945, CIOS military intelligence operations wound down, and CIOS and the TOM were soon dissolved. But the inquiry into German synthetic liquid fuels went on. The Truman administration created a successor program, involving the Department of Commerce at home and the Field Intelligence Agency, Technical (FIAT) of the U.S. military government in occupied Germany, to channel information about captured German industrial resources to American industry. Representatives of the Bureau and private energy companies made further visits to Germany from late 1945 until mid-1947, when the FIAT program ended. The Bureau's Foreign Synthetic Liquid Fuels Division translated and compiled declassified CIOS reports as well as material acquired through FIAT, including samples of chemicals and equipment from German plants.

American officials also encouraged leading German scientists to cross the Atlantic and continue working on synthetic liquid fuels in the United States. This migration was part of Project Paperclip, the federal government's initiative to attract highly skilled Germans. Beginning in 1946, Project Paperclip brought hundreds of German scientific and technical specialists and their families to the United States under the sponsorship of federal agencies. Its rationale was twofold. The government wanted to prevent the Soviet Union and other nations from gaining access to German scientific talent. Moreover, it sought to improve American capabilities in rocketry, optics, electronics, and other high-technology fields that would be essential to future national security and industrial competitiveness.

Weary of the bleak economic conditions in occupied Germany, the participating German scientists volunteered for relocation in hopes of improving their prospects. Although they worked primarily on military projects, many also developed ties to civilian agencies and private companies and eventually landed jobs in civilian organizations. Seven Project Paperclip scientists agreed to help the Bureau's new Office of Synthetic Liquid Fuels (created in 1944) design and build coal-to-liquids demonstration plants. They arrived in the United States between 1947 and 1949. Of these transplanted Germans, five were specialists in coal hydrogenation: Ernst Donath, Hans Schappert, Max Josenhaus, Kurt Bretschneider, and Eric Frese. Helmut Pichler—a former assistant to Franz Fischer at the Kaiser Wilhelm Institute—and Leonard Alberts contributed their extensive knowledge of the Fischer-Tropsch synthesis. This group of talented scientists and engineers was instrumental in translating German documents and assisting with the development of an American synthetic liquid fuels demonstration site in Louisiana Missouri during the late 1940s and the early 1950s. Several visited Bruceton and were interviewed there.

The aftermath of World War II eroded Germany's longstanding superiority in coal chemistry. Viewing coal-based synthetic fuels as intolerable expressions of German war-making power, the U.S. and its allies banned or restricted coal-to-liquids conversion in West Germany. In the East, the occupying forces of the Soviet Union partly dismantled the Leuna works and other coal-chemicals plants. Losses of intellectual property and skilled personnel hampered these industries. The United States clearly benefited from German misfortune. Nevertheless, Germany remained an important center of research on fuels and energy, and the transatlantic flow of information was not entirely one-way. As Americans learned from German synthetic-fuels scientists, Germans learned from American experts in petroleum and petrochemicals. And although postwar synthetic liquid fuels work in the United States was informed by German know-how, the Bureau of Mines and other American researchers soon contributed technical innovations of their own that went beyond German accomplishments.

A Century of Innovation

From the U.S. Bureau of Mines to the National Energy Technology Laboratory

Chapter Six: Albany, Oregon—The Center for Metals

William J. Kroll experimenting with early zirconium reactor in Albany.

Chapter Six:

Albany, Oregon—the Center for Metals

I know, that on the basis of the knowledge I acquired shortly before leaving my country, I would be in a position of making malleable zirconium within six months with little assistance. This is now the point I would like to explain: In a few days of instruction I could put your staff on the right way to save you perhaps years of wasted efforts.

--William J. Kroll in a letter to R.S. Dean, Assistant Director of the Bureau of Mines, October 12, 1944

While coal and petroleum are commonly found in large deposits in mines and reservoirs, metals and minerals, especially the rare variety, tend to be dispersed in low concentrations over large land areas. This was true of the northwestern United States, where rare metal ores like titanium and zirconium, among others, were known to be present in small percentages in the black sands of Oregon's beaches. By 1940, exploration was underway to discover methods of producing pure, ductile titanium, to take advantage of its light weight and high strength for aircraft applications. Zirconium research was virtually nonexistent because no practical applications for the metal were known. But this was about to change.

On February 10, 1942, Senator Rufus C. Holman of Oregon introduced bill S-821 in the United States Senate, calling for the establishment of a laboratory to assist the mineral industries of the northwestern part of the country. It was to be called the Northwest Electrodevelopment Laboratory, emphasizing its ostensible purpose of using for research the large amounts of excess electricity that were being produced by the Bonneville Dam; in practice, the laboratory used no more electricity than any other of similar size, so the reason was largely a fiction. But the need for a laboratory to develop methods to exploit the low-grade ores of rare metals in the American Northwest was very real. Enthusiasm ran high for the project. The jobs that such a research center would bring to the city lucky enough to land it would boost any local economy.

Candidate cities began scrambling for position as soon as the appropriations bill, which authorized $500,000 for the laboratory, was passed in late 1942 as part of the funding for the Department of the Interior. Senators from Montana, Idaho, Washington, and Oregon made preliminary proposals, but the Bureau of the Budget quickly impounded $480,000 of the appropriations, arguing that the materials for the new facility would be needed by the War Production Board for the war effort. The remaining $20,000 could be used to pay an architect to draw up plans, which could be carried out after the war. The Bureau of Mines succeeded in freeing up the impounded funds by arguing that the minerals and metals developed through research at the new laboratory would be essential to the war effort. In reinstating the funds, the Budget Bureau added one proviso: The new laboratory must use existing buildings to minimize the amount of new materials needed.

Curlee took matters into his own hands, running beside the track with a flare and a flag until the train stopped and the surprised Bureau inspector agreed to take a look at the Albany site.

Senator Wallgren of Washington, who originally proposed the appropriations bill, fully expected that the laboratory would be awarded to his state. He moved quickly and identified a site in Spokane. However, Oregon businessmen and politicians had ideas of their own, and proposed the abandoned site of Albany College, which had moved to Portland and had been renamed Lewis & Clark College.

In September 1942, a Bureau of Mines inspector was on a train from California to Spokane to check out the proposed laboratory site. Vin Hurley, President of the Albany Chamber of Commerce, and Carl "Zeke" Curlee, manager of the Chamber, thought they had arranged for the train to stop in Albany. But when they and a group of other prominent citizens arrived at the train station, the stationmaster informed them that no such stop was planned. Curlee took matters into his own hands, running beside the track with a flare and a flag

Re-enactment of Carl "Zeke" Curlee (with flag) stopping the train at Albany in September 1942.

until the train stopped and the surprised Bureau of Mines inspector agreed to take a look at the Albany College site. The inspector spent half a day in Albany, touring the proposed site of the abandoned 45-acre Albany College campus, and listening to the sales pitch from Albany spokesmen. His captors freed him to continue his journey to Spokane when the next train stopped in Albany. Without Curlee's desperate stroke of imagination in stopping the train, Albany would have had no chance in getting the laboratory.

But more challenges lay ahead. Near the end of 1942, Secretary of the Interior Harold Ickes decided to award the laboratory to Spokane. However, his decision was soon rescinded amid cries of protest from Oregon, Montana, and Idaho, who wanted a chance to propose alternate sites before an award was made. Ickes decided to hold a hearing on January 12, 1943, to listen to their arguments.

By the time of the hearing, Oregon had identified 18 potential sites for the lab, while Washington added a location in Pullman to its list. Montana and Idaho also presented candidate sites. By this time the Albany Chamber of Commerce had collected $710 from local businessmen to send Curlee to Washington, D.C., to lobby for their city. The *Albany Democrat-Herald* reported in March 1943 that Curlee remained in the nation's capital for eight weeks, "camping on [Assistant Secretary of the Interior] Mr. Chapman's office bench and conferring daily with Senator McNary, Senator Holman and Representative Ellsworth...and he only came home when it was decided that it was safe for him to leave." Curlee later wrote of his experience at the January 12 meeting: "My big moment had arrived. I did my best under pressure. What with Senators Wheeler, Murray, Cone and Walten, to say nothing of the score of 90 congressmen looking down my throat, I introduced our material. They immediately struck the fancy of the Bureau people."

Secretary Ickes was feeling intense pressure to choose a location for the laboratory. On March 10, he wrote a letter to President Franklin D. Roosevelt describing his angst: "I thought at first that I would ask you to decide the question but then I concluded that would be a mean and cowardly thing to do. So I will decide myself and keep the heat off of you. I am warning you in advance, however, that there may be a bit of a tempest in three different teapots after the decision has been announced. From a political point of view, it is the worst spot that I have been in during the past ten years."

On March 17, 1943, a decisive President Roosevelt put Ickes' mind to rest by writing to Senator McNary of Oregon: "The facilities at Albany appear to be excellent, and the information which you have supplied has been of material assistance in selecting a site that will provide satisfactory and ample housing at a point not far removed from vast resources of power and undeveloped mineral wealth….After careful review of the situation, Secretary Ickes has advised me that of all sites proposed, the Lewis and Clark College property located at Albany, Oregon, best meets all requirements for the establishment of the Bureau of Mines Laboratory, and that he will make a public announcement of his findings soon."

Despite the finality of this decision, agents in the state of Washington continued to try to disparage the Albany site, sending inspectors to write reports condemning the infrastructure of the Albany buildings. But in the end the decision remained: the Northwest Electrodevelopment Laboratory would be in Albany, Oregon. The March 17, 1943, issue of the *Albany Democrat-Herald* trumpeted the victory with the headline: "Mines Bureau Laboratory Awarded Albany."

Dr. Bruce A. Rogers, first Superintendent of the Bureau's Albany Site, 1944-1946.

GIVE DOUBLE This Year American Red Cross

Albany Democrat-Herald

GIVE DOUBLE This Year American Red Cross

Mines Bureau Laboratory Awarded Albany

Front page headline of the Albany Democrat Herald newspaper declaring victory, March 17, 1943.

Creating a New Laboratory

The Bureau of Mines took possession of the Albany site on July 21, 1943. Dr. Bruce A. Rogers from the Bureau's Pittsburgh Station was named first Supervising Engineer of the Albany laboratory, reporting to R. S. Dean, Assistant Director of the Bureau of Mines in Washington, D.C. Henry Powell Hopkins, an architect from Baltimore, had been hired by the Bureau to draw up plans for converting the former college campus to a working research laboratory. Hopkins spent about three weeks on the site making dimensional drawings and formulating plans. The formal plans were approved on January 17, 1944, and the Portland, Oregon, construction firm of Reimers & Jolivette began executing them in February.

When the remodeling was finished in August 1944, the Bureau had a new laboratory with four buildings. The fireproof brick structure with steel and concrete floors, previously used for college administration offices and class rooms, was now called Building Number 1, and was outfitted with physical and chemical labs, a library, stockrooms, and offices. The new Laboratory Building, formerly a dormitory, now had metallurgical labs on the first floor, and offices, a drafting room, and an auditorium on the top three floors. The college's gymnasium had been converted into the high-bay Operations Building, capable of housing pilot plant scale equipment. Finally, the steel and glass Service Building, which had been built for the National Youth Administration to train machinists and skilled technicians for the Works Progress Administration, was now the metalworking and woodworking shop.

The Washington office assigned the following tasks to the Northwest Electrodevelopment Laboratory: (1) the electrometallurgy of Pacific Northwest iron-nickel-chromium ore; (2) treatment of Scappoose high phosporous iron ore; (3) production of ductile zirconium from Oregon Black sands; (4) concentration of the products in the black sands of Oregon; (5) magnesium pilot plants and research; (6) Electrometallurgy of zinc and lead; and (7) conversion of quartz to vitreous silica.

But the first challenge was to find enough technically trained personnel to staff the new laboratory in wartime. Many men were joining the military effort, and those remaining could often find employment in industry at better wages than a government laboratory could offer. So the first positions at the Albany lab were filled by transferring Bureau personnel from other sites. Dr. A. W. Schlechten, a metallurgist, and Leland Yerkes, a chemist, were transferred from the Salt Lake City station in the summer of 1944. By the end of the year, eight professional or technical men, ten craftsmen and laborers, and the clerical and custodial workers formed the small staff of Northwest Electrodevelopment Laboratory.

Building 1 of the Northwest Electrodevelopment Laboratory, 1944.

Making Malleable Zirconium

Portrait of William J. Kroll, 1941.

Producing ductile zirconium quickly became the top priority at NEL. According to the first annual report issued from the new Bureau site, "The production of ductile zirconium from the black sands of southwest Oregon is being undertaken, first, with the purpose of obtaining the utmost value from this material, and second, to develop on an economic basis a new and valuable metal for the chemical industry. Zirconium is strong mechanically and because it resists the attack of a large number of chemicals, it should prove a valuable addition to the list of materials used in the construction of chemical plants. The black sands contain up to one percent of the mineral zircon which is one of the most important zirconium-containing substances. Exploitation of the black sands will demand that the zircon be utilized to make some valuable product."

Dr. Schlechten was chief of the zirconium project. Upon his arrival in Albany in the summer of 1944, he first made a literature search regarding methods to reduce zirconium metal from its mineral form, zirconia, and decided that the method of "electrolysis of aqueous solutions" held the most promise. Although small amounts of the metal had reportedly been produced by this method, Schlechten was initially unable to replicate this success. Then he heard about Wilhelm Kroll, who would prove to be instrumental in solving the zirconium problem.

Producing ductile zirconium quickly became the top priority at the Northwest Electrodevelopment Laboratory.

Kroll, who preferred to use the Americanized "William" as his first name, was a native of Luxembourg who had arrived in the United States in 1940, just ahead of the German invasion of his country. He was a metallurgist who had spent the previous ten years experimenting in the basement of his large house in Luxembourg, at his own expense, with ways to make ductile titanium. By 1938, Kroll's solitary efforts paid off, and he traveled to the United States to try to sell his invention to seven major manufacturers. His sales trip was unsuccessful and he was soon forced by war from his homeland. Kroll carefully packed his laboratory equipment in his basement in the hope that it might still be there when the war was over.

In the United States, Kroll found work as a consulting metallurgist at the Union Carbide Research Laboratory in Niagara Falls, New York. Hearing of the establishment of the Northwest Electrodevelopment Laboratory and the Bureau's interest in zirconium metal, Kroll arranged to meet with R.S. Dean in Washington in late 1943 to present his credentials and offer his services. No deal was made at this initial meeting, but apparently Kroll had made an impression on Dean. Even after the Foote Mineral Company announced in April 1944 that it had developed a process to manufacture metallic zirconium, Dean still thought there must be room for optimizing the process that could keep Kroll occupied in Albany. (Dean mistakenly thought that Foote was using Kroll's proposed zirconium process. But Kroll was not involved with Foote, and they had both developed unique processes.)

In October 1944, Dean offered Kroll a consulting position in Albany. Kroll responded boldly on October 12: "Dear Dr. Dean: I thank you for the friendly proposition of your letter of October 9th to go to Albany Oregon to look over the work you have already done in the way of making malleable zirconium…. [I] know, that on the basis of the knowledge I acquired shortly before leaving my country, I would be in a position of making malleable zirconium within six months with little assistance. This is now the point I would like to explain: In a few days of instruction I could put your staff on the right way to save you perhaps years of wasted efforts."

Kroll succeeded in producing the first strip of ductile zirconium in August 1945—just as he had predicted.

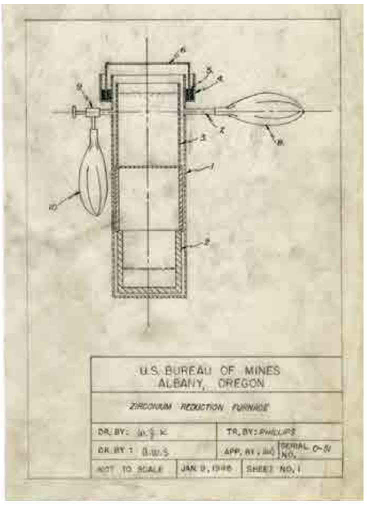
The next few months were spent getting Kroll the proper clearances to work for a government laboratory, and establishing his rights to the inventions he had already made at his own expense in Luxembourg.

On December 22, Dean wrote Kroll to inform him of his appointment as a Consulting Metallurgist, Grade P&S-8, with an annual salary of $8,000. He also noted that Congress had approved an appropriation of $55,000 for work on zirconium production. Kroll accepted the offer in a letter that included a document titled "A Proposition for a Zirconium Research Program." Dean's offer letter contained specific instructions to Kroll: "I suggest you proceed immediately with plans to start work at Albany at the earliest possible date. You will probably want to stop at Salt Lake City enroute to Albany and confer with Mr. S. R. Zimmerly regarding the work." Zimmerly worked for the Bureau of Mines in Salt Lake City on the titanium project.

After visiting Zimmerly, Kroll finally arrived at Albany, Oregon, on January 16, 1945. He immediately took control of the zirconium project. As Schlechten later wrote, "Although [Kroll's] title was consultant, it was generally assumed that he was in charge of the zirconium research project." The team of three quickly fell into a routine: "The usual procedure was for Dr. Kroll to design the equipment which he thought we needed. I was usually given the job of obtaining the material and accessory equipment that could be purchased, while Mr. Yerkes [Leland Yerkes, a chemist, who transferred with Schlechten from the Salt Lake City station] frequently constructed part of the equipment in the shop. All three of us [Kroll, Yerkes, and Schlechten] were active in operating the equipment."

Kroll's first step was to scrap the electrolysis method that Schlecten had been pursuing in favor of his own "magnesium reduction" process. The theory behind the process involved the overall conversion of zirconium oxide in the sand to zirconium chloride (ZrCl), and the reduction of ZrCl to pure Zr metal by transferring the Cl to magnesium (Mg). The Zr metal would be in the form of a porous "sponge," which would have to be melted or mechanically formed into ingots. But, as might be expected, the actual process posed some problems.

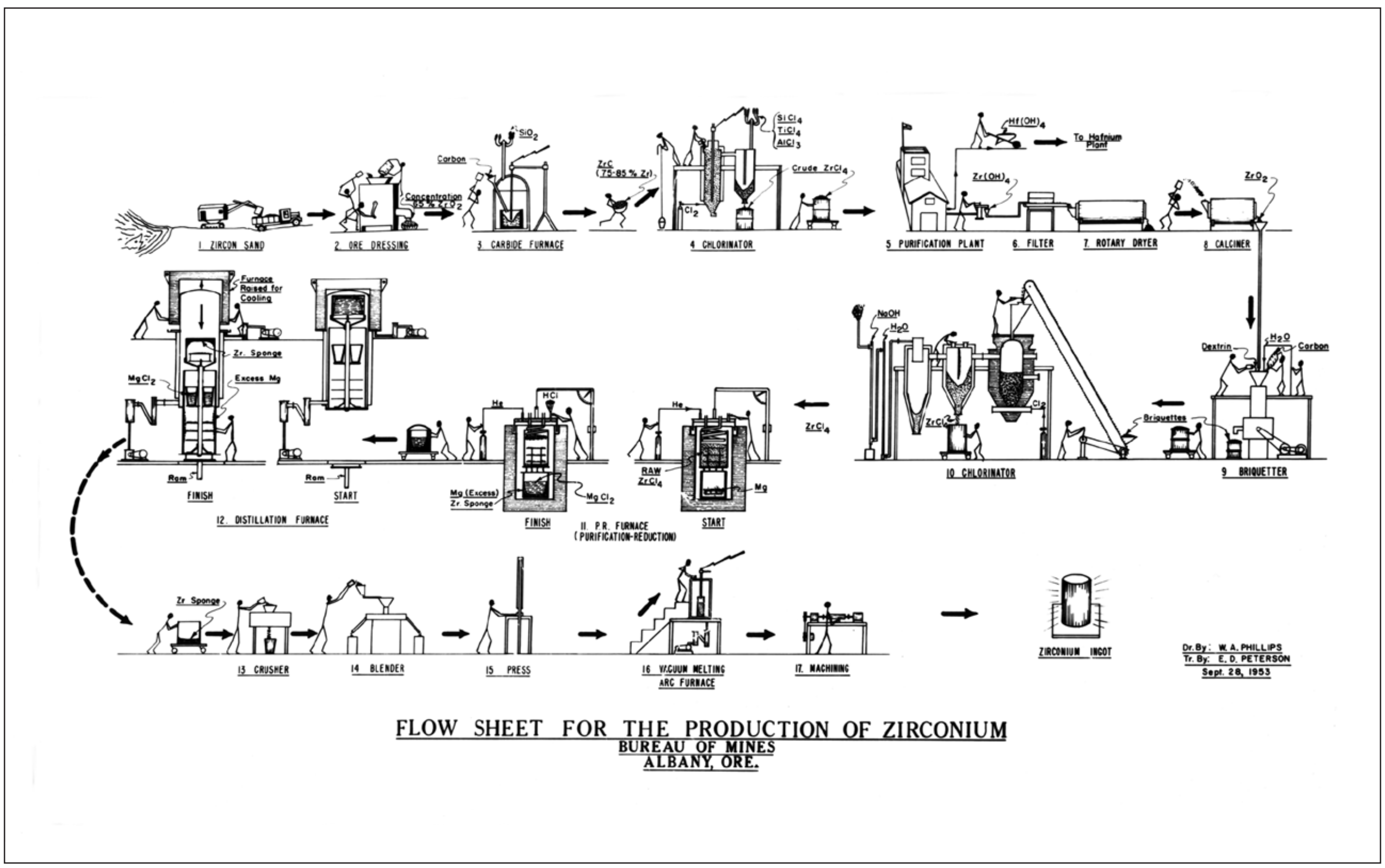
Zirconium was quite difficult to produce," Kroll wrote in a 1955 article in the *Journal of the Franklin Institute* titled "How Commercial Titanium and Zirconium were Born." "The metal is about three times as sensitive to nitrogen and oxygen as is titanium. It is pyrophoric [burns in air] when powdery. It cannot be comminuted [pulverized to a powder] by pounding under water because it reacts explosively with moisture under shock. Therefore aqueous extraction of the magnesium chloride after the reduction was out of the question, and vacuum distillation of the salts, which I had practiced in Luxembourg, became imperative. The first batches that came out of this procedure burned down until the trick of air conditioning [controlling the chemical atmosphere of the surroundings] was found."



Kroll's drawing of a zirconium furnace, 1946.

In a letter of reminiscence dated October 17, 1969, Kroll recalled the steps in his first attempts to make zirconium metal in Albany, using a typical, abbreviated laboratory notebook writing style: "January 29, 1945: Went to Coosbay to take zircon sand. March 1, 1945: First [zirconium] sponge made on small scale, from ZrCl4 + Mg under He. Observed explosion when sponge was pounded under water. Fixed up chlorinator; to make ZrCCl, carbon resistor furnace was built. Chlorination of ZrC. Arc furnace built for ZrC. Many charges for the reduction of ZrCl4 were made and a 50 lb industrial reactor was drawn up and built. Distillation of sponge in vacuum was used for salt separation, because leaching was too dangerous. [Used] Laboratory arc furnace to melt [zirconium] buttons." The team succeeded in making four pounds of zirconium that day.

Progress was rapid after the initial successes. Kroll succeeded in producing the first strip of ductile zirconium in August 1945, about six months after he started working on the challenge—just as he had predicted. The task of scaling up the laboratory process to the pilot plant would take another two years.



Flow sheet showing the many steps in the production of ductile zirconium, 1953.

Rickover and the Nuclear Navy

While the scaling-up process was taking place in Albany, events were occurring in the United States Navy that would bring the two groups together. Navy Captain Hyman Rickover and some fellow officers and civilians were working at Oak Ridge to determine whether nuclear energy could be used to propel naval ships.

Admiral Hyman Rickover inspecting the USS Nautilus, the first nuclear submarine.

Rickover was an ambitious Navy captain in 1946. The task—which he had assigned himself—was a hard one. "[A] submarine nuclear propulsion plant posed severe requirements," Rickover said in a speech commemorating his acceptance of the first William J. Kroll Medal given by the American Society for Testing and Materials (ASTM) on March 21, 1975. "It had to be compact so that it would fit into the submarine hull. It had to operate when the ship was rolling or pitching, or at an angle when it was diving or surfacing. It had to be safe and reliable. It had to be rugged to meet military demands. Finally, it would have to be operated by young sailors—men who were not scientists or engineers, but who would be carefully trained."

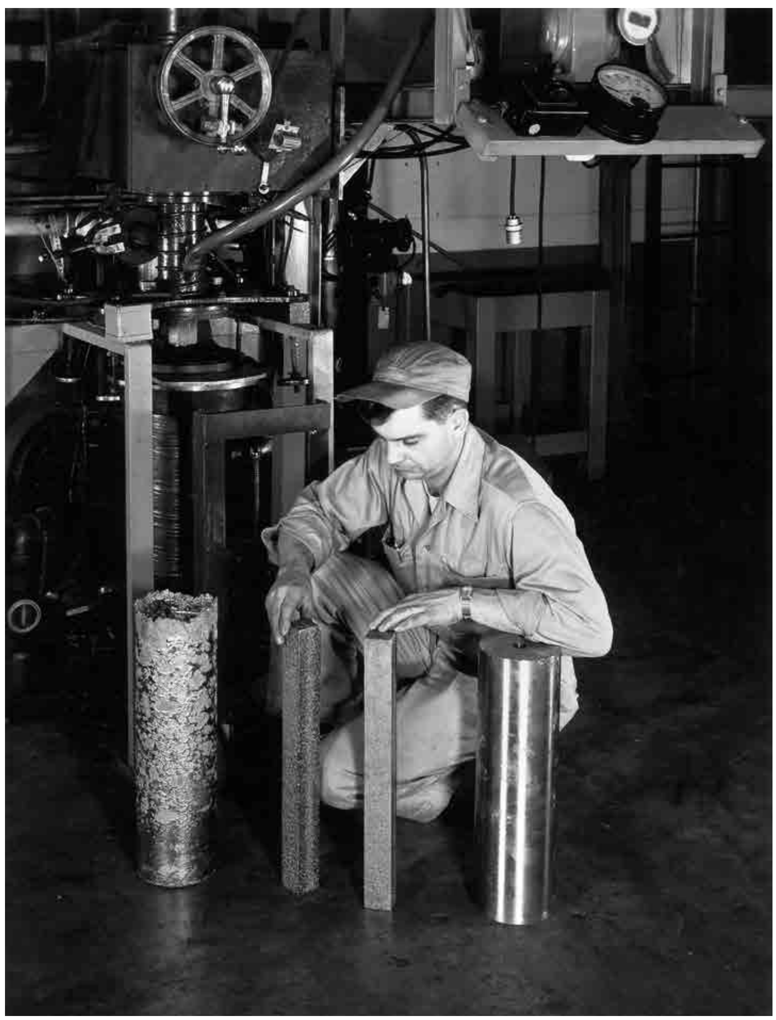
One of the greatest technical challenges was finding a metal or alloy that could survive in the demanding conditions of such a nuclear reactor over the long haul. Engineers and scientists were investigating stainless steel, aluminum, beryllium, and zirconium, among other metals, but each had its drawbacks. The "pressurized water reactor" was one type of nuclear reactor that the Navy considered favorable for submarine use, but in this case the metal chosen to build it would have to resist corrosion at high temperatures for long periods of time, maintain its structural integrity under intense radiation, and not absorb the neutrons that powered the nuclear chain reaction. The structural metal would also need to be produced in large quantities at a reasonable cost. Rickover evaluated the options in his 1975 speech:

> *Stainless steel, beryllium, and aluminum all had technical disadvantages which weighed against their use. Zirconium, too, did not look promising. Although its corrosion properties appeared reasonable, it was expensive and had never been produced in quantity. In 1945, only a few hundred pounds were manufactured in the United States. The cost was over $300 per pound. Above all, tests showed that zirconium absorbed neutrons needed for the fission process.*
>
> *The situation changed suddenly. While visiting Oak Ridge in December 1947, I learned that Dr. Kaufman of MIT and Dr. Pomerance of Oak Ridge had just found that zirconium, as occurring in nature, was combined with the element hafnium. It was the hafnium at about 2 percent by weight which gave the zirconium the high level of neutron absorption. They were able to remove the hafnium in the laboratory and obtain zirconium which absorbed only a few neutrons. This was a scientific fact of great importance. At once I decided to use zirconium for the naval reactor.*

With the decision made, the race was on. Rickover had been given a deadline of January 1955 to launch a fully functioning nuclear submarine (the Mark II, formally named the *Nautilus*), with an intermediate milestone of successfully demonstrating the operation of a land-based nuclear reactor (the Mark I, located in Idaho) of the same size by 1953.

In Albany, tremendous progress was made in producing zirconium in 1947. On March 14, 1947, Kroll and his colleagues produced 25 pounds of zirconium in a new, large-scale laboratory reactor, and soon made a 75-pound batch. They quickly made plans for the building of a larger pilot plant unit. A March 26, 1947, letter from Kroll to F. S. Wartman of the Bureau's Boulder City station described what was happening in Albany: "We have made two runs in our large scale laboratory unit and now have larger quantities of sponge available. We will send you some of it within the next few days. You may be interested to know that the large scale laboratory unit runs well, but we have much trouble with fires from the sponge magnesium as from the zirconium itself."

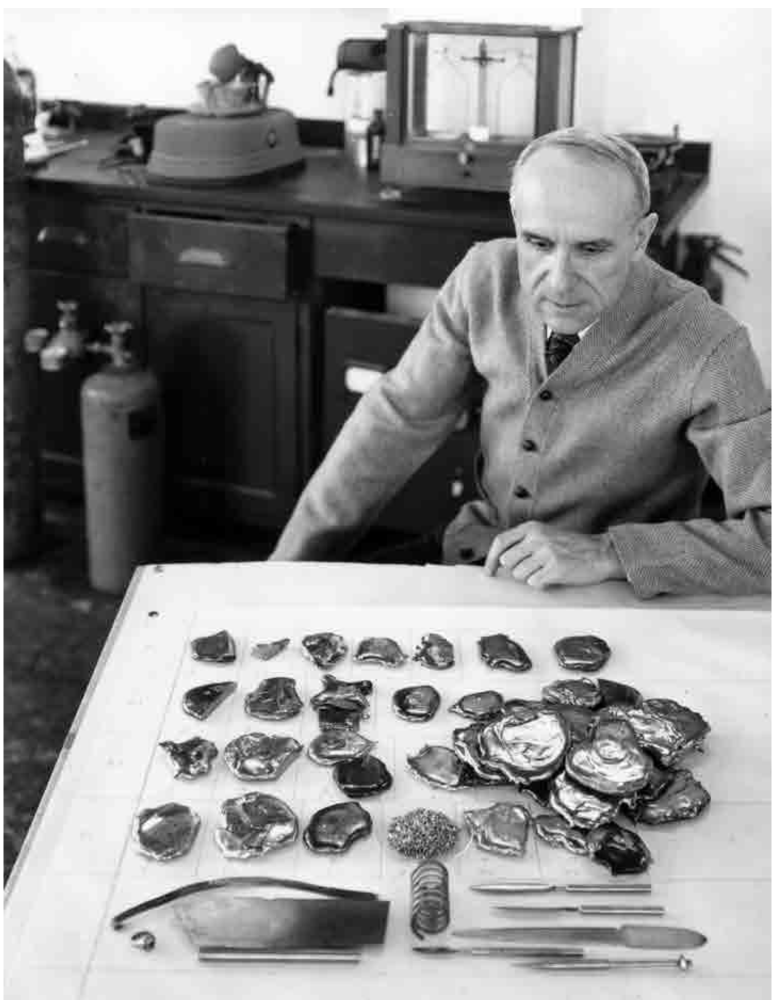
In July, Kroll flew to Europe for a five-month trip to check on the condition of his home and laboratory equipment following the war. C. T. Anderson was put in charge of the zirconium project in his absence. S. M. Shelton, the Supervising Engineer at Albany, kept Kroll updated on the progress of the zirconium work by mail. On August 29, 1947, Shelton reported that "[w]e are making con-



Albany employee showing the various stages of zirconium from sponge (left) to pressed sponges (middle) to an ingot (right).

siderable progress in the zirconium work. The larger melting furnace was very satisfactory just as built, and we have run a steady schedule of melting ingots of metal. In one case, we melted two ingots in order to get a single 10-pound ingot which was sent to Mr. Ralston [located in the Bureau offices in Washington, D.C.] for display purposes." Shelton also noted that they had received $66,000 from the Army Air Forces for a two-year program in alloy development. Also, blueprints had been completed for the zirconium pilot plant building. It was to be L-shaped, with the body of the "L" to be 60 feet wide by 30 feet, and the foot of the "L" extending an additional 30 feet. "Our allotment for the pilot plant of some $81,000 will not permit us to complete the pilot plant during the current physical [sic] year," Shelton reported, "but we should be able to get far enough along to be operating at least part of it by July 1948."

Kroll was pleased and relieved to hear of the progress being made. C. T. Anderson had presented a paper on the production of zirconium to the Boston meeting of the American Electrochemical Society. "The big sheets and ingots he certainly displayed must have knocked the bottom out of the Foote Mineral people," Kroll remarked.



Kroll looks over a large sample of ductile zirconium products, including springs and knife blades, 1948.

By the time Rickover had decided on zirconium for his nuclear submarines, the Albany team had already shown that it could be produced in ingot, sheet, and wire form, and that the process was scaleable. Plans for a large production-scale plant were underway.

By the time Rickover had decided on zirconium for his nuclear submarines, the Albany team had already shown that it could be produced in ingot, sheet, and wire form, and that the process was scaleable.

Still, as Rickover noted in his 1975 speech,

> *We did not know whether the metal could be produced in sufficient quantities or to the rigid specifications needed for naval reactors. Dr. Kroll had worked on the development of a zirconium production process at the Bureau of Mines Facility at Albany, Oregon. I made several hurried trips to see the work being done at that facility to furnish zirconium for the first naval reactors. Usually Dr. Kroll, then a consultant to the Bureau of Mines, and several senior officials of the bureau of mines met me at the Portland airport on Friday evenings. We would drive to Albany, inspect the equipment, and discuss the results of the production effort then underway. Dr. Kroll always gave me straightforward answers. He was a scientist. I am an engineer. Our common interest was zirconium. I think we both understood the problems the other faced. I believe we had this understanding because we based our discussions on principles.*

Though Albany had produced 2,060 pounds of zirconium sponge in 1948, "production application of the Kroll process was still under development and had not yet produced fully satisfactory metal," Rickover said. He decided to go with the much more expensive "crystal bar" or "iodide" process instead. This procedure started with impure zirconium, such as Albany could supply, and heated it in the presence of iodine in a vacuum to form zirconium iodide (ZrI4) gas; any impurities were left behind as solids at this point. When a white hot tungsten filament at 1,400°C was introduced into a vessel containing this gas, the Zr metal deposited on the filament while the iodide evaporated, producing a cylinder of pure zirconium.

During July 28-29, 1949, representatives of the Atomic Power Division of Westinghouse, which had just built a nuclear research lab and production plant at the abandoned Bettis airfield near Pittsburgh, Pennsylvania, visited Albany to learn more about the Kroll process. In August 1949, the Atomic Energy Commission (AEC) contracted with Albany to provide 2,000 pounds of zirconium for $60,000. The Bettis Lab received permission from the AEC to build its own crystal bar plant in July 1950.

"About 85 percent of the metal used for the Mark I reactor was made at Bettis," Rickover said, but Bettis had to get the zirconium raw material from somewhere, and it came mostly from Albany through the Kroll Process. "The successful operation of the Mark I," Rickover continued, "which achieved criticality on March 30, 1953, and reached full power on June 25, 1953, vindicated many technical decisions, among them the use of zirconium."

Though Kroll's process was essential to the success of Rickover's venture, Kroll was no longer with the Bureau. He had left in 1951 to devote his full-time efforts to legal actions against the U.S. government to try to restore his rights to a titanium patent that had been seized by the U.S. Alien Property Custodian in 1943.

Stephen M. Shelton, as Regional Director of the Bureau of Mines in Albany after B. A. Rogers' departure in 1946, led the "Zirconium College," as the August 1, 1954, edition of the *Oregon Journal* dubbed the Albany Station. "Though it is not generally known," the newspaper further reported, "Adm. Rickover has been in the past a frequent and unannounced visitor at the campus, for excellent reasons. Zirconium from Albany, for example, is a vital component in the very core of the atomic reactor which will power the submarines *Nautilus* and *Seawolf*. Indeed, without zirconium it is doubtful the Rickover's *Nautilus* project could have been undertaken." The reporter described Shelton as "a gray-haired, youngish Carolinian" with a "pleasant, drawling manner." He continued: "Probably the acid test of Shelton's good humor is his admiration for the driving Adm. Rickover, a man with few notably warm personal traits—and a man who more than once has aroused Shelton from bed for conferences in recent years. 'He's never showed up here except early Sunday mornings—real early,' Shelton grinned ruefully."

The dedication of the USS Nautilus, the first nuclear submarine, whose zirconium rods were produced at Albany.

Following up on the success of the land-based Mark I reactor in Idaho, research continued to develop an alloy of zirconium to make the material less expensive while retaining its desired anti-corrosion and neutron-transparent properties. Researchers at Bettis discovered that small percentages of tin filled these requirements, and settled on 1.45 percent tin for an alloy they called Zircaloy 2, which was used in the *Nautilus* reactor. "That reactor generated power on December 30, 1954, just one day prior to the date I had promised the Congressional Committee on Atomic Energy five years earlier," Rickover recalled in his 1975 speech. "In less than a month, on January 17, 1955, the *Nautilus* got under way. This marked the beginning of the era of naval nuclear propulsion."

The 1953 edition of the Bureau of Mines Annual Report summed up this era succinctly: "The nation's entire supply of zirconium and hafnium, both useful metals in the atomic energy field, has been produced in the Bureau's Electrodevelopment Laboratory at Albany, Oregon, by Bureau-developed techniques. Much of the zirconium furnished the Atomic Energy Commission was used in constructing the first atomic-powered submarine."

Hanging On

By 1954, the Albany station had 250 employees involved in zirconium production. The Zirconium College was turning into a manufacturing plant instead of a research center, and the government wanted out. As early as 1951 the Atomic Energy Commission had solicited bids from commercial companies to supply zirconium, but after two rounds of proposals no bids were awarded, so the government negotiated a "best obtainable deal" with the Carborundum Metals Company for a million pounds of zirconium over five years. The question was, could Carborundum deliver?

In March 1953, a new Bureau of Mines station was going up in Reno, Nevada, tentatively referred to as the "rare and precious metals experiment station." A year later, a Department of the Interior report recommended the closing of operations at Albany, Oregon; San Francisco, California; and Juneau, Alaska. The new station in Reno was proposed as the headquarters for Region I, which would include Alaska, Oregon, Washington, California, Idaho, and Nevada. The report included the recommendation that the Bureau "should not engage in production activities and should do everything possible to terminate present production activities."

At about the same time, Congressional representatives from Iowa and Idaho proposed moving the Northwest Electrodevelopment Laboratory to the middle of mining country, somewhere in Idaho or Montana. The Bureau's mining engineering division was already well established in Spokane, Washington. There seemed to be no need for a Bureau station at Albany anymore; the loss of 250 jobs was a looming threat.

But the people of Oregon were not prepared to give up so easily. In the August 20, 1954, issue of the *Albany Democrat-Herald*, an editorial entitled "Not Dead Yet" made the following arguments:

> *Some of our local crepe hangers have written off the Northwest Electrodevelopment Laboratory here because of the recently revealed recommendations of a survey team which last year toured all U.S. Bureau of Mines pilot plant and laboratory facilities...One report had it that more than 250 persons were to lose their jobs here. ... Chief personnel cuts would come through abandonment of the zirconium pilot plant…. Nevertheless the prospects for perpetuation of the plant are brighter now than they were when zirconium was first produced here. In the first place it is practically certain that that zirconium will be produced here as long as the Carborundum Company of America, [the] only commercial producer, is unable to supply demand. Thus far this situation exists. [The] biggest present customer is the Atomic Energy Commission, to which the entire local supply of zirconium has been and is being delivered. The Carborundum Company is not yet able to meet the AEC's requirements and until it does the Albany plant will make up all deficiencies. In the second place consumption of zirconium is destined to increase.... Other yet unheard-of projects may also develop. No, it is too soon to shed tears over the Northwest Electrodevelopment*

Laboratory. Who knows but what it may be destined for even greater activity than it has ever seen?

But, despite the paper's optimism, it seems the game had been lost. On May 4, 1955, an *Albany Democrat-Herald* headline read "Zirconium Plant Closed." "After more than a decade of operation, the zirconium plant at the U.S. Bureau of Mines Electrodevelopment laboratory here has been closed," the newspaper reported, "resulting in at least temporary unemployment of 65 persons."

However, due to Rickover's success with the *Nautilus*, Congress authorized the construction of several more nuclear submarines around this time, and the Albany zirconium plant was spared for a while. Rickover estimated that the Navy would need one million pounds of zirconium over the next five years, and he planned to obtain it from commercial sources. Fortunately, a company named Wah Chang had been running the Bureau's titanium production in Nevada. "In April 1956, the Wah Chang Corporation contracted to provide 600,000 pounds of zirconium at a price just under $10 per pound," Rickover noted in his 1975 speech. "In a few months, under the direction of Mr. Stephen Yih, they were in production." This was made possible through an arrangement that allowed Wah Chang to take over and operate the Bureau's Albany zirconium plant until it could fabricate a new factory of its own. Three other companies also contracted to begin making zirconium using the Kroll process. "Over ten million pounds of zirconium and about a quarter of a million pounds of hafnium—which is also used in naval reactors—were delivered under these contracts between 1957 and 1963, " Rickover said, "at an average cost of about $6 per pound."

Full-scale zirconium production underway in Building 28 at Albany, 1953.

Conclusion

From its humble beginnings as a long shot location for a national lab, Albany's Northwest Electrodevelopment Laboratory proved its viability as a metallurgical research lab in the first few years of its existence. Part of this was due to the appearance of the right man—William J. Kroll—on the scene at precisely the right time; how long it would have taken to produce ductile zirconium without his expertise is not known, but he surely sped the process along considerably. That zirconium was the right metal for Rickover's nuclear navy was another serendipitous event. But beyond these large successes, the leadership of Rogers and Shelton to establish a broad scope of research in the extraction of rare metals laid the groundwork for the laboratory to establish an international reputation in this niche field. It would serve them well in the years to come.

Other Research at Albany in the Early Years

Although it was clearly an important component of the work performed at the Albany Station in the 1940s and 50s, zirconium production was not the only project undertaken at the lab. In 1977, Albany Research Director R. R. Wells published a pamphlet entitled "Successful Research at the Albany Metallurgy research Center, 1945-1977." In it, Wells describes the factors that made a project successful:

> *To be included as a success, we decided that a study must meet one of three criteria: (1) the results were accepted and used commercially, (2) the results were given worldwide acceptance as authoritative scientific data, or (3) the results demonstrated the technical feasibility (but, as yet, not commercial acceptance) of a process. We have documented 25 projects in the first category, 7 in the second, and 4 in the third. This is an indication that 28 percent of our investigations have been successful, which is higher than is found in most research institutions.*
>
> *It is most interesting to note that using the criteria of commercial or scientific acceptance, many of the most sophisticated and 'best' research studies do not appear on the list. Very few projects appear that originated from popular interest or political motivation. Almost none of the successful studies were conducted to solve an immediate problem of industry. This would appear to confirm what many have always thought: that the Bureau should be working on imaginative research aimed at solving mineral and materials problems of the future or minimizing the effects of projects mineral supply/demand imbalances.*

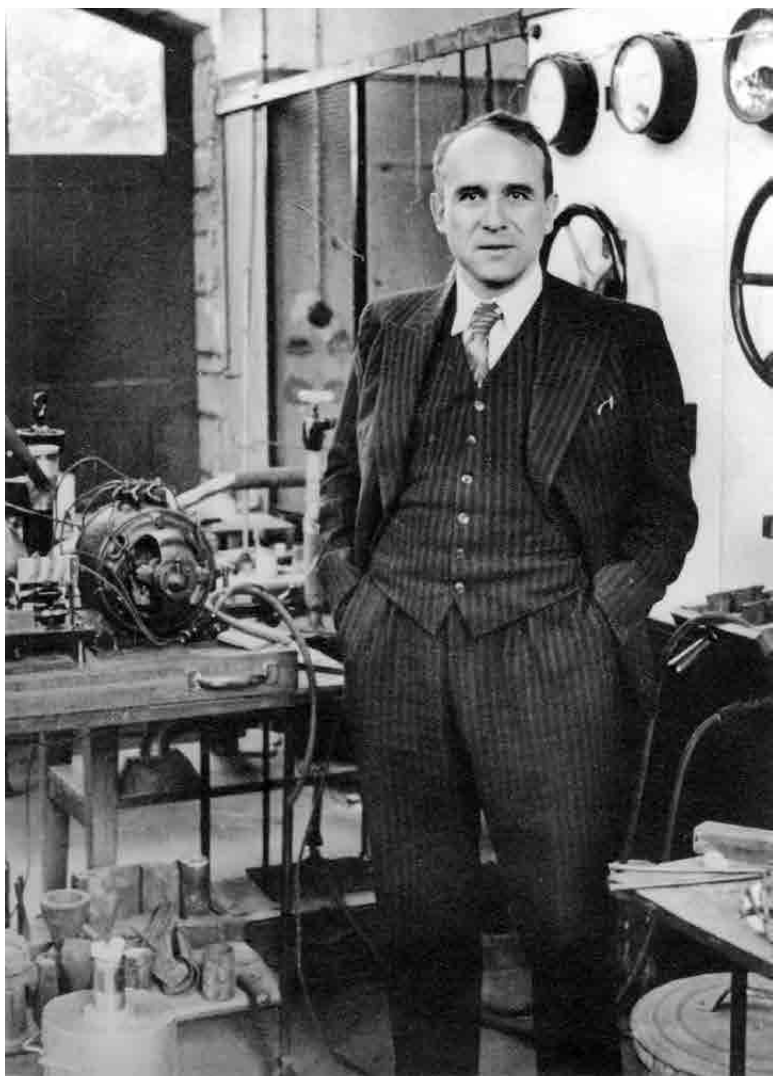
According to Wells's report, the following 15 successful projects were started or completed at Albany in the 1940s and the 1950s:

- **Beneficiation of Western Phosphate Ores, 1953-1976 (intermittent).** Bureau researchers developed procedures which allowed processing of the entire phosphate-rich areas rather than selective mining of high grade material which was wasteful and resulted in huge piles of unsightly waste.
- **Solvent Extraction and Separation of Tantalum and Columbium, 1951-54.** Columbium and tantalum have very similar properties, and so are hard to

separate. By mixing minerals with mixtures of columbium and tantalum in an acid solution, then using special organic solvents that extract the columbium and tantlum metal ions, columbium was separated from tantalum by selective stripping with carefully controlled dilute acid solutions.

- **Recovery of Fluorine from Phosphate and Fluorspar Mining Wastes, 1955-1976.** Fluorine released during the manufacture of phosphate fertilizer was recovered as fluorsilicic acid by acidulation of phosphate rock with recycled phosphoric acid.
- **Production of Ferronickel from Oregon Laterite, 1950-52.** Hanna Development Corporation of Riddle, Oregon, and the Bureau established the technical and economic feasibility of producing ferronickel from Oregon laterite ores.
- **Aluminum-Silicon Alloy from Clay, 1951.** The technical feasibility of producing aluminum-silicon allow from low-iron clays was demonstrated by the Bureau. National Metallurgical Corporation in Springfield, Oregon, adopted the process and constructed a plant in 1972.
- **Electric Smelting of Chromite Concentrates, 1958-61.** The United States consumed 600,000 tons of chromium each year, 50,000 tons domestic, with the rest imported as ore or ferrochrome. Early work on chromites, conducted by the Bureau, led to a commercial smelter at Nye, Montana, for production of high-carbon ferrochrome.
- **Chlorination of Euxenite Concentrates, 1956-60.** Euxenite contains tantalum, columbium, uranium, thorium, and the rare earth elements. The Bureau built a pilot plant chlorination system for recovery and separation of these metals from euxenite concentrate.
- **Kroll Process Zirconium: 1945-55.** See above.
- **Electrorefining of Tin, 1951-52.** Program to recover tin from highly contaminated, radioactive waste product generated at the Hanford Atomic Works. Both tin and uranium, critical materials in short supply at the time, were being accumulated as unusable waste. The Bureau operated a 1,000 pound per day electrolytic pilot plant at Albany for one year to return high purity tin to Hanford. During one year, 200,000 lbs of crude copper-tin alloy were fed in, and 135,000 lbs of purified tin were recovered and shipped to Hanford.
- **Ductile Chromium, 1948-53.** Ductile chromium development did not result in commercial high temperature chromium alloys, but it was an encouraging step that facilitated other research because a greater variety of sample shapes could be fabricated. The Bureau supplied chromium samples all over the country for other research laboratories.
- **Double Consumable Electrode Vacuum Arc Melting, 1949-59.** The Bureau developed double vacuum arc melting as an improved method to produce zirconium ingots for submarine reactors. This method permitted the use of sponge zirconium rather than highly purified and expensive DeBoer process metal.

- **Casting of Reactive or Refractory Metals, 1954-60.** At the Army's request, the Bureau developed a method for casting titanium without contamination. The method also was used for beryllium, titanium, tungsten, and hafnium. Previously, there was no casting technology for refractory and reactive metals.
- **Thorium Melting Development, 1954-57.** The Bureau developed a method for consolidating thorium metal into an ingot for the Savannah River reactor operated by the Union Carbide Nuclear Company at Oak Ridge, Tennessee.
- **Development of Methods for the Analysis of Zirconium and Hafnium, 1948-1952.** Wet chemistry, gas analysis, and optical and x-ray emission methods were developed for analysis of zirconium-containing ores, the pure metal, and alloys.
- **Use of Zirconium Crucibles for Peroxide Fusions, 1949-51.** The need for improved crucibles for analysis involving peroxide fusion of refractory metals led the Bureau to develop a technique for fabricating zirconium crucibles.



Kroll as a young man in his home laboratory, 1934.

William J. Kroll, Father of Titanium and Zirconium

"We all at the Bureau of Mines had a glorious time with titanium and zirconium, and some of the progress made was just miraculous…"
--William J. Kroll, in a letter to Earl T. Hayes, Director of the Albany Bureau of Mines Laboratory, February 1972

The mansion known as "Villa Leclerc," located in the residential Belair section of Luxembourg, looked normal from the outside—appropriately stately and palatial. But from 1923 to 1940, the goings on inside were decidedly not typical of most mansions. The owner, Wilhelm (later William) J. Kroll, was a noted metallurgist who performed dangerous experiments in the laboratory he had set up in the mansion's basement. He recalled that when he approached the police inspector to obtain authorization for operating a laboratory in a residential neighborhood, the inspector "turned pale" on seeing the list of flammable and corrosive chemicals that were in his inventory. "I never obtained the authorization for the laboratory," Kroll

Villa LeClerc, Kroll's home in Luxembourg where he invented the titanium reduction process, 1934.

wrote in 1956, "even though I operated it for 17 years." He also noted his neighbors' reactions: "In the beginning, my neighbors didn't trust me an inch, and in the cafes of Merl Street they said that I one day would blow Villa Leclerc up together with the whole neighborhood. The roses however, that I grew in abundance in my front garden—say it with flowers—cooled feelings down."

"The years I spent in Albany were the happiest of my career."

Kroll was a careful experimenter, so the neighbors' fears were unfounded. He was also a brilliant scientist who succeeded in developing a patented process for the production of pure titanium from mineral sources, without having to leave his house. The techniques he invented for producing titanium would prove to be very useful to the Bureau of Mines' Northwest Electrodevelopment Laboratory in Albany, Oregon, for the production of pure zirconium in the 1940s. However, United States patent number 2,205,854, issued to him in 1940 for a "Method for Manufacturing Titanium and its Alloys," would prove to be a source of legal wrangling and disappointment.

Wilhelm J. Kroll was born on November 24, 1889, in Esch/Alzette, Luxembourg. His father was in charge of the local blast furnace plant that produced pig iron, so metallurgy was in William's blood. After his years of formal schooling, which resulted in a doctorate from the Technische Hochschule Berlin-Charlottenburg, he worked for a number of metallurgy concerns in Germany, Austria, and Hungary. He made a name for himself while accumulating patents for the invention of "Lurgimetal," a lead-based alloy used for bearings, and "Alusil," an aluminum/silicon alloy used for cast aluminum pistons.

In 1926, he was introduced to the field of vacuum metallurgy while working for Siemens and Halske. This new technique was just what he needed for his titanium—and later zirconium—work. Because these metals in their powdered forms burst into flame when combined with oxygen in the air, distilling the metals under vacuum was necessary. The vacuum also eliminated gases that could dissolve in the molten metal, thereby resulting in a pure metal. Kroll realized that purity was the key to ductility—the ability to form the metal into useful shapes such as rods, sheets, and plates.

Kroll left Luxembourg on February 10, 1940, three months before the arrival of German troops, and by May was working as a consultant at the Union Carbide and Carbon Research Laboratories in Niagara Falls, New York. Upon hearing of the Bureau of Mines' interest in extracting and purifying zirconium at its new Northwest Electrodevelopment Laboratory, Kroll wrote to Bureau chief R. S. Dean to offer his services. After a flurry of letters establishing his role and compensation as a consulting engineer, outlining his ideas for zirconium production, and protecting his rights to the titanium patent and other work he had done at his own expense in Villa Leclerc, Kroll arrived in Albany in January 1945. Neither Kroll nor Dean had an inkling that Kroll's titanium patent had already been seized by the United States Alien Property Custodian in 1943. The reason was ostensibly that Kroll had worked as a consultant for several German companies while self-employed in Luxembourg.

Kroll quickly made a good impression on his colleagues at Albany. "Dr. Kroll appears to fit in well with our organization," B. A. Rogers, Superintendent of the Albany station, wrote to Dean in March 1945. "He has a wide range of knowledge, a fertile and an ingenious mind, and the ability to get results with very little fuss and fury. My attitude is that until he is ready to return to Luxembourg, we might well retain his services to work on special projects such as the chromium job, even after the zirconium work is in hand."

Much of the zirconium work was in hand by 1947, and plans for a pilot plant for producing large quantities of the metal were in the works. Kroll returned to Luxembourg in July 1947 to check on his house and possessions. He was happy to report that all the laboratory equipment he had packed in boxes before he left was intact; the house itself, however, had suffered greatly from German occupation and later neglect. He sold Villa Leclerc and his laboratory equipment at a great loss during his trip.

Kroll continued to improve the zirconium process after his return in January 1948, while also working with hafnium and other rare metals. But his time was more and more wrapped up in his legal troubles. There was increasing interest in the lightweight, strong titanium metal for use in airplanes, and he stood to make a lot of money from the patented Kroll process for producing ductile titanium. But he had to sue the United States government to regain the patent that had been taken by the Alien Property Custodian in 1943. Kroll resigned from the Bureau of Mines on January 10, 1951, with the lawsuit still unsettled.

After six years of court battles, in December 1954 the United States Court of Appeals retroactively awarded Kroll a royalty of one-half of 1 percent of the sales of titanium metal sponge. Still, according to Kroll, there would be little left after he paid off his legal bills. He was 65 years old at the time. "He lives alone at Corvallis, Ore., within walking distance of the Oregon State College Campus, in a house he built several years ago," a local newspaper reported. "Dr. Kroll spends much of his time at the college library, writing or translating technical papers. He does some metallurgical consulting work, occasionally lectures to engineering classes, and, for recreation, goes salmon fishing or listens to classical music." The unassuming house, which still stands in Corvallis, was built with steel and concrete because Kroll planned to continue his metallurgical experimentation in his home, just as he had in Villa Leclerc so many years ago. Whether he ever performed any experiments in his Corvallis home is not known.

He received numerous honorary doctoral degrees from universities around the world, as well as fellowships and medals for his life's work in metallurgy. In 1958, the American Section of the Society of the Chemical Industry honored him with the presentation of the Perkin Medal during ceremonies at the Waldorf-Astoria hotel in New York.

William Kroll left the United States in 1961 and retired to Rhode St. Genese near Brussels, Belgium, close to one of his brothers. He occasionally corresponded with his old colleagues in Oregon. In an October 18, 1969, letter to Frank Block (who would later become Research Director at Albany), Kroll wrote, "The years I spent in Albany were the happiest of my career." In a 1972 letter to Earl T. Hayes, he revealed that he was suffering from "'myotony' which is a muscle disease whereby synchronization of pull and push is desynchronized, which leads to a progressive hardening of muscles and tendons. The stiffening of the joints may ultimately lead to ataxy, or impossibility to move." By then he had taken to signing his name "Bill." Kroll died of the disease in 1973.

A fitting tribute to William J. Kroll was given by Admiral Hyman Rickover on March 21, 1975, in Denver, Colorado, when Rickover became the first recipient of William J. Kroll Medal established by the American Society for Testing and Materials (ASTM): "When Dr. Kroll and I met at Albany, we dealt with details. We had to. We understood each other because we based our discussion on principles—his were scientific, mine were engineering. Far too frequently people, particularly those who have just come from universities, are convinced that if they learn the principles, that is all they need to know. As the decision on zirconium shows, this is not so. Of course you need principles, but that is not enough. The Devil is in the details, but so is salvation."

A Century of Innovation

From the U.S. Bureau of Mines to the National Energy Technology Laboratory

Chapter Seven: Morgantown—the Center for Coal Gasification


DEPARTMENT OF THE INTERIOR
A CENTURY OF CONSERVATION
1849 - 1949
THIS VEHICLE IS BEING OPERATED ON
GASOLINE
MADE FROM
WEST VIRGINIA COAL

Chapter Seven:

Morgantown—the Center for Coal Gasification

The problem of gasifying pulverized coal in an atmosphere of oxygen and steam had been studied extensively in Europe, particularly in Germany, but practically no research of this kind was attempted in this country until 1946 when the Bureau of Mines started its program in Morgantown.

--Bureau of Mines, "History of the Morgantown Station of the Bureau of Mines," 1953

On August 6, 1943, at about 1:00 PM, a small convoy of automobiles made a three-mile trip from the Pittsburgh Central Experiment Station to the prestigious Duquesne Club in downtown Pittsburgh. The cars ran on synthetic gasoline made in the station's coal-hydrogenation pilot plant. They carried members of Congress who were in town for a hearing on synthetic liquid fuels and national energy policy. After a stint at the wheel of one of these cars, Representative Jennings Randolph of West Virginia reported approvingly that "there wasn't a sputter in the engine." The coal-based fuel performed just like its petroleum counterpart. "If it hadn't been for the fact that this gasoline made from coal was being fed from a glass jar on the hood," Randolph enthused, "we wouldn't have known that we were driving with hydrogenated gasoline."

The Synthetic Liquid Fuels Act of 1944 authorized the largest investment that the federal government had ever made in civilian energy research and development.

The bill that these legislators were considering became the Synthetic Liquid Fuels Act of 1944, which authorized what was then the largest investment that the federal government had ever made in civilian energy research and development. Between 1944 and 1955, the act gave the Bureau of Mines $87.6 million to study the production of liquid fuels from coal and oil shale. This program, intended to safeguard the United States against the threat of petroleum shortages and to promote economic development, had a lasting and transformative impact on fossil-fuels research at the Bureau. One of its consequences was the creation of a new experiment station in Representative Randolph's home state at Morgantown, West Virginia.

A Bureau of Mines station wagon, powered by synthetic gasoline made from coal, participating in the Labor Day parade at Morgantown in 1949. (photo credit: National Archives and Records Administration)

Established in January 1946, the Morgantown station was initially called the Synthesis Gas Production Laboratories. Its name reflected its original assignment: Find quicker, cheaper ways of gasifying coal to produce synthesis gas, the versatile mixture of hydrogen and carbon monoxide that was an essential input for the rest of the synthetic liquid fuels program. Coal gasification—both above ground and underground—and the removal of harmful impurities from manufactured gas were thus the station's earliest specialties. In 1950, however, Congress decided that Morgantown would also become the regional headquarters for the Bureau's broader efforts to promote the development of coal, petroleum, and natural-gas resources in the Appalachian Mountains. A new campus called the Appalachian Experiment Station opened in 1955 to accommodate this expanded agenda.

In 1942, the Bureau of Mines set up a field office that would help private companies increase output from the old petroleum and natural-gas reservoirs of the Appalachian Plateau.

The Synthetic Liquid Fuels Act of 1944

The revival of interest in synthetic liquid fuels during the 1940s reflected the strains that American engagement in World War II placed upon the nation's petroleum resources. Not only did the United States require enough petroleum to supply its own armies, navies, and industrial needs, but it also exported large amounts to its overseas allies. These heavy demands eroded domestic petroleum reserves. New fields were identified and existing ones enlarged throughout the war years, but increases in supply lagged behind increases in consumption. For every barrel of petroleum that augmented American reserves between 1941 and 1945, 1.7 barrels were extracted. Especially troubling was the lack of any spectacular new fields comparable to the great discoveries of the late 1920s and the early 1930s. Large reservoirs of petroleum were apparently becoming harder to find, and the costs of exploration and retrieval were rising.

One obvious policy response was to create new incentives for exploratory drilling and for more intensive development of known petroleum fields. Congress did so in 1942 by lowering royalties on the withdrawal of petroleum from public lands. In the same year, it also authorized the Bureau of Mines to set up a field office that would help private companies increase output from the old petroleum and natural-gas reservoirs of the Appalachian Plateau. This region, the birthplace of the American fossil-fuels industries, had many wells that were no longer producing but that might be reinvigorated with secondary-recovery techniques. Since most of the oil and gas firms that operated there were small and unable to afford research programs on their own, they could benefit greatly from the Bureau's assistance.

The Appalachian field office of the Petroleum and Natural Gas Branch was established at Franklin, Pennsylvania, on April 16, 1942, with four employees, some of whom had transferred from the Bartlesville or Laramie stations. Sam S. Taylor, a chemical engineer with expertise on using brine injections to stimulate the flow of petroleum, and Edgar M. Tignor, a natural-gas specialist, were among those who brought the Franklin Petroleum Field Office to life. Setting up shop in leased offices on the third floor of the landmark Galena Building in downtown Franklin, the tiny staff had a twofold mission. It aided the war effort by advising local companies on how to expand petroleum and gas production, and it conducted fundamental research on the geology of petroleum reservoirs in the region.

According to the best estimates available in the 1940s, Appalachian reservoirs contained billions of barrels of high-grade petroleum that was inaccessible via ordinary drilling techniques. This petroleum, if it could be made available, would have exceptional value to American industry due to its lubricating qualities and the ease of refining it. The Franklin station assisted well operators with injections of pressurized water or gases at key points to force petroleum into the wells and toward the surface. In the face of wartime materials shortages, Bureau engineers collaborated with private firms to improvise improved drilling processes and use available equipment more efficiently.

Revitalization of the Appalachian reservoirs could not proceed far without a better scientific understanding of the natural structures of rock and sand that contained them. The Franklin station analyzed the physical and chemical composition of local rocks. It observed the movement of fluids through underground formations, seeking clues to identify propitious sites for waterflooding. It launched detailed engineering studies of individual petroleum fields and estimated the amount of petroleum remaining versus the amount that had already been recovered. These evaluations resembled inquiries that the Bureau had previously begun in other regions to develop a detailed portrait of major American petroleum resources.

E. M. Tignor adjusting the controls of a model oil well in the field office at Franklin, Pennsylvania.

Sam S. Taylor (left) and C. E. Whieldon, Jr., of the Franklin field office mixing drilling mud at a well in the Cranberry petroleum field, Venango County, Pennsylvania, 1947.

However, even the most vigorous effort to expand domestic petroleum supplies could not guarantee that new sources would actually be found, or that any discoveries could keep pace with soaring wartime needs and anticipated high postwar energy demand. Even before the December 1941 attack on Pearl Harbor that brought the U.S. fully into the war, Secretary of the Interior Harold Ickes and some influential members of Congress argued that the tightening supply of petroleum might not be merely a temporary phenomenon. The country, they insisted, could not afford to gamble its military and economic security on the assumption that adequate new reserves would materialize. It had to prepare synthetic alternatives that could fill in if and when petroleum shortages arose. Since experience in Germany and Great Britain had shown that bringing synthetic liquid fuel industries from concept stage to mass production could take many years, the necessary development work should commence promptly.

Senator Joseph C. O'Mahoney of Wyoming speaking at the Laramie station of the Bureau of Mines, 1945. (photo credit: National Archives and Records Administration)

A series of legislative hearings grew out of this line of reasoning. In both houses of Congress, leadership came from individual lawmakers who were attuned to the economic and strategic dimensions of energy policy and who, not coincidentally, represented states that had plentiful raw materials for making synthetic liquid fuels. Senator Joseph C. O'Mahoney, a Democrat from Wyoming, headed the War Minerals Subcommittee of the Senate Committee on Public Lands and Surveys. He was a staunch advocate of a cause that resonated deeply with many Westerners: promoting regional industrial development in order to make the Western states wealthier and less dependent on Eastern goods and capital. Beginning in 1941, O'Mahoney led his subcommittee to examine the possible creation of new manufacturing industries based on mineral resources, including coal and oil shale, which abounded on Western public lands.

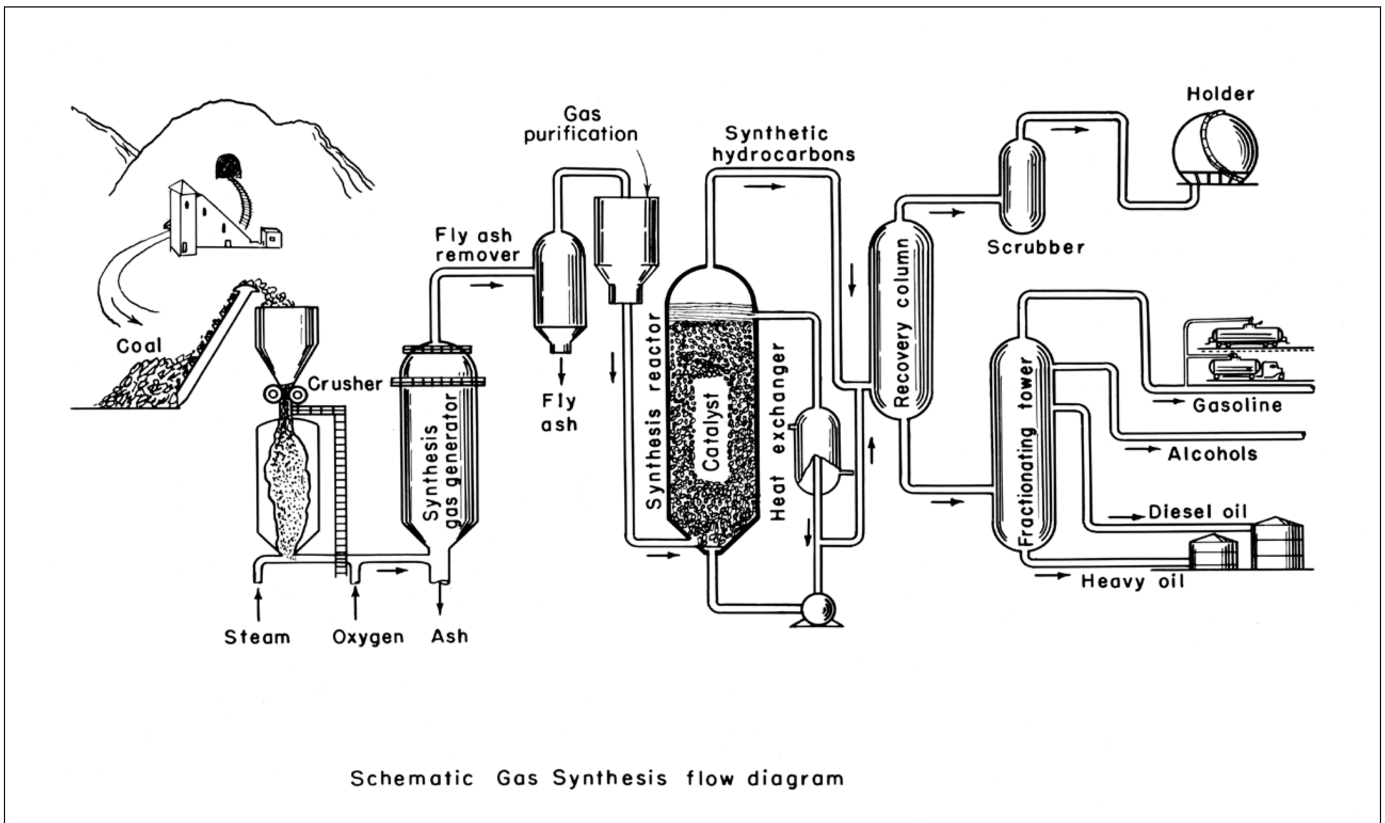
Representative Jennings Randolph of West Virginia. (photo credit: Library of Congress)

O'Mahoney's counterpart and ally in the House of Representatives, Jennings Randolph of West Virginia, chaired the Subcommittee on Gasoline and Chemical Products from Coal of the House Committee on Mines and Mining. In addition to his solicitude for West Virginia coal interests, Randolph contributed his knowledge of and passion for American aviation. A skilled pilot himself, he had been instrumental in establishing the federal Civil Aeronautics Administration and the Civil Air Patrol during the 1930s. His recognition of the burgeoning importance of aircraft—and the specialty fuels that powered them—to national defense and commerce informed his strong backing for synthetic liquid fuels, which his subcommittee began to investigate in 1942.

The hearings that O'Mahoney and Randolph jointly held on S.1243 in August 1943 constituted the most thorough inquiry that Congress had ever conducted on alternatives to petroleum. Experts from universities, energy companies, and federal and state agencies testified. The Bureau of Mines was well represented. Director Royd R. Sayers, Arno Fieldner, Wilburn C. Schroeder, and Henry Storch of the Fuels and Explosives Service were key witnesses. They carefully walked the committee members through the similarities and differences among the available methods of obtaining liquid oil from coal: low-temperature coal carbonization, the Bergius-I.G. Farben hydrogenation process, and the Fischer-Tropsch gas synthesis.

Citing what he had learned during his recent visit to the commercial coal-hydrogenation works at Billingham, England, Storch emphasized that information gleaned from small pilot plants such as the Bureau's experimental units in Pittsburgh did not reliably scale up to indicate how larger coal-to-liquids plants would perform. Demonstration plants of much greater size—for example, a coal-hydrogenation facility with a capacity of around 300,000 barrels of oil per year—would be needed to gather adequate technical and cost data. Moreover, the Bergius-I.G. Farben process and the Fischer-Tropsch process merited equal consideration. Both had strengths and weaknesses, which were often complementary. Coal hydrogenation was superior for gasoline and aviation fuels, while Fischer-Tropsch oil made a better base for diesel fuel and lubricants.

Several former Bureau employees who had taken part in the prewar oil-shale program testified in favor of resuming oil-shale research. Martin J. Gavin, who had spearheaded the Bureau's work on this subject in the 1920s, asserted that "[g]asoline may be produced more cheaply from oil shale than from coal, on the basis of present data." He argued that the recent catalytic-cracking revolution in petroleum refining might lead to even lower costs if the new refining techniques were applicable to shale oil. Lewis C. Karrick and Albert J. Kraemer supported Gavin's stance that the earlier oil-shale experi-



Although most early coal-to-liquids research at the Bureau of Mines focused on direct coal hydrogenation, interest in the indirect Fischer-Tropsch method revived during World War II. This diagram illustrates the basic steps of the Fischer-Tropsch process.

ments in Colorado were still relevant and should be updated in a new demonstration plant.

Congress was initially slow to act, prompting Representative Randolph to dramatize the issue again by flying a light plane powered by synthetic gasoline from Morgantown, West Virginia, to National Airport in Washington, D. C., on November 6, 1943. But the vision of an American synthetic-liquid-fuels industry that would bolster national security, create jobs to cushion the upcoming transition from war mobilization to a peacetime economy, and advance regional economic development in many sections of the country had sufficiently wide political appeal to prevail. Legislation based on S.1243 advanced through the 78th Congress with some modifications, including the addition of a program to investigate alcohol fuels made from wood or agricultural wastes.

The vision of an American synthetic liquid fuels industry that would bolster national security, create jobs to cushion the upcoming transition from war mobilization to a peacetime economy, and advance regional economic development in many sections of the country had sufficiently wide political appeal to prevail.

On April 5, 1944, President Roosevelt signed the Synthetic Liquid Fuels Act (Public Law 290) into law. This measure allocated $30 million over five years for synthetic-fuels research and development. The Bureau of Mines became the lead agency for all components of the program:

> *Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, That the Secretary of the Interior, acting through the Bureau of Mines, within the limits of critical materials available, is authorized for not more than five years to construct, maintain, and operate one or more demonstration plants to produce synthetic liquid fuels from coal, oil shale, and other substances, and one or more demonstration plants to produce liquid fuels from agricultural and forestry products, with all facilities and accessories for the manufacture, purification, storage, and distribution of the products.* [1*] *The plants shall be of the minimum size which will allow the Government to furnish industry the necessary cost and engineering data for the development of a synthetic liquid-fuel industry and of such size that the combined product of all the plants constructed in accordance with this Act will not constitute a commercially significant amount of the total national commercial sale and distribution of petroleum and petroleum products.*

In charging the Bureau of Mines with this responsibility, Congress recognized that much preliminary research would be necessary before demonstration plants could be built and run successfully. The Synthetic Liquid Fuels Act empowered the Secretary of the Interior "to conduct laboratory research and development work, and with pilot plants and semiworks plants to make careful process engineering studies along with structural engineering studies in order to ascertain lowest investment and operating costs, necessary to determine the best demonstration plant designs and conditions of operation . . .

1* The Department of the Interior delegated responsibility for implementing the provision regarding alcohol-based biomass fuels to the Department of Agriculture, which operated one small biomass demonstration plant at its Northern Regional Research Laboratory at Peoria, Illinois, from 1946 to 1950. Focusing on the production of ethanol from corncobs, this project resulted in a few studies that indicated the potential value of alcohol-based fuels as additives to petroleum. It never received as much attention or support as the coal and oil-shale sections of the synthetic liquid fuels program did.

Later amendments to the act expanded its scale and reach. In March 1948, Public Law 443 extended the program for three more years to 1952, increased the funding by $30 million, and specifically designated $1 million of that amount for research on secondary petroleum recovery. An amendment in September 1950 (Public Law 812) provided another three-year extension to 1955 and an additional $27.6 million, bringing the total appropriations to $87.6 million.

Commercialization of synthetic liquid fuels technologies was the ultimate goal. The legal language stipulating that demonstration plants could not manufacture synthetic oils in "commercially significant" quantities reinforced the distinction between governmental action and private enterprise. Under the Synthetic Liquid Fuels Act, no public agency would enter the oil business, or even appear to be doing so. Traditional cooperative agreements between the Bureau of Mines and industry to aid technological development were politically acceptable, but any hint of public competition with the private sector was not. Public expenditures were intended to lay the groundwork for private investment that would lead to for-profit synthetic oil production in the United States as soon as economic conditions warranted.

Commercialization of synthetic liquid fuels technologies was the ultimate goal.

The Beginnings of Coal-Gasification Research at Morgantown

Key to the eventual commercialization of coal-based synthetic liquid fuels was devising cheaper ways to make synthesis gas. Every barrel of oil produced by the Fischer-Tropsch process required over 30,000 cubic feet of synthesis gas, which constituted 50 to 80 percent of the oil's total cost. In the coal-hydrogenation process, synthesis gas was the source of hydrogen; obtaining and compressing that hydrogen accounted for at least 40 percent of the cost of producing oil through this method. Reducing these costs was imperative if coal-based synthetic liquid fuels were to be mass-produced and sold at prices comparable to what Americans had come to expect for petroleum products.

The Office of Synthetic Liquid Fuels, which was created within the Bureau of Mines on September 4, 1944, established a Synthesis Gas Branch devoted solely to this task. Initially, this agency made slow progress because so many Americans with relevant knowledge were busy with the Technical Oil Mission, examining German synthetic-fuels plants and analyzing information obtained from overseas. Long before the Synthesis Gas Production Laboratories were officially created in January 1946, however, groundwork had already been done to secure a base of operations for the new organization in Morgantown, West Virginia.

Situated about 75 miles south of Pittsburgh amid the rich Central Appalachian bituminous coal fields, Morgantown served as a regional educational and technological hub. It was home to West Virginia University (WVU), which had a noted School of Mines and an engineering faculty that did considerable coal research. During the late 1930s, the university had sponsored an Annual Coal Conference, at which Henry Storch and Arno Fieldner had presented a paper on "Hydrogenation and Liquefaction of American Coals" in 1939. Morgantown also harbored the offices of the West Virginia Geological and Economic Survey, which exemplified the state government's interest in cataloging natural resources and using them to promote economic development. R. C. Tucker, who was the acting state geologist in 1943 during the United States Senate hearings on synthetic fuels, had argued that northern West Virginia was ideally positioned for coal-to-liquids manufacturing because of its vast coal resources and its proximity to the great industrial centers of the East Coast and the Ohio Valley.

The Morgantown station began with a tiny nucleus of Bureau staff members in the winter of 1946.

The political leaders of the state and the university worked assiduously to ensure that Morgantown would have a stake in the Synthetic Liquid Fuels program. On August 4, 1943, Representative Randolph had floated the possibility of a Bureau of Mines-WVU partnership. He asked rhetorically whether "our own school of mines at Morgantown, which is an excellent institution, can join hands with the Federal Government perhaps in carrying on certain experiments at the direction of Dr. Storch and others?" This idea was shrewd and timely. The Bureau of Mines had always preferred to co-locate its facilities with universities and technical schools, a policy that received further reinforcement from the rapid growth of federally funded scientific research during and after World War II. Unable to handle the volume of research work, federal laboratories increasingly reached out to institutions of higher education for help. WVU was eager to participate, and on October 23, 1945, its officers signed a cooperative agreement with the Bureau of Mines to host the experimental work of the Synthesis Gas Branch.

Under the cooperative agreement, the Bureau set up the Synthesis Gas Produc-

The Mineral Industries Building on the West Virginia University campus, home of the first Bureau of Mines offices and laboratories at Morgantown.

tion Laboratories on the WVU campus in downtown Morgantown, primarily in the new Mineral Industries Building—which had been dedicated in 1942—and an area near the university field house. Additional rented space elsewhere in and around the city housed administrative offices and warehouses. Bureau personnel had access to all campus resources and frequently collaborated with WVU faculty and students. The arrangement was mutually beneficial. Between the spring of 1946 and the summer of 1955, 192 different WVU students worked part-time for the Synthesis Gas Branch, and some of them completed their master's or doctoral theses on aspects of the synthesis-gas research.

George R. Strimbeck (left) and Colt Pears (right) at the Morgantown station, 1949. (photo credit: NETL via Donald Strimbeck)

The Morgantown station began with a tiny nucleus of Bureau staff members in the winter of 1946, and by the end of its first year it had only 17 full-time employees. E. D. Schmidt, who headed the Synthesis Gas Branch, had overall charge of the station. Among his colleagues were several veterans of the Bureau's Pittsburgh laboratories. For example, Edgar W. Donaldson had worked at Pittsburgh before entering wartime naval service; following his return, he transferred to Morgantown to organize the administrative side of the new agency. James L. Elder had also served at Pittsburgh as a chemical engineer specializing in coal oxidation and carbonization. Others came from private industry. James Paul McGee, the chief engineer of the Synthesis Gas Branch, was a mechanical engineer who had gained diverse experience with natural-gas pipelines, blast-furnace equipment, ammonia manufacturing, and turbine engines for United States Navy ships before turning his attention to synthesis-gas production. George Richard Strimbeck, a chemical engineer from Michigan who had moved to Morgantown during World War II to help run a federal munitions plant there, became the supervising engineer of the station and subsequently the head of the Pilot Plant Operations Section.

Work began with a review of the pertinent scientific literature, including and especially the recently obtained information about synthetic-fuels development in Germany. At first glance, German precedents seemed unhelpful because they largely ignored the economic considerations that were central to the Bureau of Mines program. Driven by military needs and supported by government subsidies, the German synthetic liquid fuels industry had lacked market incentives for cost discipline. Alfred R. Powell, an American member of the Technical Oil Mission, had marveled at the "huge and cumbersome" German plants that were outwardly impressive but inwardly inefficient. "By American standards," Powell wrote in 1946, "these 27 plants, many of them so large as almost to defy description, should have produced a quantity of oil much greater than they did." Simply copying what the Germans had done was thus not an option.

But the German records contained valuable clues about how to improve the synthesis-gas piece of the synthetic-fuels puzzle. Most synthesis gas used in Germany had been created in a two-step process that was essentially the traditional method of making water gas for urban light and heat. Coke or coal tar was first produced by heating bituminous coal or brown coal (similar to lignite) and then gasified in a separate reactor—usually in a conventional water-gas generator, which blew alternating blasts of air and steam through a stationary bed of hot coke or tar. However, several German firms had developed alternative designs for gasifiers that were capable of obtaining synthesis gas directly from raw coal in a single step. Such gasifiers operated continuously, instead of in the intermittent manner that prevailed in water-gas manufacturing. These streamlined processes increased production capacity, required less labor, and worked well on inexpensive, low-quality coals.

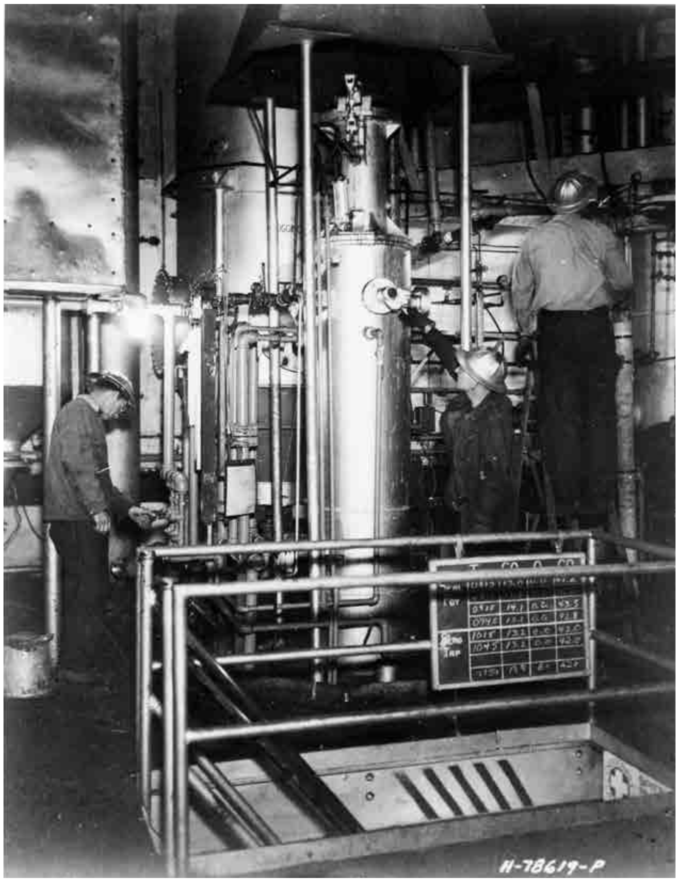
Morgantown engineers concluded that no existing coal-gasification technologies could fully meet the need for a low-cost source of synthesis gas, so they set out to design and build their own gasifier.

Although the American water-gas industry was doing work along similar lines, the innovative German gasifiers were more advanced than domestic practices. German engineers had made particular progress with reactors that supplied the heat necessary for the water-gas reaction through internal combustion, by introducing pure oxygen to burn some of the feedstock—whether coke or raw coal—inside the reactor. They used several different methods of bringing coal or coke, oxygen, and steam into close contact to achieve efficient combustion and gasification. Common to most of these methods was the pulverization of the feedstock into small fragments. In some German designs, the pulverized material formed a stationary bed, as in a standard water-gas generator. In others, it became *fluidized* when oxygen and steam were blown upward through it to put the solid particles into rolling, fluid-like motion. Some companies had developed *entrained-bed* processes, in which finely ground coal was suspended in a flow of steam and oxygen through the reactor.

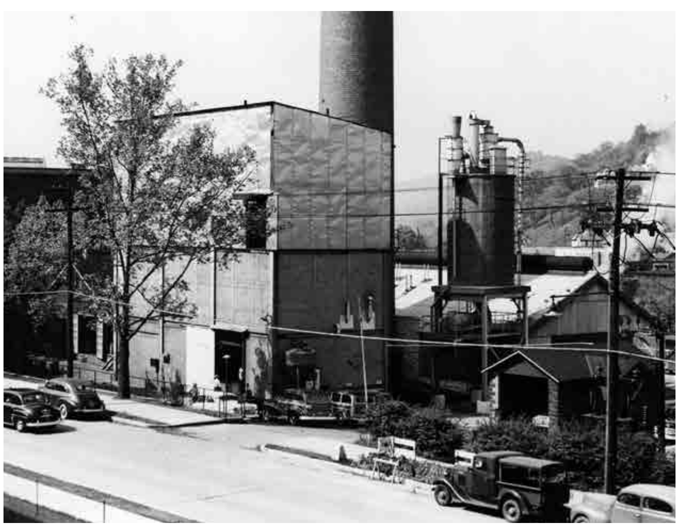
After thoroughly studying German and American ideas, the engineers on the Synthesis Gas Production Laboratories staff at Morgantown concluded that no existing coal-gasification technologies in either country could fully meet the need for a low-cost source of synthesis gas. So they set out to design and build their own gasifier, one that would be simple, reliable, and able to make synthesis gas directly from a wide variety of American coals. Laboratory research began in 1946. In 1947, the researchers began operating a small gasifier that could process about 50 pounds of coal per hour. This device, which used the entrained-bed method, may have been the first continuous oxygen-and-pulverized-coal gasifier ever operated in the United States. According to the 1948 Office of Synthetic Liquid Fuels annual report, it allowed the researchers to examine "the operating variables on which the efficiency and cost of gasification depend," such as temperature, pressure, type of coal, and the ratios of oxygen to coal and steam to coal.

Work on a much larger pilot plant that could gasify up to 500 pounds of coal per day also got underway in 1947, proceeding in tandem with the laboratory studies. This plant took shape in a humble industrial building on Beechurst Avenue in Morgantown, next door to the WVU field house and a few city blocks inland from the Monongahela River. It commenced operations in October 1948.

For the pilot plant, Schmidt, McGee, Strimbeck, and their team again chose the entrained-bed method as the basic gasifier technology, although their design also made some use of the concept of fluidization. Aided by WVU engineers, they devised a system in which bituminous coal from West Virginia mines was



Interior view of the Beechurst Avenue building, showing the top section of Gasifier No. 4, the second-generation atmospheric-pressure coal gasifier that the Bureau of Mines completed in 1951 with assistance from Babcock & Wilcox.



Exterior view of the Beechurst Avenue pilot-plant building.

Gas-purification pilot plant under construction at Beechurst Avenue.

ground to form a powder and then sent through an innovative fluidized pneumatic feeder that delivered it to the reactor in a stream of inert gas. The reactor itself was a tall steel cylinder, thickly lined with refractory brick. Powdered coal, oxygen, and steam all entered through ports near the bottom, swirled together, and reacted as they rose through the hot gasification chamber, forming synthesis gas that exited near the top.

Oxygen was the most expensive ingredient, and during the immediate post-World War II years it was still hard to obtain in large quantities. To reduce the amount of oxygen required, the Morgantown staff decided that only part of the heat supply for the pilot plant could come from internal combustion. The rest had to come from preheating the steam to very high temperatures. P. H. Royster, a metallurgist at the Bureau of Mines headquarters in Washington, D. C., designed stoves especially for this purpose. Each stove contained a stationary bed of pebbles, made from a highly refractory material, that was heated by a natural-gas-fired burner.

As they worked with the laboratory plant and the pilot plant, the Morgantown researchers often had to innovate when they encountered unusual technical problems that no commercially available equipment could solve. The fluidized pneumatic feeder for the powdered coal was developed in-house because mechanical devices could not deliver the coal to the reactor at a uniform rate and existing industrial pneumatic feeders were inadequate. When the engineers needed to measure the ratio of powdered coal to the gas in which the coal was suspended, they created an electrical instrument that could give them instantaneous data on dust concentrations in a stream of gas. And after the valve for the connection between the pebble stoves and the pilot-plant reactor performed badly under intense heat, the Morgantown staff designed a new water-cooled valve system. The applicability of these unglamorous but important inventions extended far beyond coal gasification to other chemical-engineering processes.

Researchers also made advances in eliminating dust (a serious problem when making gas directly from coal), carbon dioxide, sulfur, and other impurities from the synthesis gas after it left the reactor. Because sulfur would ruin the catalysts that were used to produce synthetic liquid fuels in the Fischer-Tropsch process, its removal was essential. The Gas Treating and Testing Section, led by the chemist Howard W. Wainwright, devised or improved methods for detecting and measuring sulfur compounds and scrubbing them out of the gas.

Experience soon convinced the Morgantown engineers that their pilot plant, although promising, was flawed and needed major revisions. The pebble stoves were temperamental and difficult to maintain. So was the brick lining of the reactor, which suffered frequent damage from erosion and uneven heating. A second-generation pilot plant was accordingly developed through collaboration with the boiler manufacturer Babcock & Wilcox and put into service in 1951. With this partnership, the Bureau gained access to the latest in boiler technology—which had many parallels to gasifier design—and identified cost-saving opportunities. For example, burners inspired by those used in commercial boiler furnaces mixed the coal, steam, and oxygen faster and more completely, while also safeguarding the reactor lining. The pebble stoves gave way to a standard industrial steam preheater that operated at lower temperatures. This change meant that more oxygen was required. However, since oxygen costs had fallen and the upkeep of the stoves was eliminated, the tradeoff was acceptable.

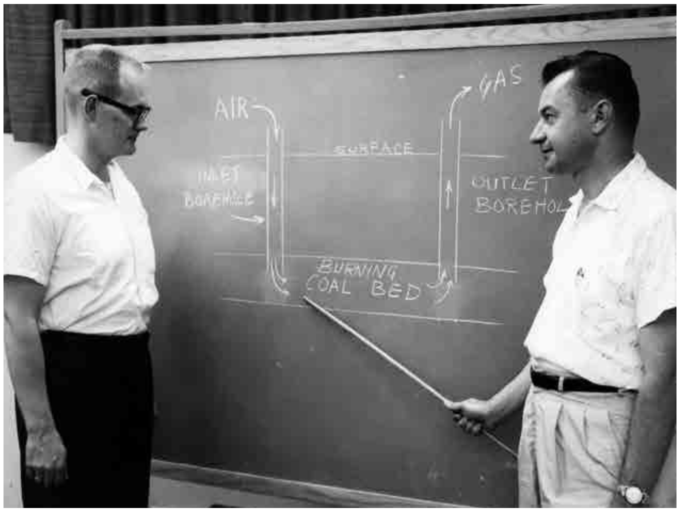
By 1954, the second edition of the pilot plant had proven itself as a dependable generator of high-quality synthesis gas. Tests made with coals from different regions of the country—bituminous coals from West Virginia, Kentucky, and Washington State, lignite from Wyoming, and anthracite from Pennsylvania—demonstrated the versatility of the Bureau's coal-gasification process. Experimentation had settled into a rhythm. Each test run began by heating up the gasifier overnight, proceeded through an early-morning startup phase, and culminated in a sustained gasification phase in which the equipment ran steadily for at least three hours. Based on meticulously recorded data, the staff and WVU students who worked under the direction of John H. Holden in the Data Evaluation and Planning Section analyzed the results and planned future experiments.

By 1954, the Morgantown station had become internationally recognized for its participation in developing underground coal gasification.

A topic of great interest to the scientists and engineers at Morgantown was pressurization. The laboratory plant and the early pilot plants all operated at or very near normal atmospheric pressure, but potentially large advantages could be gained by conducting gasification at higher pressures, a possibility that the Germans had explored. Since the Fischer-Tropsch process required pressurized synthesis gas, producing the gas in the form in which it would be used—thus reducing the cost of compressing it later on—made economic sense. Pressurization also promised to allow greater output for any given size of equipment and to simplify dust removal.

The Synthesis Gas Branch decided in 1949 to proceed with the construction of a high-pressure gasifier. Babcock & Wilcox once again supplied engineering expertise. Like the atmospheric-pressure pilot plants, this gasifier was an entrained-bed type with a capacity of about 500 tons of coal per day, but it operated under pressures of around 450 pounds per square inch. The project introduced water cooling and a new burner design that injected the powdered coal, steam, and oxygen at the top of the reactor. Testing started in 1951 and soon confirmed that the high-pressure plant yielded much greater output. However, pressurization also created problems with the coal-feeding system and reintroduced problems with damage to the reactor lining. Improving the high-pressure gasifier subsequently became the main focus of the Morgantown researchers.

By 1954, the Morgantown station was solidly established. Its staff had grown to 120 people, who crowded the available space at WVU. Its process for gasifying coal at atmospheric pressure had reached the threshold of commercialization. It had also become internationally recognized for its participation in developing another potential source of synthesis gas: underground coal gasification.



Donald C. Strimbeck (left) and John P. Clapp (right) explaining the concept of underground coal gasification, an important focus of research at Morgantown during the late 1940s and the early 1950s.

Wilburn C. Schroeder (left), chief of the Office of Synthetic Liquid Fuels, assisting as an incendiary device is dropped into a shaft to start the first underground coal gasification experiment at Gorgas, Alabama, in January 1947. (photo credit: National Archives and Records Administration)

Minutes after the initial fire was lit at Gorgas, billowing smoke revealed the progress of underground coal combustion and gasification. (photo credit: National Archives and Records Administration)

Producer gas generated by an electrolinking experiment at Gorgas is flared off into the night sky.

Underground Coal Gasification

The idea of gasifying coal underground to tap its energy without mining it had intrigued scientists and engineers in Europe and the United States since the mid-nineteenth century. Underground gasification promised to save money and human lives. In principle, this process could eliminate the need for employing large numbers of miners, exposing them to the hazards of dust and mine collapses, and hauling away voluminous amounts of coal and wastes. Rather, a seam of coal could be burned in place and turned into a giant subterranean gasifier through injections of air and steam, thus creating heat and valuable gases that could be channeled to the surface.

Yet the challenges of translating this idea into reality were formidable. Observing and controlling the behavior of hot gases deep below the earth's surface was difficult, as was assuring that the output would be of high enough quality for industrial use. Deliberately setting fire to a coal seam could be dangerous—especially if a burn got out of control and smoldered unchecked for years, as accidental mine fires often did. Wary of the up-front costs and risks, the mining industry had done little with underground gasification before World War II. Only in the Soviet Union, where the communist government underwrote a long-term program of research and experimentation on the subject, had underground coal gasification been implemented on a significant scale.

Wartime demand for energy spurred international interest in underground gasification during the 1940s. Among the proponents were researchers at the Bureau of Mines, who in 1943 recommended that the Bureau experiment with the underground gasification of American coals. They argued that this work could lead to the recovery of energy from coal seams that were too thin, inaccessible, or depleted for conventional mining. The passage of the Synthetic Liquid Fuels Act supplied both funding for such tests and a new rationale: Underground coal gasification might answer the call for a cheap method of producing synthesis gas.

Decisive support for the project came from the Alabama Power Company, which entered a cooperative agreement with the Bureau in 1946 to share the expenses. Company executives were eager to identify with an innovative technology that could reduce the future cost of electricity generation and stimulate economic development in their state. They also owned a tract of land in Walker County, Alabama, that constituted a nearly ideal site for experimental purposes. Located at the southernmost end of the Appalachian coal fields, this property encompassed a commercial power plant—the William Crawford Gorgas Electric Generating Plant, with its nearby company town of Gorgas—and several active coal mines.[2*] One particular hill held coal deposits that were naturally isolated from the surrounding territory, minimizing the danger that

2* The plant and the town were named after a hero of Alabama and of American applied science: Dr. William Crawford Gorgas (1854-1920), an Alabamian who, as the surgeon general of the U.S. Army from 1914 to 1918, systematically applied sanitary measures that reduced malaria and facilitated the construction of the Panama Canal.

an underground fire set there could spread. The Black Warrior River furnished an abundant water supply. Any usable gas that underground-gasification experiments created might be sent to the power plant for combustion in the boilers, or burned in an on-site turbine engine to generate heat and power directly.

At 2:00 PM on January 21, 1947, the first American field experiment with underground coal gasification got underway.

Using land and labor donated by Alabama Power, a team of engineers from both the company and the Bureau of Mines began site-preparation work near Gorgas in October 1946. Their initial plan applied what was called the stream method of underground gasification, in which hot coal interacted with a flow of gases. Two parallel tunnels were dug into the hill that contained the isolated section of bituminous coal. A perpendicular crosscut connected the tunnels at their farthest ends, thus forming a U-shaped underground path around an intact pillar of coal. Intended as the main combustion and gasification zone, this crosscut was to be filled with broken coal and kindling and ignited to start a fire that would turn the coal in the exposed faces of the pillar into coke and then burn and gasify it. Compressed air and steam would be blown in through one tunnel, while the output gases would be drawn out through a stack at the exterior end of the other tunnel. Through boreholes and observation ports, the researchers could insert temperature sensors, take gas samples, and assess what was happening below ground.

At 2:00 PM on January 21, 1947, the first American field experiment with underground coal gasification got underway. Magnesium incendiary devices were dropped into the crosscut to light the fire. Initially, only air was blown through the inlet tunnel, yielding producer gas (a gas that was usable as fuel but had low heating value). Adding steam—or using steam alone, or a mixture of steam with pure oxygen—created a weak water gas. After fifty days, the experiment ended, and the tunnels were cooled by flooding them with water. They were then drained and supplemented with new passages so that people could enter to examine firsthand the burned-out areas, melted stone from collapsed tunnel roofs, and layers of coke that the fire had left behind.

Back in the Synthesis Gas Branch laboratories at Morgantown, members of the team built a model of an underground-gasification chamber and continued their inquiries. They knew that they needed to gain greater control over the progress of underground gasification, and to improve efficiency by keeping air or steam in closer contact with the hot faces of the coal seam. They also sought to operate an underground gasifier at temperatures and pressures higher than those previously attained. One key to doing so was stopping the constant leaks of input and output gases that had plagued the pioneering test.

James L. Elder of the Synthesis Gas Branch staff became the supervising engineer for the underground-gasification program in July 1948, when planning began for a second phase of field experimentation at Gorgas. The new scheme used the stream method again, but with a different design. Under another section of the test hill, two nearly straight parallel tunnels, spaced ten feet apart, were excavated. Multiple crosscuts through the intervening pillar of coal divided them into five chambers, each of which was 300 feet long and was equipped with boreholes for air injection (using steam and oxygen on a large scale had proven to be too expensive) and gas withdrawal. An underground fire could gradually advance from one chamber to the next, thus allowing the experiment to continue for a year or more of continuous operation.

Launched in March 1949, this second series of tests lasted over 22 months, ending in February 1951. It accumulated data about the quantities of coal consumed and gases produced; the physical characteristics of the burned-out areas; and the flow of gases through the site. Compared to the original 1947 trial, numerous improvements were evident. Leaks, although still plentiful, were reduced due to better sealing. The researchers learned how to boost pressure and focus the airflow toward the hot coal by filling extraneous underground spaces with sand. They also found that they could affect the pace and direction of the fire's movement through the coal seam by drilling additional boreholes. In 1950, the project reached a milestone when coal gas made underground was first used to do work on the surface by powering turbines that helped supply the works with compressed air.

A third set of experiments, commenced in June 1951, relied on a different principle called electrolinking. This approach addressed the two main drawbacks of the stream method: the costly need to dig tunnels and the persistent difficulty of sustaining good contact between air and coal in the combustion zone. Electrolinking created an underground path by inserting two electrodes into a coal seam and running an electric current between them. The current produced enough heat to coke the coal through which it passed, thus opening a fissure into which air could be introduced to start combustion. Because electrolinked paths were narrower and better integrated into the coal seam than were passages formed by normal mining techniques, they seemed likely to foster more intense, complete reactions of air and coal.

On another section of the Gorgas site, engineers drilled several pairs of boreholes and used electrolinking to establish paths between them. Infusions of air generated small quantities of producer gas that was indeed of much higher quality than the stream method had yielded, and during 1952 test runs with oxygen and steam made synthesis gas. There were many technical problems, such as high heat loss and difficulty in charting the exact locations of the underground passages. However, the outcome suggested that the dream of obtaining energy from coal without any mining at all was feasible.

One other mining-free method of underground gasification was tried at Gorgas. Known as hydraulic fracturing, this technique, recently commercialized by oil-well drillers, involved the injection of pressurized liquids to create or widen fractures within a coal seam. In theory, the fractures could form the nuclei of gasification chambers. In June 1954, an injection well was drilled into a deep portion of a coal seam, and mixtures of petroleum-based fluids and sand were forced underground. Measurements of airflow through the seam showed that the process did create usable pathways, and in February 1955 the researchers began gasifying coal in one section of the affected area.

Underground coal gasification by any method still fell far short of the expectations that surrounded it. It was expensive; site preparation costs were high. It was inefficient; most of the heat and gases that it produced dispersed into the surrounding rock or was lost via leaks to the atmosphere. Whether it could work effectively with different types of coal—or at locations less geologically suitable than Gorgas was—remained to be seen. But in a short time, the Bureau of Mines had demonstrated the viability of the concept in an American setting and had entered the vanguard of research on underground gasification. The significance of this work was confirmed at the First International Congress on the Underground Gasification of Coal, held in Birmingham, Alabama, in February 1952, which showcased the accomplishments at Gorgas.

Creating the Appalachian Experiment Station

As the Synthetic Liquid Fuels Act expanded federal support for research and development on fossil fuels, many people within the government and the energy industries began looking for ways to make the gains permanent. The act was a temporary measure; the technical and economic problems of meeting Americans' rising demand for energy would certainly outlive it. Proposals consequently emerged during the mid-to-late 1940s for a publicly funded research center that could continue to explore fossil fuels, fossil-fuel derivatives, and relationships among them indefinitely, without being tied to the specific agenda and timeline of the synthetic-fuels program.

The logic of locating such a center in a place where the Bureau of Mines already had a presence was clear from the outset, but the final choice emerged only after a lengthy process of review and interstate political competition. Franklin, Pennsylvania, where the Bureau's Appalachian petroleum work was based, initially had the edge; the *New York Times* reported in April 1948 that a subcommittee of the United States House of Representatives Committee on Public Lands favored the establishment of an "oil and natural gas experimental station" there. Sites in Washington State were also seriously considered. By early 1949, however, momentum had swung toward Morgantown. Members of the West Virginia congressional delegation, led first by the indefatigable Jennings Randolph (who left Congress in January 1947) and then by Representatives Melvin C. Snyder and Harley O. Staggers, reiterated their arguments that the state was well suited for energy research.

Prominent residents of Morgantown boosted their cause by offering to donate land for the proposed facility. The local Chamber of Commerce had formed an economic-development subsidiary, the Morgantown Community Association (MCA). An MCA committee, chaired by West Virginia State Geologist Paul H. Price, consulted with the Bureau of Mines and scoured the area for appropriate sites. After examining several possibilities, the committee recommended a

45-acre tract of undeveloped property on Collins Ferry Road, just to the north of the city. The MCA acquired this tract and pledged to transfer it to the federal government without charge.

Bills to establish an "Appalachian Experiment Station" at Morgantown were introduced in both chambers of Congress in April 1949. Outmaneuvering the rival Washington State delegation, Representative Staggers secured a federal authorization of up to $2.6 million for this purpose. The proposal became part of the September 1950 amendments to the Synthetic Liquid Fuels Act, even though Congress stipulated that the mission of the station extended well beyond synthetic fuels to include "research and investigation in the mining, preparation and utilization of coal, petroleum, natural gas, peat, and other materials." Three existing Bureau of Mines programs—the Synthesis Gas Production Laboratories at WVU, the Petroleum Field Office at Franklin, and a mine-safety inspection unit that had existed since September 1944 at Fairmont, West Virginia—were to be consolidated at the new Morgantown location.

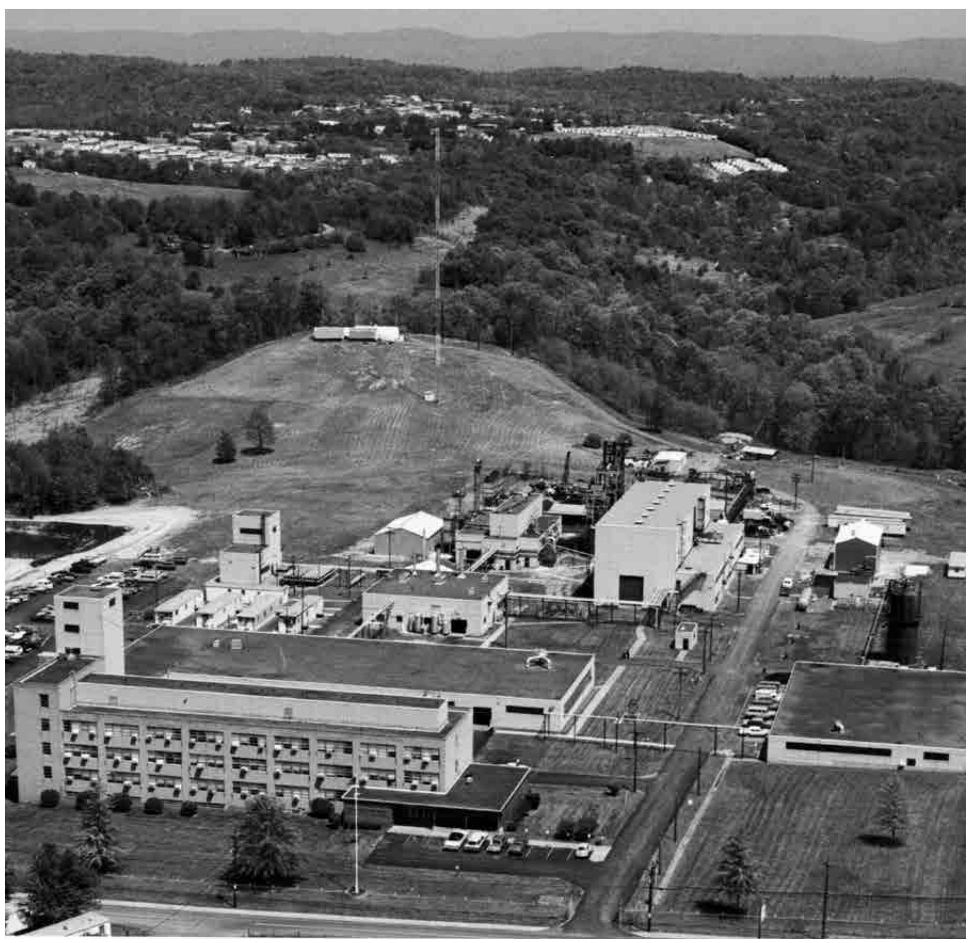
Construction of the Appalachian Experiment Station began in June 1952.

Representative Harley O. Staggers of West Virginia visiting Morgantown in 1949, accompanied by Bureau of Mines officials and local dignitaries. From left to right: West Virginia State Geologist P. H. Price; George R. Strimbeck; Representative Staggers; E. D. Schmidt, head of the Synthesis Gas Branch; A. E. Sands; and Walter L. Hart, editor of the Morgantown Dominion-News. (photo credit: National Archives and Records Administration)

The rolling landscape of the Collins Ferry Road site was swiftly remade into a modern campus for scientific research. Nearest to the road rose the main administrative building, which included offices for the general management of the station and laboratories for the study of petroleum production and coal gasification. A tall structure housed a 1,150-foot-deep experimental well that the Division of Petroleum Technology could use to test methods of oil-well design and operation. Additional specialized buildings were designated for coal-gasification pilot plants, coal preparation, and equipment to supply oxygen for synthesis-gas manufacture.

Sam S. Taylor, the first superintendent of the Appalachian Experiment Station campus at Morgantown.

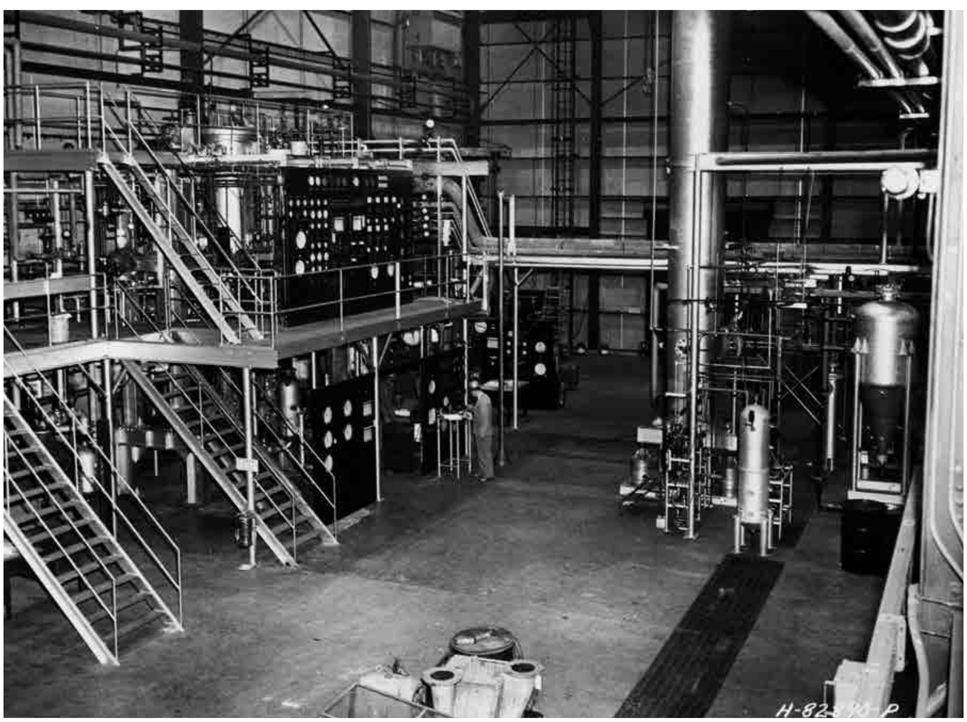
The physical facilities were completed by the end of June 1954, on time and on budget, but the difficult process of moving machinery and personnel without unduly disrupting the work of the Bureau took another year. Of the two coal-gasification pilot plants at WVU, only the high-pressure gasifier made the transition to Collins Ferry Road; the atmospheric-pressure gasifier was dismantled and not rebuilt because Bureau officials decided that this technology was sufficiently advanced that it no longer merited extensive governmental support. Mine inspectors relocated to Morgantown from the Bureau's branch



Panoramic view of the Appalachian Experiment Station site on Collins Ferry Road.

office at Fairmont, which closed in June 1954. They constituted the Morgantown Subdistrict in District C of the Health and Safety Activity, which enforced federal mine-safety laws in fifteen counties across northern West Virginia and Maryland. The final components of the new station came together when the Petroleum Field Office at Franklin, Pennsylvania, shut down in July 1955 and its responsibilities for research on secondary recovery in the Appalachian petroleum fields were transferred to Morgantown. Sam Taylor, who had been the supervising engineer of the Franklin office since 1945, became the first superintendent of the Appalachian Experiment Station.

On May 14, 1955, some 600 people assembled on the grounds of the new station for an official dedication ceremony. Rainy weather obliged them to take cover inside Building No. 2, a cavernous garage that ordinarily contained vehicles and maintenance equipment. There they heard from visiting dignitaries, including Secretary of the Interior Douglas McKay and John J. Forbes, the director of the Bureau of Mines. Jennings Randolph, now working in the private sector as an assistant to the president of Capital Airlines, spoke eloquently about the importance of the station to the future of West Virginia and the country. The very word "research," Randolph argued, had thrilling overtones of mystery and questing, of "reaching out to touch the over there—the beyond." It also had practical implications. "Here in the United States and at Morgantown particularly," Randolph asserted, "the dividends of research and experimentation will include ultimately—and often quickly—better goods, produced at lower unit costs by men and



View of Gasifier No. 3, the first-generation pressurized coal gasifer, after it was moved from its original Beechurst Avenue location to the Appalachian Experiment Station.

women who shall receive higher wages."

Randolph's words captured mid-twentieth-century American confidence that scientific knowledge could solve economic and social problems. The Appalachian Experiment Station illustrated the application of that confidence to energy issues. It was the second-costliest project in the history of the Bureau of Mines, exceeded only by a set of coal-to-liquids demonstration plants in Missouri. It represented an important, if still modest, step toward integrating investigations of petroleum, coal, and synthetic fuels into an overall program of fossil-energy research that could inform federal energy policy.

The new Appalachian Experiment Station at Morgantown represented an important step toward integrating investigations of petroleum, coal, and synthetic fuels into an overall program of fossil-energy research that could inform federal energy policy.

Secretary of the Interior Douglas McKay at the dedication of the new Morgantown station in May 1955.

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

Chapter Eight: Synthetic Liquid Fuels for the
United States, 1944–1955

Fischer-Tropsch coal-to-liquids pilot plant at Bruceton, early 1950s.

Chapter Eight:

Synthetic Liquid Fuels for the United States, 1944–1955

Any reasonable national policy to insure the future of our country in peace or war demands that we develop processes for making liquid fuels from the raw materials known to be available in abundant supply to the point where large-sized plants can be built quickly when the need arises.

--Royd R. Sayers, Director, Bureau of Mines, August 1943

The coal-gasification work at Morgantown was only one element of the many-sided research and development program that the Synthetic Liquid Fuels Act supported. Between 1944 and 1955, the Bureau of Mines built and operated two industrial-scale coal-to-liquids demonstration plants and a comparable oil-shale mining and processing plant. It conducted extensive scientific investigations that probed into the fundamental nature of coal and oil shale and the reactions that converted these solid materials into liquids. The results established the technical feasibility of mass-producing synthetic fuels in the United States. They moved the country a step closer to realizing the vision that energy planners during World War II had outlined, in which the vast domestic deposits of oil shale and coal would function as strategic reserves of fuel for transportation and industrial uses that normally relied on petroleum.

In several respects, the federal synthetic liquid fuels program was a thoroughly American enterprise. The distinctive geographies and geologies of many regions—from the Upper Colorado Valley to the Upper Ohio Valley to metropolitan St. Louis—contributed to its development. As the Bureau worked with methods that had originated in Great Britain and Germany for processing oil shale and coal, it improved them with a characteristically American insistence on making them simpler, faster, and cheaper to facilitate commercial mass production. Ironically, however, the program peaked just as a surge of inexpensive petroleum from domestic and overseas sources in the early 1950s rendered hard-won knowledge of how to turn solid minerals into oil less relevant to the nation's military and economic security.

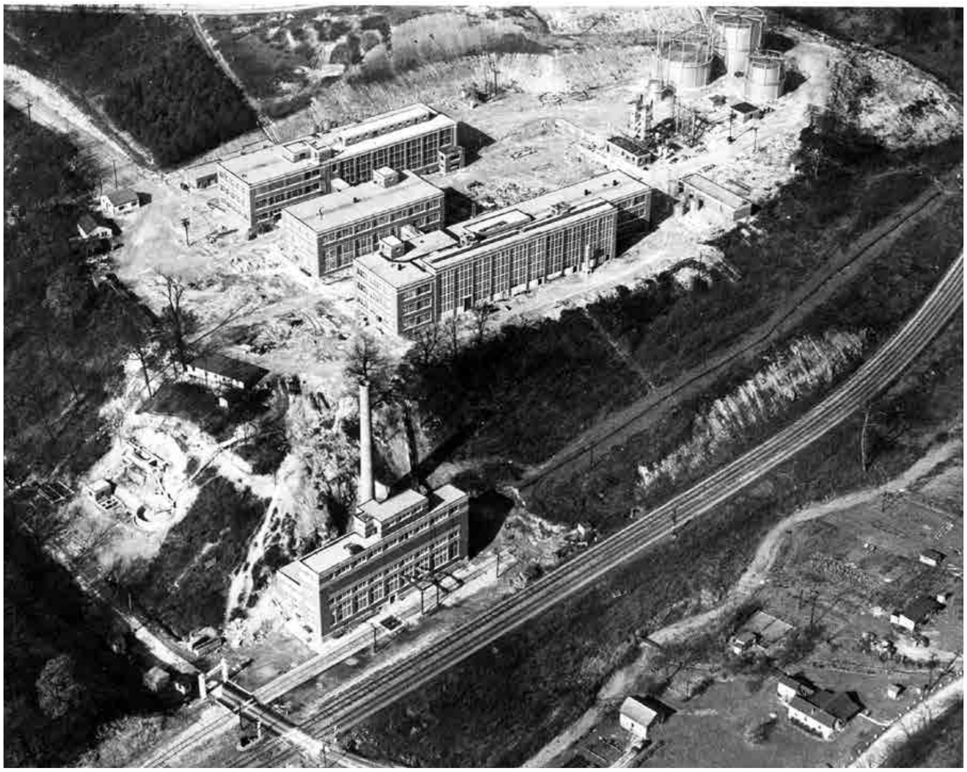
Expansion of Research at Pittsburgh and Bruceton

When the Office of Synthetic Liquid Fuels came into being in 1944, the principal research facilities available to it were the synthetic-fuels laboratories at the Pittsburgh Experiment Station. They were inadequate to accommodate a drastic expansion of activity. Henry Storch, in his new capacity as the director of the Research and Development Division, made clear that he needed far more space for the contemplated larger coal-hydrogenation and Fischer-Tropsch pilot plants—and for all the new people whom he was hiring. The Pittsburgh synthetic liquid fuels staff, which mushroomed from 30 members in 1944 to 100 by April 1946, threatened to overwhelm the station's normal work on mine safety, coal analysis, and industrial problem-solving.

The solution, following the precedent that the Bureau of Mines had established with explosives research, was to move all synthetic liquid fuels operations in Pittsburgh from the central city out to the Bruceton site of the Experimental Mine. Vacant, federally owned land was still available there, and despite encroaching suburban development, the area remained physically isolated enough to minimize conflict with local residents. In November 1945, construction began at Bruceton on a set of buildings that was tailored to the requirements of the Synthetic Fuels Research Branch. Lingering postwar shortages of materials and labor often delayed this $4 million project, which finally reached completion in March 1948.

Built on a high plateau to the north of the Experimental Mine, the new research station covered 12 acres. Three main buildings, arranged in a U-shaped pattern, covered about half of the site. The Coal Hydrogenation Building and the Gas Synthesis Building were parallel but not identical structures, each three stories high and around 300 feet long, constructed of steel with red-brick curtain walls and many tall windows. They provided space for coal-to-liquids pilot plants and laboratories. Between them at the southern end of the property nestled a similarly designed but smaller administration building that included offices, central machine and instrument shops, drafting rooms, and the cafeteria. The atmosphere inside was rigorously utilitarian. "Here the visitor will find no paneled board rooms, no richly furnished offices," the Bureau's official description in 1948 assured the public. "This is a workshop, a research and engineering workshop, designed for efficiency and safety."

Other prominent structures housed support services. Looming up from the bottom of the Lick Run Valley, where the main entrance road crossed the Baltimore & Ohio Railroad tracks, were the boiler house and the coal-preparation plant. On the plateau above, a gas-production plant contained commercial equipment for producing both synthesis gas and pure hydrogen from natural gas. Powerful compressors fed air and inert gases through piping systems that served the various laboratories. Water came from local municipal sources but received additional treatment and distillation before being stored in reservoirs on the rooftops of the main buildings.



Aerial view of the synthetic-fuels laboratories at Bruceton soon after construction. From left to right, the three main buildings on the hilltop are the Gas Synthesis Building, the warehouse and administration building, and the Coal Hydrogenation Building. The main entrance gate is at the lower left, and the combined boiler house and coal preparation plant stands beside the railroad tracks.

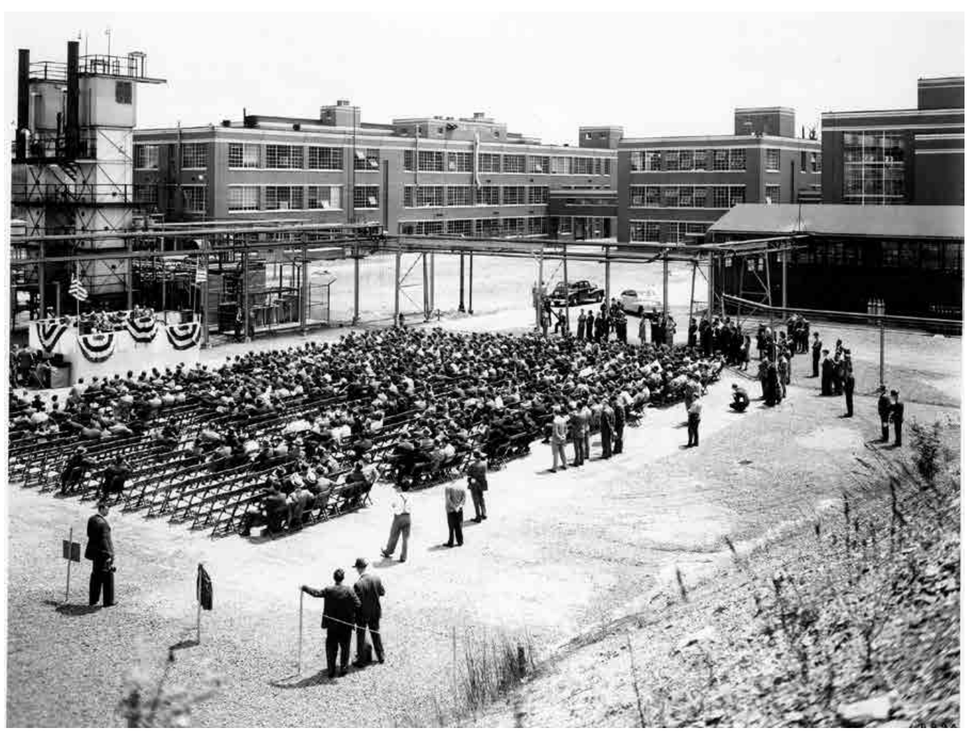
Cafeteria at Bruceton, early 1950s.

The transfer of synthetic liquid fuels research from Pittsburgh to Bruceton took place gradually. In April 1947, the original Pittsburgh coal-hydrogenation pilot plant was dismantled and transported to the Coal Hydrogenation Building. Catalyst testing units and the laboratory-scale Fischer-Tropsch equipment followed within a year. An official dedication was held on May 21, 1948, with some 2,000 people—government officials, executives of coal and petroleum companies, and inquisitive Pittsburghers—attending the ceremony and touring the site.

As the largest, most complex component of the synthetic liquid fuels program, the Bruceton station exemplified the trend of mid-twentieth-century science toward large team projects that required a division of labor among many specialists.

Tragedy struck less than three months after the station was completed. At 6:20 P.M. on August 13, 1948, two chemical engineers, Sidney Weinstein and Robert H. Kallenberger, were wheeling a cylindrical tank full of pressurized hydrogen from the gas-production plant to the Coal Hydrogenation Building. The tank exploded, killing both men. Four other nearby Bureau of Mines employees were slightly injured. According to a news account in the *Pittsburgh Press*, the ferocious blast shattered hundreds of windows, "dug a hole into the concrete pavement . . . and crumpled four 30-foot sections of the wall of the block-long building." The accident was a reminder of the risks that Bureau employees accepted in the course of their normal duties. However, the physical damage and psychological shock that it caused were quickly repaired.

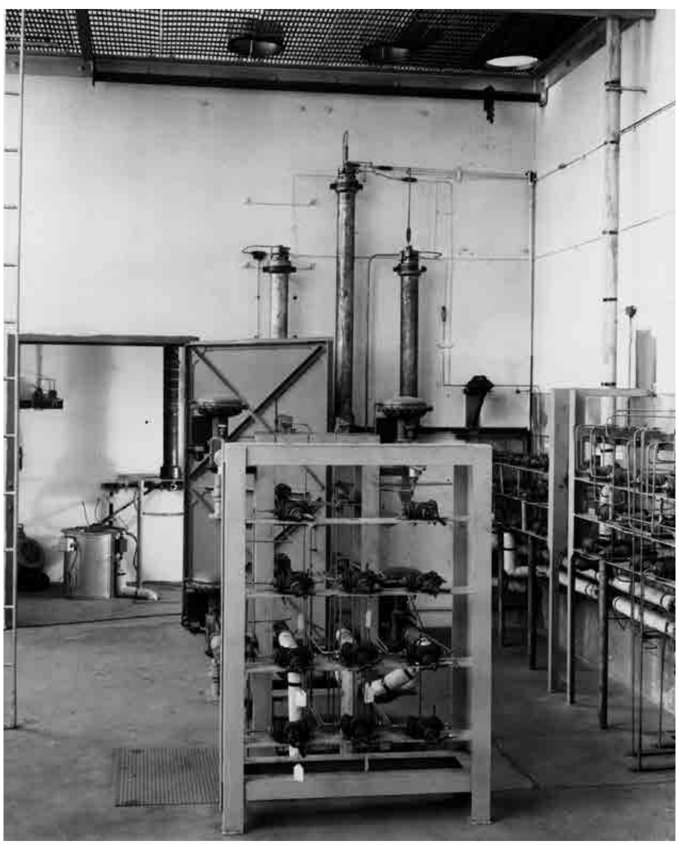
As the largest, most complex component of the synthetic liquid fuels program, the Bruceton station exemplified the trend of mid-twentieth-century science toward large team projects that required a division of labor among many specialists. The number of people who worked there on coal-to-liquids research



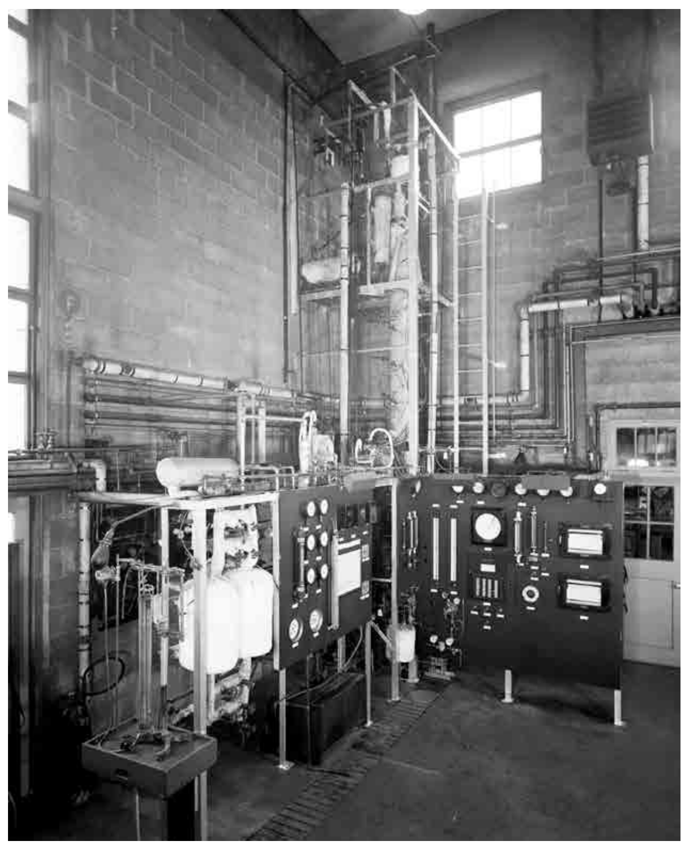
Dedication ceremony for the synthetic-fuels laboratories.

continued to climb, reaching 260 by mid-1953. Henry Storch proved to be a talented manager, adeptly coordinating the placement of new and long-term employees into research groups that matched their skills. Key participants included R. A. Anderson, Sol Weller, and Martin D. Schlesinger, who studied the Fischer-Tropsch process; R. A. Friedel, the head of the Spectroscopy Section; D. Milton Orchin and Irving Wender (a veteran of the Manhattan Project) in the Organic Chemistry Section; and Homer E. Benson, who oversaw the pilot plants.

At Bruceton, engineers tested several variants of the coal-hydrogenation and Fischer-Tropsch processes. A conventional high-pressure coal-hydrogenation pilot plant, yielding up to ten gallons of crude oil and three gallons of gasoline per day, entered service in 1949. The effects of different coals and catalysts, as well as changes in pressure and the length of time that coal stayed in the reactor, were studied with this plant and in smaller, laboratory-scale units. Concurrently, the researchers explored whether they could make fuel oil by hydrogenating coal at moderate pressures below 3,500 psi to reduce energy costs and eliminate the need for expensive, custom-built equipment. They gave particular attention to fluidized hydrogenation, a moderate-pressure process that used dry powdered coal alone instead of the usual messy mixture of powdered coal and heavy oil. A small fluidized-hydrogenation pilot plant was built in 1951.



A small coal-hydrogenation pilot plant and related equipment in the Coal Hydrogenation Building.



The first internally oil-cooled Fischer-Tropsch pilot plant at the Pittsburgh station, as it looked in 1946. (photo credit: National Archives and Records Administration)

Another attractive possibility was to consolidate the two basic stages of the Bergius-I. G. Farben hydrogenation process—the liquid phase and the vapor phase—into a single jump directly from raw coal to gasoline. Laboratory experiments and, beginning in 1954, pilot-plant tests showed that this approach worked in principle but was trouble-prone. Temperature control was tricky, and particles of coal tended to stick together and foul the reactor.

For the Fischer-Tropsch process, the primary engineering challenge was removing the excess heat that the reaction generated. Industrial Fischer-Tropsch plants in Germany had elaborate external cooling systems that ran pressurized water through steel plates or tubes in close proximity to fixed beds of catalyst. These systems were inefficient; they required too much steel and too much energy. By the late 1940s, American companies had developed an improved technology that used a fluidized-bed reactor equipped with heat exchangers. The Bureau of Mines research program focused on alternative solutions that German engineers had investigated during the war years, chiefly the oil-circulation process and the oil-catalyst slurry process.

The oil-circulation process, which became the main focus of the work at Bruceton, addressed the heat problem by submerging the catalyst bed directly in cooling oil. A constantly recirculating flow of coolant was pumped into the bottom of the reactor along with the incoming synthesis gas and moved upward, conducting heat away as it exited near the top and passed through a heat exchanger. Preliminary engineering studies of this process were done at the Pittsburgh Experiment Station from 1944 to 1946, and the first small oil-cooled reactor was built there. In 1948, the Fischer-Tropsch research program migrated to the new Gas Synthesis Building at the Bruceton site, and in 1951 a larger oil-cooled pilot plant that could turn out one barrel of synthetic oil per day came on stream. Tests indicated that this design effectively held the temperature inside the reactor at the proper level to optimize the output of liquid fuels while discouraging the formation of unwanted gases such as methane.

A distinctive Bureau of Mines modification was the "jiggling bed" oil-cooled reactor. This innovation came about in response to a stubborn difficulty: Particles of catalyst cemented themselves into uneven clumps, making them less active in promoting the Fischer-Tropsch synthesis and blocking the flow of coolant. By increasing the velocities of the incoming synthesis gas and coolant, the catalyst particles could be kept agitated just enough to prevent them from agglomerating. The gentle agitation was quite unlike the rapid, boiling motion of a fluidized bed; Bureau engineers called it a jiggle, and the humorous name stuck.

The oil-catalyst slurry process was a variation on the theme of cooling a Fischer-Tropsch reactor internally with a flow of oil. In this design, very fine particles of catalyst were suspended within the coolant, and the resulting mixture of solid and liquid—a slurry—circulated through the reactor, removing heat when it passed through a heat exchanger. A small slurry pilot plant at Bruceton was erected in 1948, and a larger 5-gallons-per-day unit followed in 1950. Simple and versatile, this process proved to be especially well suited for making alcohols from synthesis gas. However, as the Bureau's final report on synthetic liquid fuels research noted, the slurry plants also suffered from "unpredictable erratic behavior," often because the slurry tended to break up as solid particles settled out of the liquid coolant.

On the purification of synthesis gas, research conducted at Bruceton overlapped to some extent with the interests of the Synthesis Gas Branch at Morgantown. Researchers at both stations aimed to reduce the time and expense involved in removing impurities that could damage Fischer-Tropsch catalysts. Bruceton's major contribution was an economical process for ridding synthesis gas of carbon dioxide (CO_2) by applying a solution of hot potassium carbonate under pressure. A direct outgrowth of this research was the Benfield process—named for its inventors, Homer Benson and Joseph Field—of using activated hot potassium carbide to remove CO_2 and other acidic gases during the manufacture of industrial chemicals such as ammonia. Benson and Field left the Bureau in the early 1960s to start their own company, and the Benfield process was subsequently commercialized and licensed worldwide.

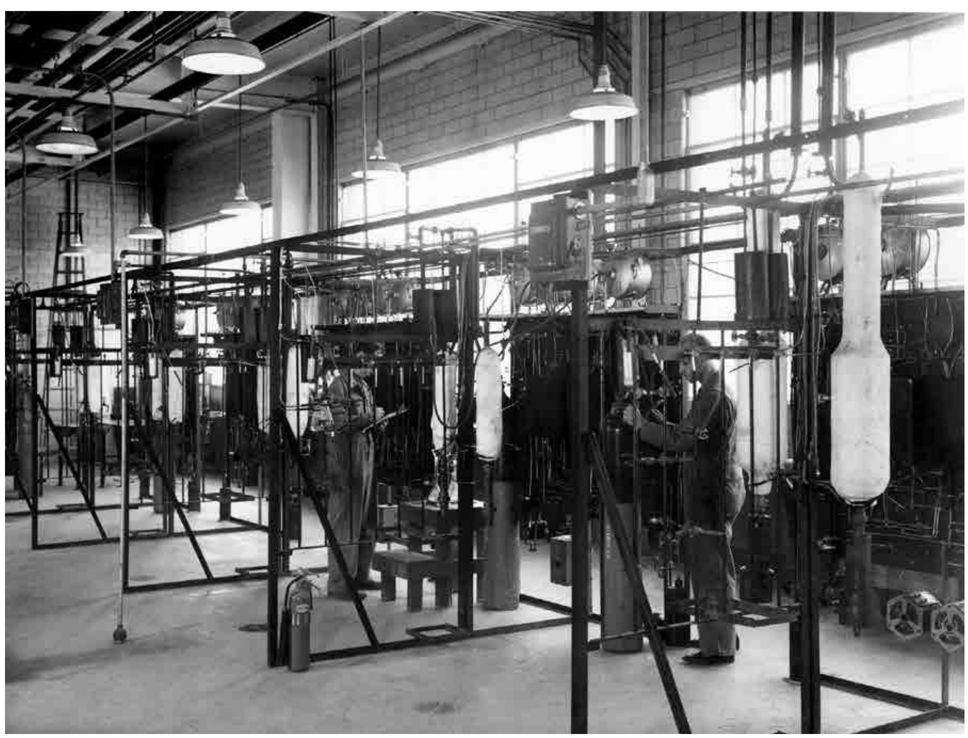
Chemical engineers—including the inventors of the Benfield process—and Bureau of Mines officials assembled at Bruceton to receive a Department of the Interior Incentive Award in October 1957. Front row, left to right: Homer E. Benson; Robert B. Anderson, chief of the Branch of Coal-to-Oil Research; Acting Regional Director Earl P. Shoub; and Joseph H. Field. Back row, left to right: Daniel Bienstock; J. S. Tosh; G. E. Johnson; R. M. Jimeson; and W. P. Haynes. (photo credit: National Archives and Records Administration)

Catalyst preparation and analysis was vital to process-development work. For Fischer-Tropsch reactors, cobalt was the most effective catalyst; for coal hydrogenation, tin worked best. But cobalt and tin were expensive, relatively scarce worldwide, and not present in commercially significant quantities within the borders of the United States. Identifying cheaper, more plentiful catalysts was therefore another prerequisite for the establishment of an American coal-to-liquids industry. Using standardized apparatus to obtain consistent data, the catalyst laboratory at Bruceton sampled dozens of potential substitute materials, subjecting each to weeks of testing that assessed its activity and durability. Promising catalysts were further examined in laboratory-scale reactors and the pilot plants.

Steel lathe turnings proved to be effective as catalyst material for experimental Fischer-Tropsch reactors. (photo credit: National Archives and Records Administration)

By far the most suitable catalysts for the mass production of synthetic liquid fuels from coal were iron compounds, which the Germans had employed. Many Bureau of Mines experiments on the Fischer-Tropsch process used a commercially available iron catalyst that had been invented for the manufacture of synthetic ammonia. Bureau engineers achieved good results in Fischer-Tropsch reactors with iron catalysts derived from commonplace industrial materials: iron-oxide byproducts of steel and aluminum production, steel lathe turnings, and even iron or steel shot. Ferrous sulfate proved to be an acceptable catalyst for the liquid phase of coal hydrogenation.

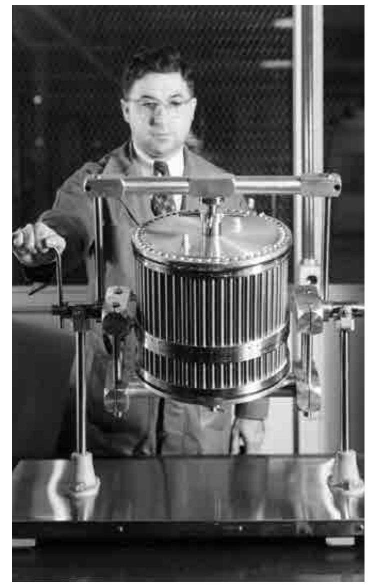
A special assignment for the Bruceton chemical engineers was to replicate a complex catalyst known as K-536 that their German counterparts had developed for the vapor phase of coal hydrogenation. Made by adding a combination of molybdenum, chromium, zinc, and sulfur to certain kinds of clay, this catalyst had barely entered industrial use when World War II ended. It marked



Fischer-Tropsch catalyst-testing laboratory at Bruceton.

an important advance because it made possible the production of aviation-grade gasoline in a single vapor-phase step, in contrast to the multiple steps that had characterized earlier forms of that process. In 1952, the Bruceton team succeeded in reproducing the K-536 formula.

Not all of the Bureau's catalyst research targeted specific engineering problems. Chemists and physicists also conducted fundamental investigations, using tools that embodied decades of revolutionary change in analytical chemistry. Since the early twentieth century, magnetic analysis, X-ray diffraction, mass spectrometry, and infrared and ultraviolet spectrometry had all come into widespread use. Yet these techniques had seldom been comprehensively applied to coal-to-liquids processes. European scientists, preoccupied with learning how to increase commercial synthetic-oil yields, had often underinvested in basic research. With the luxuries of time, state-of-the-art instruments, and ample funding, the laboratories at Bruceton compiled much-needed data on the physical properties (such as surface area) and the behavior of catalysts.



Countercurrent distribution apparatus, used for separating and identifying the products of coal-conversion reactions.

Basic research cast new light on the nature of the coal-hydrogenation and Fischer-Tropsch reactions. For example, the Bureau's findings contributed to a long-running debate about the chemical reactions involved in liquefying synthesis gas. Scientists had observed that during the Fischer-Tropsch process, synthesis gas reacted with metal catalysts to form carbide compounds. A theory had developed that the carbide compounds were important intermediate steps in the creation of liquids. By correlating data obtained from multiple types of analysis, researchers at Bruceton added to a growing and persuasive body of evidence that cast doubt on this theory. Building upon research that the Bureau had initiated in the 1920s, they proposed an alternative explanation that pointed to oxygenated compounds, such as cobalt carbonyl or iron carbonyl, as key intermediates in the formation of alcohols and liquid hydrocarbons through the Fischer-Tropsch synthesis and other, similar chemical reactions.

Equally painstaking inquiry was directed at the end results of coal-to-liquids reactions. Both coal hydrogenation and the Fischer-Tropsch process yielded intricate arrays of gases, liquids, and solids, the exact chemical makeup of which was hard to determine. Three distinct laboratories at Bruceton worked on isolating and identifying these products: the precision distillation laboratory, the spectrometric laboratory, and the organic-chemistry laboratory. An example of their work was the use of countercurrent distribution to analyze tar-acid byproducts that were possible sources of industrial chemicals. This technique was often the best—and sometimes the only—known way to separate tiny quantities of very closely related organic substances.

As an outgrowth of their research on catalysts, reactions, and products, the Bruceton laboratories devised statistical methods for predicting the distribution of various hydrocarbons and hydrocarbon isomers (alternative structures of a molecule) in the output of synthetic liquid fuels processes. The most notable and widely used method of this type became known as the Anderson-Schulz-Flory distribution, which applied specifically to the products of the

Fischer-Tropsch synthesis but was also of interest to scientists who studied polymerization in general.

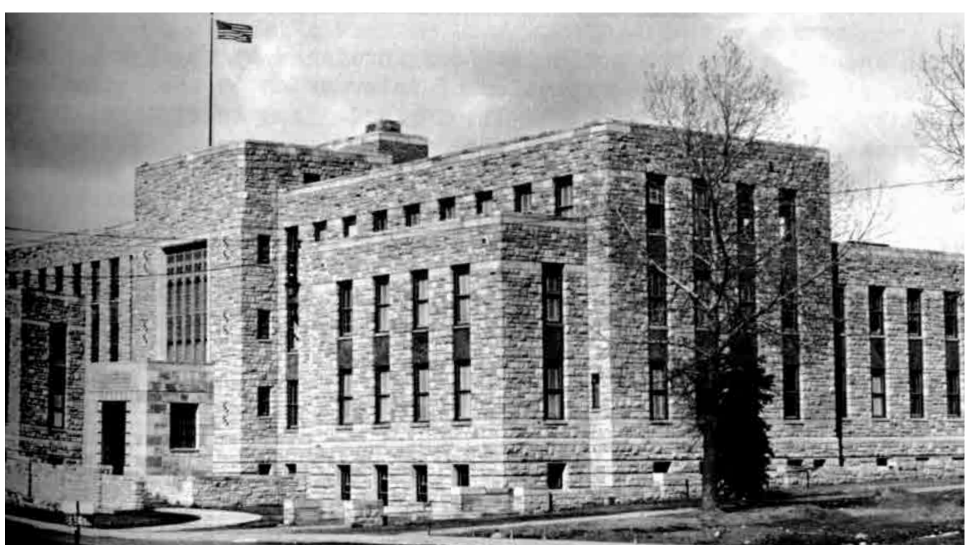
The Bruceton station was the principal storehouse of theoretical and practical knowledge for the synthetic liquid fuels program. It reviewed German coal-to-liquids practices and adapted them to American priorities. It provided technical assistance to other Bureau of Mines research stations, as when it cooperated on studies of shale-oil hydrogenation during the early 1950s. Above all, the information that the Bruceton staff developed through its systematic investigations advanced the scope and sophistication of American coal chemistry.

The information that the Bruceton staff developed through systematic investigations advanced the scope and sophistication of American coal chemistry.

Expansion of Research at Laramie

The Office of Synthetic Liquid Fuels established a third concentration of research activity to revive the dormant federal oil-shale program. Overseen by the Oil-Shale Research and Demonstration Plant Branch, which was created in 1944 under the direction of R. A. Cattell, this group picked up where its forerunners in the 1920s had left off. In 1945, the Bureau of Mines designated the University of Wyoming at Laramie as its headquarters for oil-shale investigations.

Since 1924, the Laramie station had been a field office of the Bureau's Petroleum Branch, working under cooperative agreements with the university staff and local industries to improve petroleum production in the Rocky Mountains. Following a brief shutdown early in the Great Depression, it had become a full-fledged Petroleum Experiment Station in 1935, and had participated in the development of aviation fuels during World War II. The University of Wyoming, like the West Virginia University, was eager to join in the postwar synthetic liquid fuels program and agreed to donate land to the Bureau for the construction of a research center that would study oil shale as well as petroleum.



View of the Petroleum and Oil-Shale Experiment Station at Laramie. (photo credit: Bureau of Mines publication)

Opened in the spring of 1947, the renamed Petroleum and Oil-Shale Experiment Station occupied an entirely new building that bordered the university campus. This structure housed 33 well-equipped laboratories; one of them had what was then the only operational mass spectrometer anywhere in the Rockies, and another was an engineering laboratory in which researchers could erect small pilot plants. Offices, fabrication and maintenance shops, and storage rooms for oil-shale samples were included. Of the initial 100 technical employees at the expanded station, 75 were assigned to the oil-shale program, reflecting the Bureau's intense focus on synthetic fuels research. Only 25 continued to carry forward Laramie's well-established program of petroleum research, which centered on studies of regional oil fields, primary and secondary oil recovery, and ways to reduce the high sulfur content of crude petroleum from Rocky Mountain wells.

Research at Laramie responded to a great need for basic chemical and physical analysis of oil shale and the products that could be obtained from it.

Research at Laramie responded to a great need for basic chemical and physical analysis of oil shale and the products that could be obtained from it. The chemical composition of kerogen, the complex organic material in oil shale, remained mysterious. During the late 1940s and the early 1950s, the Laramie station assayed thousands of shale samples on behalf of the Bureau, the U.S. Navy, and private companies. Led by H. M. Thorne (a senior engineer with the Oil-Shale Research and Demonstration Plant Branch) and Supervising Engineer H. P. Rue, staff members compiled data on variations in the kerogen content and oil yield of different deposits. They improved methods for separating kerogen from inorganic matter and decomposing the kerogen into its constituent parts so that it could be examined more closely.

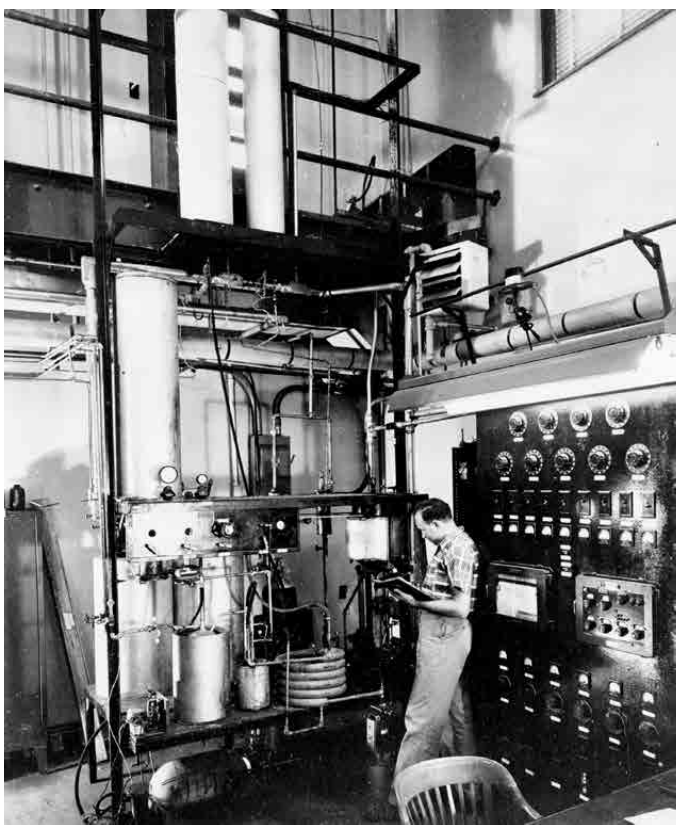
A related, and especially important, aspect of this work was examination of how heat transformed kerogen during the retorting process. Existing oil-shale retorts shared a common limitation: None had demonstrated the ability to turn more than two-thirds of the kerogen in any given shale sample into liquid oil. Attempts to increase shale-oil yields had foundered because scientists lacked understanding of the solid-to-liquid conversion reaction, and because, as several engineers at Laramie wrote in 1951, "few data have been available on the quantity of heat required to retort an oil shale." To help fill these gaps, Bureau engineers conducted small-scale retorting experiments that measured heat requirements under varying conditions. The results indicated that conversion was very fast and took relatively little thermal energy.

Informed by these findings, the researchers looked for ways to increase oil output while further minimizing energy use. Entraining very small shale particles in a stream of gas and bringing them rapidly to high temperatures was identified as a likely avenue for future development. Another option was thermal solution, a possible alternative to conventional retorting. The thermal-solution process involved heating a mixture of pulverized shale and shale oil in a pressurized reactor.

Scientists and engineers at Laramie also studied the composition of shale oil. Their inquiries verified that, compared to petroleum, this oil contained higher proportions of sulfur compounds, nitrogen compounds, and unsaturated hydrocarbons that made its distilled products less chemically stable and less amenable to conventional refining methods. Shale naphtha and shale gasoline, for example, had the unwelcome habits of discoloring quickly and forming gummy residues. In consequence, applying catalytic cracking processes directly to shale oil was impractical. Extra steps, such as hydrogenation or treatment with solvents to remove undesirable chemicals, were necessary to prepare the oil for further upgrading into high-quality liquid fuels.

Oil shale mattered strategically not only as an alternative source of liquid fuels but also as a potential reservoir of essential chemicals for the American manufacturing industry.

Oil-shale byproducts other than liquid fuels received attention, particularly after the outbreak of the Korean War in June 1950 spurred economic growth and increased demand for organic chemicals. The Bureau determined that asphalt and paraffin wax could be produced from the oil shales of the Green River Formation in the Rockies. Shale tars could serve as feedstocks for the manufacture of substances that were crucial to the plastics and synthetic-rubber industries. Experiments at the Laramie station showed that byproduct gases from oil shale that was retorted at high temperatures abounded in ethylene, benzene, naphthalene, and other industrially important hydrocarbons that were in short supply. Such findings indicated that oil shale mattered strategically not only as an alternative source of liquid fuels but also as a potential reservoir of essential chemicals for the American manufacturing industry.



Laboratory equipment for processing shale oil at the Laramie station. (photo credit: National Archives and Records Administration)

Like its counterparts at Morgantown and Bruceton, the staff of the Petroleum and Oil-Shale Experiment Station was strongly oriented toward applied research. Even its inquiries into the basic physical and chemical properties of oil shale had the ultimate purpose of guiding the engineers who would fulfill Congress's mandate to build demonstration plants for testing large-scale production of synthetic liquid fuels. Work in the laboratories and in the field proceeded in tandem, with frequent back-and-forth communications between the experiment stations and the demonstration sites. As early as 1947, the program showed results as significant quantities of synthetic oil began flowing from Bureau of Mines facilities.

The improvement of mining techniques was a main focus of the Oil-Shale Experiment Station.

Putting it Together: Demonstration Plants on the Mississippi and in the Rockies

The first large-scale demonstration plant built under the Synthetic Liquid Fuels Act mined, retorted, and refined oil shale. For this component of the program, the Bureau of Mines returned to the scene of its prewar oil-shale experiments: the rugged cliffs and canyons of the Green River Formation in northwestern Colorado. Bureau officials surveyed potential sites on Naval Oil Shale Reserve lands during the closing months of 1944 and chose to locate an Oil-Shale Experiment Station at Anvil Points, near the small Colorado River town of Rifle. Anvil Points lay within the Piceance Creek Basin, which governmental and private studies had consistently identified as the area with the best potential for commercial exploitation of Green River shales.

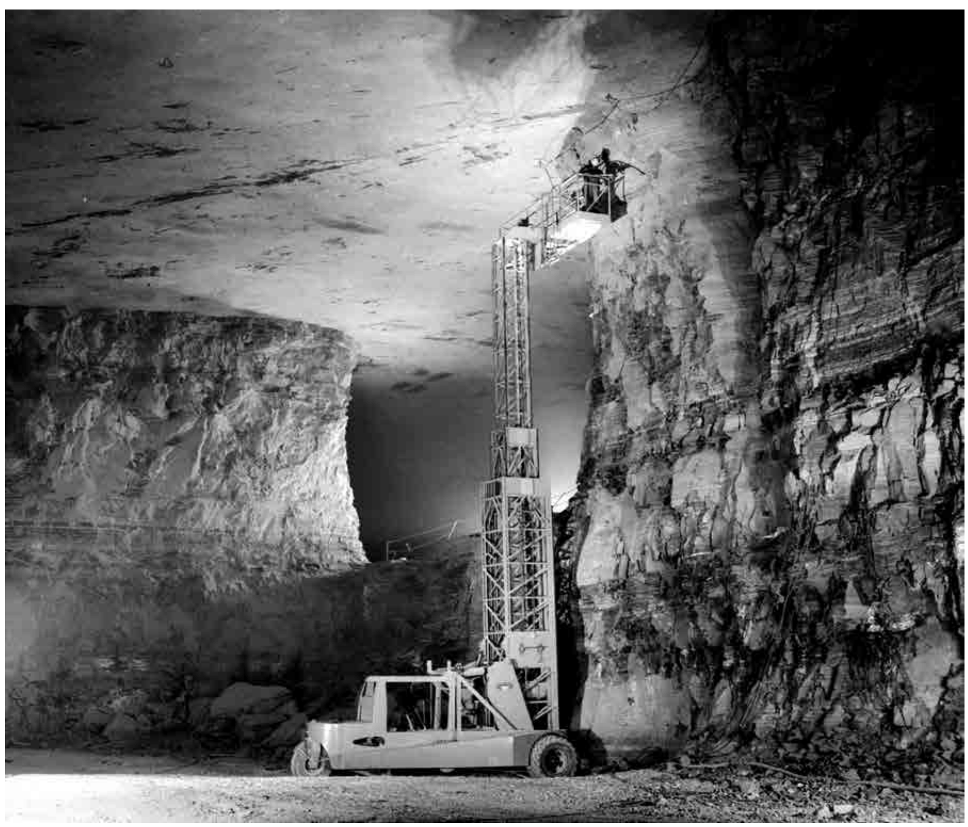
The improvement of mining techniques was a main focus of the Oil-Shale Experiment Station. Before World War II, scientists and engineers had concentrated on extracting usable oil and had paid little attention to oil-shale mining. That balance of priorities changed in the 1940s as the importance of lowering mining costs was recognized. In 1945, the Bureau's Oil Shale Mining Branch set the ambitious goal of obtaining oil shale from the Piceance Creek deposits at a price of 50 cents per ton—a rate that many mining experts at the time thought was impossible to achieve. Mining engineers at Anvil Points succeeded in driving the price down to 29 cents per ton within five years by systematically applying the latest advances in mine mechanization.

Mining at Anvil Points took place in two distinct quarries, both situated near the top of a sheer escarpment about 8,200 feet above sea level. The Selective Mine opened in 1946 to supply high-quality oil shale for initial retorting and refining trials, and to provide space for experimentation with new mining technologies. It remained active until 1949, when the far larger Underground Quarry succeeded it. Five and a half miles of paved switchback roadway, plied regularly by buses and heavy diesel-powered trucks, connected these mines to the valley almost 3,000 feet below.

In the Underground Quarry, low-cost methods that had originated in open-pit surface mining were adapted to an underground setting. The quarry consisted of huge subterranean rooms, each 60 feet square and at least 22 feet high, arranged in "benches" or terraces that stepped downward through the shale bed. Staggered pillars of intact shale, also measuring 60 feet square and extending over 70 feet high, separated the rooms and supported the roof. This layout was carefully determined on the basis of experiments conducted at the Bureau's Pittsburgh and College Park stations, Columbia University, and a test section of the on-site Selective Mine to verify that the roof stone could span large openings without risk of collapse. It allowed large trucks, bulldozers, and electric shovels to enter and exit without difficulty and to work several exposed faces of the shale bed simultaneously.

The quarry consisted of huge subterranean rooms, each 60 feet square and at least 22 feet high, to allow large trucks, bulldozers, and electric shovels to enter and exit without difficulty and to work several exposed faces of the shale bed simultaneously.

Every aspect of quarry operation took full advantage of machinery that saved labor and increased output. Mobile drilling rigs, created by mounting four separate pneumatic drills at the rear of a truck, reduced the number of workers and the amount of time required to prepare a section of the shale bed for blasting. The drills initially could not go more than five feet into the hard shale before they became dull and had to be withdrawn for sharpening, but the Bureau collaborated with makers of mining equipment to devise a new tungsten-carbon drill bit that retained its edge for up to 70 feet. Mechanical lifting



Interior view of the Underground Quarry oil-shale mine at Anvil Points, Colorado, showing the tall-ceilinged rooms carved out of the rock . (photo credit: National Archives and Records Administration) platforms were developed to raise and lower the miners who had the dangerous jobs of setting the blasting charges and inspecting the walls and roof of the quarry. Together, these and other innovations allowed the Underground Quarry to turn out vast amounts of broken oil shale—322,000 tons during the first three years of operation—rapidly and inexpensively.

The retorting plant that drew oil from the shale evolved through several stages. Two N-T-U retorts, the same type that the Bureau of Mines had used at the nearby Rulison site in the 1920s, were the first production units built at Anvil Points. This familiar technology allowed shale-oil manufacturing to get underway by May 1947 so that the researchers had a supply of oil for analysis and could resume investigating the effects of varied operating conditions on the quantity and quality of the output. However, Bureau engineers had already concluded that in order to mass-produce shale oil, they needed a retort with greater capacity and efficiency, one that could run continuously (instead of batch-by-batch, as the N-T-U retort did) and that permitted better temperature control as the shale was heated. Of several possibilities that they explored, the most promising was what became known as the Bureau of Mines gas-combustion process.

Like the N-T-U retort, the gas-combustion process relied on internal combustion. The heat that converted solid kerogen to liquid oil came from burning a mixture of gases and carbon residue from the shale inside the retort. Raw shale entered a cylindrical reactor at the top and moved downward by gravity, gaseous fuel—which, after the initial startup, consisted mostly of recycled byproducts from the process—rose from the bottom, and combustion took place near the center. Hot exhaust gas traveled upward, increasing the temperature of the incoming shale until gases and vapors of liquid oil formed. After condensing into a fine mist near the top of the reactor, the liquid exited in the exhaust stream and was recovered as it passed through several separating devices. Waste shale was removed automatically, thus permitting continuous operation, and neither the reactor nor the waste required water cooling (a major advantage in an arid region).

This approach was innovative in its use of the exhaust flow to create and transport oil mist. In an N-T-U retort, such mist was a nuisance; most liquid oil was drawn off at the base of the reactor, and oil vapor that remained in the exhaust became a useless, hazardous pollutant—as the oily fogs that had regularly engulfed the Bureau's nearby Rulison site in the 1920s attested. In a gas-combustion retort, by contrast, the oil-laden exhaust was central to the process. Chemical engineers extensively studied shale-oil mist, trying to optimize the conditions that caused misting in the retort and to improve the subsequent removal of the liquid oil from the gases that carried it.

Simple, thermally efficient, and reliable, the gas-combustion process gradually superseded the N-T-U process as the mainstay of the Anvil Points works during the early 1950s. The first retort of this design, a small experimental unit that could handle six tons of shale per day, began operation in 1949. A pilot plant with a capacity of 25 tons per day followed in 1952, and in 1953 a much larger, 150-ton-per-day demonstration plant was completed. The 150-ton version was expressly designed to provide cost data that could be used to estimate the expense of building and operating a commercial shale-oil facility.

Tourists passing by on U.S. Route 6 were invited to take a bus trip up the switchback road to view the Anvil Points Underground Quarry and then back down to the retorting plant to watch the extraction of oil.

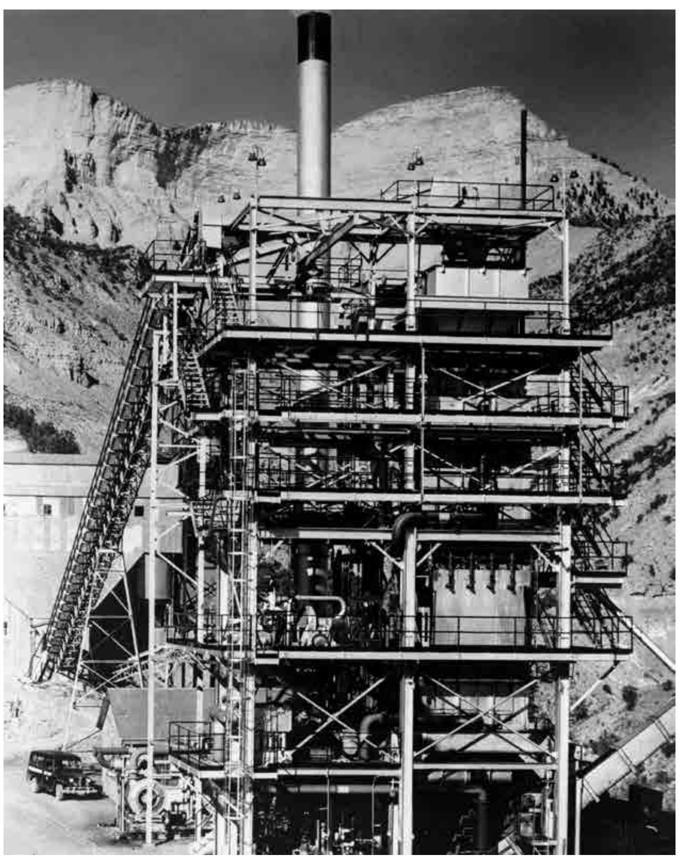
Initially, the Oil-Shale Experiment Station did not have its own refining capability. Early samples of its crude shale oil had to be sent elsewhere for further processing. This situation changed during the summer of 1949, when a demonstration refinery with a capacity of 200 barrels per day became operational at Anvil Points. As described by two Bureau of Mines staff members, the facility was "designed on the smallest scale that could retain features and equipment found in standard petroleum refining practice and give data that could be extrapolated readily to large size operations."

The Anvil Points refinery featured a distillation cracking plant that divided crude shale oil into fractions equivalent to petroleum products—such as naphtha, gasoline, and diesel fuel—and could also perform thermal-cracking and reforming processes to overcome the oil's many practical shortcomings. For example, shale oil was too thick to send through pipelines until it underwent a process called visbreaking, which reduced the viscosity of the oil so that it could flow more easily, and also boosted its otherwise low yield of valuable light- and middle-grade hydrocarbons such as gasoline. Furthermore, a chemical treating plant removed tars and decreased the troublesome sulfur and nitrogen compounds. Refined shale-oil products provided satisfactory fuel for the station's motor vehicles and mining equipment, and the Denver & Rio Grande Railroad reported good results from tests of shale diesel in locomotives.

Based on experience at the Oil-Shale Experiment Station, Bureau of Mines engineers calculated in 1951 that a profitable "industry scale" works capable of supplying 250,000 barrels of shale oil per day was feasible in the Green River Formation. Such a facility would require mines with a total output of more than 21 times the volume of the Underground Quarry. Crushed shale would be processed in sets of gas-combustion retorts, whose excess byproduct gas could be used for fuel and to generate electrical power. After preliminary refining on-site, shale oil would travel via a 710-mile pipeline to terminals at Los Angeles, where existing petroleum companies could finish turning it into salable products. The plan would require a total investment of roughly $872 million in 1951 dollars—and the resulting shale gasoline could have a wholesale price as low as $1.50 per barrel and 12 cents per gallon, similar to the contemporary price of gasoline made from petroleum.

Such upbeat assessments of the prospects for oil shale were common as the 1950s began. It was widely assumed that the first synthetic liquid fuels to reach the U.S. consumer market would be derived from shale, and that the Green River Formation was finally becoming a true energy reserve. So confident was the Bureau in the oil-shale program that, beginning in mid-1949, it relaxed its security precautions and opened the Anvil Points site to public inspection. Tourists passing by on U.S. Route 6 were invited to take a bus trip up the switchback road to view the Underground Quarry and then back down to the retorting plant to watch the extraction of oil. According to a *New York Times* reporter, the journey was worthwhile for both the fabulous mountain scenery and the chance to observe a piece of industrial history in the making: "the mammoth plant that may alter the national economy by wringing oil from solid rock."

A parallel effort to wring oil from coal unfolded half a continent away, in the Mississippi Valley. On May 8, 1949, almost 20,000 people gathered near the riverside town of Louisiana, Missouri, roughly a hundred miles north of St. Louis. The focus of their attention was the Missouri Ordnance Works, a U.S. Army arsenal. During World War II, this site had made synthetic ammonia. Now the Coal-to-Oil Demonstration Branch of the Office of Synthetic Liquid Fuels was retooling it to manufacture liquid fuels from coal. Twin demonstration plants were rising there: one to use the Bergius-I. G. Farben coal-hydrogenation process, the other to use the Fischer-Tropsch gas synthesis. The coal-hydrogenation plant had already generated enough synthetic diesel fuel to power a special Chicago, Burlington & Quincy Railroad train that brought visiting dignitaries from St. Louis to Louisiana for the official dedication of the site.

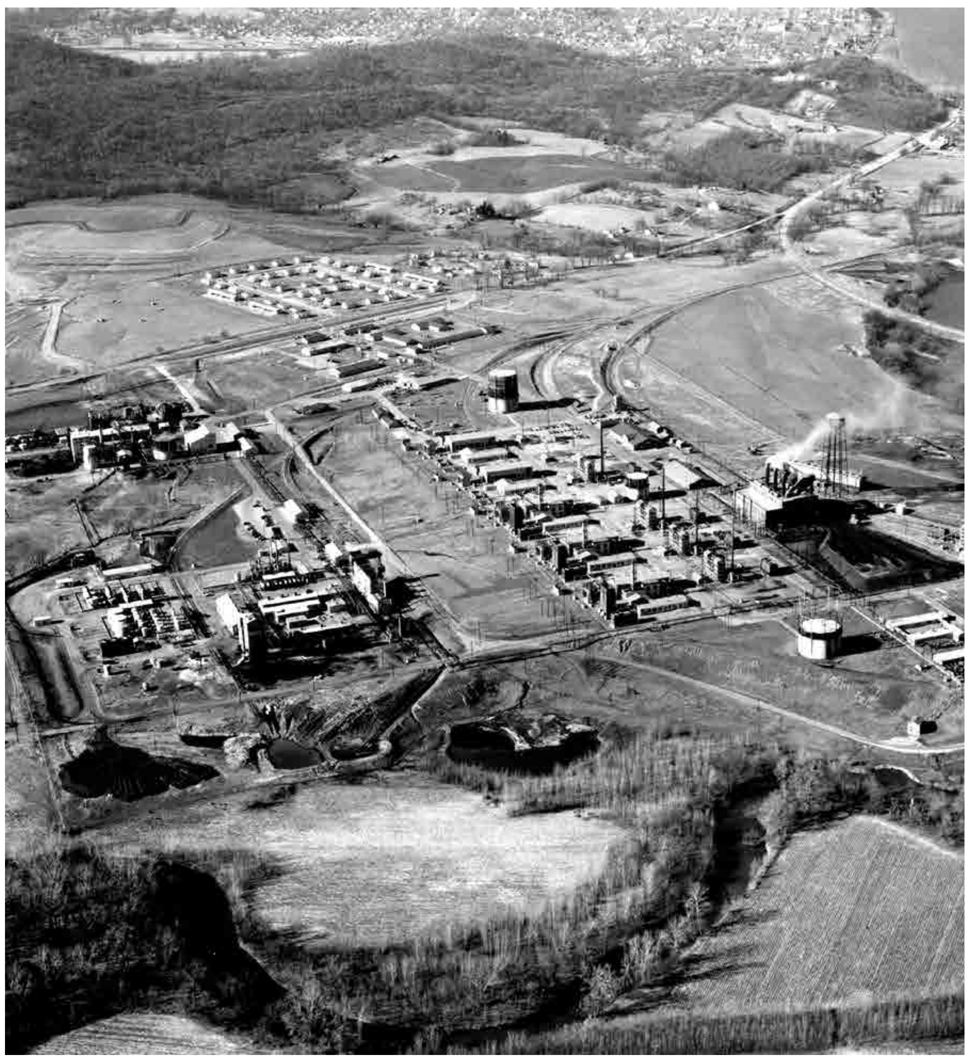


Gas Combustion Retorting Plant No. 3 at Anvil Points. (photo credit: National Archives and Records Administration)

Loading synthetic gasoline made from oil shale. (photo credit: National Archives and Records Administration)

Secretary of the Interior Julius A. Krug spoke at the dedication ceremony. In keeping with this fourth anniversary of the end of World War II in Europe, he emphasized the national-security implications of the project. "Foreign oil is not sure oil in time of war," he reminded the audience. He urged American companies to move swiftly toward establishing a viable synthetic liquid fuels industry. Lester L. Hirst, the chief of the Coal-to-Oil Demonstration Branch, noted that the facility at Louisiana was meant to help do just that. As Congress had envisioned, it would translate the findings of research at Pittsburgh, Bruceton, and Morgantown into practical terms to guide private investment decisions. "Our task is . . . to operate these plants and to improve the processes so that commercial plants may be built at the earliest opportunity," Hirst affirmed.

Planning for the coal-to-liquids demonstration plants had always been integral to the Synthetic Liquid Fuels program. Krug's predecessor, Secretary Ickes,



Aerial view of the Missouri Ordnance Works site at Louisiana, Missouri. The Mississippi River is at the upper right. The original synthetic-ammonia plant is at the center; the synthetic liquid fuels demonstration area is to the left. (photo credit: National Archives and Records Administration) had gained the right to use the Missouri Ordnance Works in 1945 after the Army indicated that the property would not be needed for postwar ammonia production. The location was ideal for the purpose. It had good rail access to every major coal-mining district in the country, and so was politically acceptable to Easterners and Westerners alike. It contained equipment for generating and compressing hydrogen. With utility lines and other infrastructure already in place, site-preparation costs were modest.

The coal-hydrogenation plant was the first part of the Louisiana works to be completed. Designed by the San Francisco-based Bechtel Corporation and constructed between April 1947 and February 1949, it could produce 200 barrels of gasoline per day. The several stages of coal-to-liquid manufacturing at this plant were brought on stream in reverse order, beginning with the distillation units for turning synthetic crude oil into motor fuels and ending with the machinery for pulverizing and liquefying coal. Using an Oklahoma City crude petroleum that approximated the oil derived from coal, Bureau of Mines engineers conducted trial runs of the distillation units in late 1948. They then gradually started the hydrogenation units during 1949, with petroleum and coal-tar oil as the initial feedstocks. Not until November 24, 1949, did the plant make oil from raw coal.

Coal hydrogenation at Louisiana took place in one liquid-phase unit and one vapor-phase unit. In the liquid phase, a conventional mixture of coal powder, heavy oil, a tin or iron catalyst, and a small dose of hydrogen passed through a preheater. Its temperature rose incrementally to over 400 °C while more hydrogen was added. The paste next entered two massive converters, each of which was 39 feet tall and weighed roughly 105 tons. There it reacted with yet more hydrogen at the extraordinarily high pressure of 10,000 pounds per square inch (psi). That reaction created more than enough heat to increase the operating temperature to 477 °C. Finally, the resulting hot output underwent the complicated process of "letting down," in which the pressure was reduced as gases, liquids, and solids were separated.

A blend of synthetic oils from the liquid phase became the feedstock for the vapor phase. This second step closely resembled the first. The oil was combined with hydrogen, stepped back up to a pressure of 10,000 psi, and vaporized. Inside another pair of converters, the vapors interacted with the German K-536 catalyst. Unused hydrogen was removed and recycled, and the liquids, condensed and dropped to much lower pressures, went to the vapor-phase distillation unit for final separation and finishing.

Because it used combustible gases at high pressures and temperatures, the Louisiana hydrogenation plant required many special safety precautions. Thick reinforced-concrete stalls, open on one side and roofless at the top, shielded the preheaters and converters from one another and from the rest of the facility to limit the impact of any explosion. All pressurized pipes and vessels were built to tolerate extreme stress. The Coal-to-Oil Demonstration Branch carefully trained the workers in its Hydrogenation Operating Section to emphasize safety.

Meeting the Bureau's exacting standards was not easy. American engineers and makers of industrial equipment in the late 1940s and the early 1950s lacked experience in designing and fabricating components that could withstand high-pressure operation. As Assistant Chief J. A. Markowitz of the Coal-to-Oil Demonstration Branch lamented, specifications that sufficed for ordinary industrial equipment at pressures up to 2,500 psi "were not necessarily good enough for 10,000 psi work." Often the Bureau either had to build its own components or lure private firms with attractive offers of government aid. For example, a manufacturer of stainless-steel tubing agreed to participate only if the Bureau agreed to accept the manufacturer's products even if they failed to work correctly.

"When there was a choice between importing equipment from Germany or building it here, the latter was done," Assistant Chief Markowitz wrote in 1949. "It was the hard way, but it was considered desirable in order to acquire design 'know-how' and to give American manufacturers an idea of the basic requirements for the design of future commercial-size plants."

Such concerns were well founded, since many things did fail to work correctly under the harsh conditions in the Louisiana hydrogenation plant. Pipes and gaskets leaked. Valves and pumps wore prematurely. During Midwestern winters, cold-weather operation was so difficult that the plant operators postponed runs until at least the end of March. An alarming series of events transpired in mid-April 1950, when solid residues plugged the converters and runaway chemical reactions forced an emergency shutdown.

The Bureau's response to these problems illustrated the economic as well as scientific value of government-sponsored demonstration projects. Patiently,

Coal-hydrogenation converter stalls bracketed by thick concrete at the Louisiana demonstration plant. (photo credit: National Archives and Records Administration) deliberately, Bureau officials encouraged corrective innovations and spurred American contractors to develop capabilities that had previously existed only in Europe. "When there was a choice between importing equipment from Germany or building it here, the latter was done," Assistant Chief Markowitz wrote in 1949. "It was the hard way, but it was considered desirable in order to acquire design 'know-how' and to give American manufacturers an idea of the basic requirements for the design of future commercial-size plants." The cultivation of engineering skill paid off in effective problem solving. By early 1953, after a multitude of improvements, the hydrogenation plant ran smoothly even in the depths of winter.

First carload of synthetic diesel oil produced at Louisiana, 1949. (photo credit: National Archives and Records Administration)

Between November 1949 and June 1953, the Louisiana station produced 1.5 million gallons of gasoline and small amounts of diesel, aviation gasoline, and jet fuel from hydrogenated coal. Some of its products powered Bureau of Mines vehicles that served the demonstration plant. Most of its gasoline went to the U.S. military, which concluded that the synthetic performed as well as the petroleum version. The project was a technical success; it proved that applying the Bergius-I. G. Farben process to American coals could yield large volumes of motor fuels that met United States government specifications.

The Fischer-Tropsch side of the Louisiana works took longer to design and build. Its construction began in April 1948, after the Bureau of Mines awarded a general contract to the Pittsburgh-based Koppers Company for a facility that could produce up to 80 barrels of liquid fuels and chemicals per day. Among the first components to arrive was a transplant from across the Atlantic: an oxygen generator that had been part of an I. G. Farben chemical plant at Frankfurt am Main, Germany, during World War II. Tests of equipment for producing and purifying synthesis gas took place during 1949 and 1950, and by mid-1951 the entire site was ready.

Three different gasifiers provided synthesis gas for the Fischer-Tropsch process at this demonstration plant. The first was an entrained-bed coal gasifier that the Koppers Company built on the basis of a German design. It consisted of a horizontal, brick-lined steel cylinder with two identical sets of inlets—one set at each end—for coal, oxygen, and superheated steam. A stream of oxygen carried powdered coal into the reactor, where combustion and gasification produced synthesis gas that flowed out through a discharge pipe atop the cylinder. Beginning in May 1949 and continuing through April 1950, Bureau engineers experimented with this gasifier and found it to be satisfactory. However, they believed that they could convert a higher proportion of coal to gas by incorporating some of the ideas that the Morgantown research staff had developed. So the Koppers unit was set aside, and what official reports described as a "Morgantown-type" coal gasifier was installed at the demonstration plant in late 1950 for use in 1951.

In its basic design, this Morgantown-type gasifier at Louisiana closely resembled the first-generation atmospheric-pressure pilot plant that the Morgantown station had operated since 1948. Its reactor was a vertical cylinder, with intakes for all raw materials near the bottom and an outlet for the synthesis gas near the top. But it did not include the original version's fluidized coal feeder, and there was also a major change in the interior lining of the reactor. Concerned about the erosion of brick linings, which had been a serious problem at Morgantown and had recurred with the Koppers gasifier, the Bureau of Mines decided to try a different refractory material. It established a cooperative agreement with the Aluminum Company of America for the installation of a lining made from aluminum oxide.

Although the first results from the Morgantown-type gasifier seemed promising, the modifications made in the transition from West Virginia to Missouri did not work well. The new aluminum-oxide lining partially melted, and its debris combined with slag—molten coal ash—to clog the reactor. Subsequent changes to the coal feeder and the geometry of the intakes limited the damage, but also reduced gas output below the levels achieved earlier at Morgantown and in the Koppers gasifier. This situation, Lester Hirst and his colleagues acknowledged, was "distinctly disappointing."

More disappointment followed when the engineers learned in the spring of 1952 that neither the Morgantown-type coal gasifier nor the Koppers coal gasifier would be used in tests of the fully integrated Fischer-Tropsch plant. Doubts about the reliability of these experimental machines, coupled with delays in reconfiguring the Morgantown-type unit, led the Coal-to-Oil-Dem-

The Fischer-Tropsch demonstration plant at Louisiana. On the left side of the plant, the leftmost of the two tall cylinders is the "Morgantown-type" vertical gasifier. (photo credit: National Archives and Records Administration) onstration Branch to postpone its goal of operating with synthesis gas made directly from coal. Instead, the Louisiana works did as German synthetic-fuels makers had done before: It relied on a conventional manufactured-gas producer that made acceptable synthesis gas from coke. As a prudent backstop, the Bureau had purchased a secondhand gas producer in 1948 from the Laclede Gas Light Company, the utility that supplied manufactured gas and natural gas to metropolitan St. Louis. This lowly device became the workhorse of the demonstration plant.

Advances in gas purification met with greater success. The pooled expertise of researchers at the Morgantown, Bruceton, and Louisiana stations resulted in a purification system that was both inexpensive and reasonably effective. After being cleansed of dust and mildly pressurized, synthesis gas passed through a scrubber to remove carbon dioxide. It next entered two containers filled with iron-oxide-bearing wood chips, which absorbed inorganic sulfur. Activated carbon then reduced the presence of organic sulfur compounds.

The synthesis reactor itself was the internally oil-cooled, jiggling-bed type that the Bruceton laboratories had developed. It operated at a pressure of about 350 psi and temperatures around 260 °C. A 30-foot vertical steel cylinder, lined with a mix of sand and lime, contained about seven tons of catalyst particles. These particles were made from mill scale, a type of iron oxide (magnetite) that formed as a normal byproduct in steel mills and was thus abundant. As it rose through the catalyst bed, the synthesis gas underwent the Fischer-Tropsch conversion into gases and liquid oil, which exited at the top of the reactor. The cooling oil was recaptured and recirculated.

On September 4, 1951, the synthesis reactor began its first test run, which lasted only eight days. Three much longer runs of the entire plant ensued between October 1951 and January 1953. Output ranged between 50 to 80 barrels of liquids per day, mostly in the form of gasoline, which were processed in an on-site distillery. Like the coal-hydrogenation plant, the Fischer-Tropsch plant experienced assorted problems, from leaking pumps to failures of the instruments that monitored the flow of materials and the progress of chemical reactions. The staff resolved most of them quickly. One significant exception, however, was the persistent tendency of the catalyst to disintegrate and lose its effectiveness over time.

Although the setbacks with coal gasification and the puzzle of the disintegrating catalyst were dismaying, the Fischer-Tropsch plant did prove the general concept of an oil-cooled reactor for making liquid fuels from synthesis gas. It turned out slightly over 40,000 gallons of liquids during its brief lifetime, including a high-quality diesel fuel that exceeded U.S. military standards. In their final assessment, R. G. Dressler—who headed the plant—and Lester Hirst were guardedly positive. They observed that "most of the mechanical difficulties were eliminated" over the course of the tests and concluded that "a commercial unit probably could be designed and operated on the basis of the information obtained at Bruceton and Louisiana."

End of the Line

Like the petroleum discoveries of the late 1920s that had doomed the first round of American research on synthetic fuels, new sources of petroleum and natural gas during the late 1940s and the early 1950s discouraged further pursuit of alternatives.

A conjunction of changes in energy markets, philosophical disagreements about the proper relationship of government and industry, and a gradual reappraisal of national-security strategy undercut the Synthetic Liquid Fuels Act. The improving outlook for energy supply was the most conspicuous of these influences. Like the petroleum discoveries of the late 1920s that had doomed the first round of American research on synthetic fuels, new sources of petroleum and natural gas during the late 1940s and the early 1950s discouraged further pursuit of alternatives. Substantial petroleum reservoirs were identified in West Texas and the northern Great Plains, as well as beneath ocean waters along the continental shelf. Although these finds did not close the whole gap between rising demand and more slowly increasing reserves, they suggested that wartime forecasts had been too conservative.

Readily available foreign sources further eased public concerns about shortages. The country's petroleum imports exceeded its petroleum exports for the first time in 1947. A year later, the president of research and development for Standard Oil of New Jersey advised Secretary of the Interior Krug that with the immense reserves of the Middle East factored in, no "over-all world shortage" of petroleum existed or would exist "in the near future, that is, say, looking ten years ahead." This conclusion was borne out over the next several years as additions such as the mammoth Ghawar field in Saudi Arabia—the largest known petroleum reservoir when it became operational in 1951—greatly expanded the global supply.

The natural-gas industry underwent an even more unexpected and profound postwar transformation. During the 1943 congressional hearings on synthetic liquid fuels, Bureau of Mines experts had concluded that natural gas would only become a major fuel source or industrial raw material in a few regions where it was locally superabundant. American gas supplies were judged to be too limited and too valuable to use for purposes where coal could substitute. Such cautious evaluations changed after long-distance pipelines, built during the war to carry petroleum from Texas to the East Coast, were converted to transport natural gas in the late 1940s. Households and businesses in Eastern cities thereby gained their first access to the vast gas fields of the Mid-Continent and the Gulf Coast; for example, Philadelphia obtained natural-gas connections in 1948 and New York City in 1951. Convenient, clean-burning natural gas swiftly replaced coal and coal-based manufactured gas in industrial processes and as the preferred fuel for residential and industrial heating in most parts of the country.

To a much greater extent than the framers of the Synthetic Liquid Fuels Act had anticipated, therefore, petroleum and natural gas were abundant and cheap by the early 1950s. This situation highlighted the problem of relative prices. Despite all the strides that the Bureau of Mines and its allies had made, synthetic liquids made from coal or oil shale still cost more than did natural petroleum or synthetic liquids derived from natural gas. The exact amount of the difference was uncertain and hotly disputed, but no one doubted that a gap existed. If the federal government wanted to bring coal- or shale-based liquid fuels to market quickly, then it would have to follow the prewar German and British course of offsetting the price differential through subsidies. That idea was politically unattractive, especially because the petroleum industry strongly rejected it.

Petroleum companies had generally supported the Synthetic Liquid Fuels Act. Viewing synthetic-fuels capability as a valuable hedge against future contingencies, they welcomed government sponsorship of basic research and process development. But they did not want the program to evolve into an instrument for publicly funding a synthetic liquid fuels industry that would compete directly with them. After the Interior Department and Congress began floating specific proposals in 1948 for using public financing to underwrite the construction and operation of commercial synthetic liquid fuels plants, petroleum-industry representatives became alarmed. They perceived that the distinction between public-sector research and private-sector implementation was breaking down. The National Petroleum Council became the core of a well-organized opposition movement. Its public-relations campaigns stressed that synthetic liquid fuels were uncompetitive under current economic conditions and, in the absence of any imminent energy crisis, were unnecessary.

This position tapped into more general public discontent about economic policy. During World War II and its immediate aftermath, and again during the Korean War, Americans endured a vexing web of price controls, restrictions on key materials, and other official constraints on economic activity. A sense of fatigue and apprehension built up over time. People wondered when normality would return, and feared that the emergency measures foreshadowed a more permanent expansion of centralized governmental power at the expense of private enterprise. In this context, the notion that the federal government, instead of market forces, might determine whether synthetic liquid fuels contributed substantially to the country's energy supply was unpopular. Even the underlying premise that the United States should plan ahead against the possibility of future fuel shortages came to seem unduly limiting and pessimistic.

Arguments about the importance of synthetic liquid fuels to national security remained potent amid the debate over the program's future. Wilburn C. Schroeder, who headed the Office of Synthetic Liquid Fuels, appealed to this rationale in March 1948 when he testified to the House Interstate and Foreign Commerce Committee that military considerations should trump concerns about expense and the scope of government:

> *I believe that the United States would be denying its own heritage of superb initiative and refusing to use its own resources to meet the people's needs, if it does not develop synthetic fuels. Costs may be higher now than oil from foreign sources, but security can be worth this added cost, and if a synthetic industry should prevent a war or make it possible to win a war if we must fight one, then the added cost will be a small one to pay. In addition, we should not sell short*

> *American ingenuity and technology. Repeatedly in the past, the cost of synthetic products has been high in the beginning, but in the end they have been as cheap or cheaper than the natural products.*

But these arguments, too, were losing force. After the Soviet Union joined the United States as a nuclear power in 1949 and the Cold War between them settled into a stalemate, the likelihood that the United States would have to fight another protracted hot war comparable to World War II diminished. Military planners scaled back their estimates of defense-related energy and raw-materials requirements. Expert opinion became divided about whether energy self-sufficiency was a wise and feasible goal. An emerging counterargument held that the country could tolerate—and perhaps should encourage—reliance on inexpensive imported petroleum for everyday needs, while conserving its own petroleum reserves for emergency use. With that approach, there would be no need to draw liquid fuels from the much larger reserves of coal or oil shale.

By 1952, the Synthetic Liquid Fuels Act had lost much of its former broad base of support in Congress. Its potential to spur local and regional economic development had fizzled, as there was no longer much chance that commercial synthetic liquid fuels plants would be built in significant numbers anytime soon. It increasingly seemed anachronistic, tied to particular economic and strategic assumptions that had perhaps been reasonable during the exceptional circumstances of World War II but that had not panned out since.

The synthetic liquid fuels program ended in piecemeal fashion. Congress first mandated that the coal-to-liquids plants at Louisiana be shut down by the end of May 1953. On January 13, 1954, the Eisenhower administration, in the person of Secretary of the Interior Douglas McKay, announced that it would not seek to extend or renew the Synthetic Liquid Fuels Act. Underground coal gasification at Gorgas and oil-shale mining and retorting at Anvil Points ceased after the Synthetic Liquid Fuels Act finally expired in April 1955. Only such research as could be funded out of regular Bureau of Mines appropriations continued at Morgantown, Bruceton, and Laramie.

Scientists and engineers who had devoted years of their lives to the program were dismayed at its demise. As the Bureau's final report on the oil-shale work—which did not see print until 1964—diplomatically complained, the development of the gas-combustion retort design "was halted . . . before a logical termination point was reached, and many unsolved problems remain." Similar claims of illogical termination pertained to other "unsolved problems" such as disintegrating catalysts in Fischer-Tropsch reactors and the damaged linings of Morgantown's experimental gasifiers. However, the Eisenhower administration countered that the Bureau could still address these problems through the normal budget process. The federal government, in this view, should focus its resources on basic research and small-scale pilot plants. It could then leave the development of larger-scale synthetic liquid fuels plants—if any were ever needed—to private firms.

Over its eleven-year lifespan, the Synthetic Liquid Fuels Act had resulted in expenditures of $85.2 million. That public investment had clearly not yielded the promised alternative supply of synthetic motor fuels. But it had yielded two other lasting achievements. One was a body of knowledge. The United States had no meaningful capability to produce synthetic liquid fuels from coal or oil shale in 1944. By 1955, it had at least a solid foundation for that capability. Along the way, the Bureau of Mines and its private-sector partners had learned much about basic coal chemistry, oil-shale chemistry, and catalysts, and about engineering for industrial processes that operated at high pressures and high temperatures.

The other legacy was a core of physical facilities and human talent. The expanded Bruceton Experiment Station, the new Appalachian Experiment Station campus at Morgantown, and the enlarged Petroleum and Oil-Shale Experiment Station at Laramie were permanent assets. Many staff members who had been hired to work on the synthetic liquid fuels program remained with the Bureau, contributing their expertise to other projects. Cooperative agreements with universities and private companies endured. The seeds of a unified federal fossil-energy research and development program had emerged, although their potential was not immediately appreciated.

Overview of the Anvil Points oil-shale works in the mid-1950s. Anvil Points, the first of the Synthetic Liquid Fuels Act demonstration plants to be completed, was the last to shut down. During the 1960s, the Bureau of Mines would begin leasing this site to private organizations for further studies of shale-oil production. (photo credit: National Archives and Records Administration)

Henry H. Storch and the Chemistry of Fuels

Henry Herman Storch was one of the leading figures in the Bureau of Mines and in American physical chemistry during the mid-twentieth century. Born in New York City in 1894, he received his undergraduate education at City College of New York and his graduate training on the other side of the continent at the University of California, culminating with a Ph.D. in physics in 1923. He moved back and forth between the East Coast and the West, holding teaching and research positions at universities and working for several manufacturing firms. Like many other American scientists and engineers of his generation, Storch was interested in breaking the near-monopoly that Germany held on the mass production of many industrial chemicals. Synthetic methanol intrigued him, and he investigated that topic at the New Jersey-based Roessler & Hasslacher Chemical Company during the 1920s, obtaining several patents along the way.

Henry H. Storch (photo credit: National Archives and Records Administration)

In 1928, Storch accepted the position of supervising engineer at the Bureau of Mines experiment station in New Brunswick, New Jersey. The New Brunswick station had been established five years earlier, in cooperation with Rutgers College, to study nonmetallic minerals—such as lime, phosphate, sulfur, and sand—that were commonly used in the chemical industries and in other types of manufacturing. It was located within the New York City metropolitan area, which harbored the greatest concentration of chemical production and chemistry research in the nation. For a young scientist with a bent for industrial innovation, the position might have seemed ideal.

But Storch chose to leave the attractions of his home region in 1931 and transfer to the Pittsburgh Experiment Station in response to an appeal from the Bureau's chief chemist, Arno C. Fieldner. The struggling little program of synthetic-fuels research and other coal-chemistry activities at Pittsburgh needed help, and Fieldner thought that Storch was just the person for the job. Storch was interested, seeing obvious continuities with his earlier work on methanol. He held the title of chief physical chemist at the station for 13 years. As the synthetic fuels program gradually lost its marginal status and became more central to the research agenda of the Bureau during the late 1930s and the early 1940s, Storch's fortunes rose with it. He supervised the first experimental coal-hydrogenation plant at the Pittsburgh station beginning in 1936 and became one of the few American experts on the Bergius-I. G. Farben and Fischer-Tropsch processes.

With the advent of the Synthetic Liquid Fuels Act of 1944, Storch moved into a position of national importance at the Bureau as the director of research and development for the newly created Office of Synthetic Liquid Fuels. There he found his stride in both applied science and public administration. Still based at Pittsburgh, he organized the rapid postwar expansion of the Bureau's synthetic-fuels research laboratories. He was knowledgeable about virtually every aspect of coal-to-liquids conversion, from basic coal chemistry to catalytic reactions. Storch contributed frequently to scientific books and journals. His numerous publications—especially his masterpiece, *The Fischer-Tropsch and Related Syntheses*, which first appeared in 1951—held up well over the years; his work was still being cited as valuable source material half a century later. As his colleagues in the Pittsburgh Section of the American Chemical society later explained in a 1964 retrospective, his effectiveness derived from his "intuitive appreciation of engineering problems and their solutions."

Storch became the chief of the Fuels Technical Division in 1951 and then headed the Synthetic Liquid Fuels Branch from 1953 to 1954, during which time he oversaw the implementation of the policy decision to shut down the Bureau's coal-to-liquids demonstration plants. Since he had never quite approved of those plants, he did not find this step as traumatic as some of his colleagues did; he was of the school of thought that believed the Bureau should concentrate its resources on fundamental coal science and process development rather than participating in large commercial-scale projects.

As the Synthetic Liquid Fuels Act wound down, Storch left the government for the position of director of basic research at American Cyanamid Company, a chemical manufacturer. He retired in 1959 and taught chemistry at New York University until he died at his home in Greenwich, Connecticut, on November 20, 1961.

Storch's many friends, associates, and admirers acted through the American Chemical Society to establish a memorial in the form of the Henry H. Storch Award in Fuel Science. This prestigious award, begun in 1964, is conferred in recognition of outstanding accomplishments in research on the chemistry and utilization of coal or any other fossil fuel except petroleum. Initially limited to American citizens, eligibility for the Storch Award later broadened to include fuel researchers anywhere in the world. Forty people received the honor during its first 45 years of existence.

Robert A. Friedel, a key participant in coal-to-liquids research at Bruceton, receiving the Storch Award in 1966. (photo credit: National Archives and Records Administration)

Henry H. Storch Award Recipients			
Year	**Honoree**	**Year**	**Honoree**
1964	Irving Wender*	1985	John W. Larsen
1965	Everett Gorin	1987	Leon M. Stock
1966	Robert A. Friedel	1988	Randall E. Winans
1967	Henry R. Linden	1989	Harry Marsh
1968	Joseph A. Field	1990	Bradley C. Bockrath*
1969	Philip L. Walker, Jr.	1991	Peter R. Solomon
1971	George R. Hill	1992	Stephen E. Stein
1972	Robert W. Van Dolah	1993	Martin L. Gorbaty
1973	Arthur M. Squires	1994	Gary R. Drykacz
1974	R. Tracy Eddinger	1995	Donald F. McMillen
1975	G. Alex Mills	1996	Isao Mochida
1976	Heinz Sternberg	1997	Frank Derbyshire
1977	Frank C. Schora	1999	Eric M. Suuberg
1978	Wendell H. Wiser	2000	Yuzo Sanada
1979	D. D. Whitehurst	2002	Burtron Davis
1980	Richard C. Neavel	2004	Harold Schobert
1981	Sol W. Weller	2006	Colin Snape
1982	Herbert L. Retcofsky*	2007	Ronald Pugmire
1983	Jack B. Howard	2008	Simon Kelemen
1984	Peter H. Given	2009	Akira Tomita

* Storch Award winners who worked at NETL

A Century of Innovation

From the U.S. Bureau of Mines to the National Energy Technology Laboratory

Chapter Nine: Energy Research during the Postwar Economic Boom, 1956–1972

Radiation Instrument Laboratory at Bartlesville, 1963.
(photo credit: National Archives and Records Administration)

Chapter Nine:

Energy Research during the Postwar Economic Boom, 1956–1972

It isn't often that local events cause fluctuations on the New York stock market… but that is just what has happened…The announcement by the U.S. Bureau of Mines at Washington, D.C., Thursday that molybdenum had been cast successfully for the first time at the Bureau of Mines Northwest Electrodevelopment laboratory here was reflected immediately on Wall Street, where stocks of the light metals industries, particularly those that are producing molybdenum for use as an alloy, rose sharply.

--editorial in the January 19, 1959 edition of the Albany Democrat-Herald

The Bureau of Mines marked its fiftieth anniversary on July 1, 1960. In a commemorative article, the *New York Times* observed that the agency had grown immensely in size and scope. Approximately 4,000 employees worked for the Bureau in 1960, compared to 124 in 1910. Research programs extended far beyond the initial focus on coal and other fossil fuels to the frontiers of mid-twentieth-century high technology, including nuclear power, space exploration, and exotic materials. "Clearly, the bureau's record underground has been outstanding; its record in the skies of the space age is now being written," the *Times* concluded.

"Clearly, the bureau's record underground has been outstanding; its record in the skies of the space age is now being written." --The New York Times, 1960

For energy researchers, the period from the late 1950s to the early 1970s was full of transitions. Economic prosperity and abundant energy supplies had replaced the crisis atmosphere of World War II and the immediate postwar years. Coal, which had long been central to organic chemistry, industrial growth, and national security, slipped toward the margins of scientific inquiry as the dominance of petroleum solidified. Indeed, a signal accomplishment of the Bureau and the Department of the Interior was their pivotal role in keeping American coal chemistry alive and progressing at a time when other, more glamorous fields received far more public and scholarly attention. Atomic energy created a host of new opportunities, but also brought new dangers and disappointments. Rising public interest in the environmental consequences of energy use was reflected in several

Bureau programs, including the restoration of lands damaged by mining and efforts to control smog-causing emissions from power plants and automobile engines.

But the Bureau's space-age advances were firmly rooted in its past. Equipment and analytical techniques that had originated in the study of coal and petroleum found new uses on the cutting edge of research in geology and materials science. Innovations in areas such as mine safety, coal gasification, and the shaping of rare metals built step by step upon previous accomplishments. In many ways, the distance between contemporary and historical energy research was not as great as it seemed at first glance.

Bureau of Mines Director Marling J. Ankeny (photo credit: National Archives and Records Administration).

Reorganizations

After reflecting on its wartime experiences, the Bureau had altered the division of labor between the field offices and the national office in 1949. Nine regional directorates—seven in the continental United States, one in Alaska, and one covering the rest of the world—were established to manage the day-to-day work of the experiment stations and other local activities. The regional directors could enter into contracts and hire personnel for projects within their districts, instead of constantly having to route requests through Washington, D.C. This arrangement permitted better horizontal coordination among the field staffs of the three operating divisions: Fuels and Explosives, Health and Safety, and Minerals. Previously, Director James Boyd explained, Bureau employees who represented different divisions but worked "in the same field offices" had "received orders from separate individuals in far away Washington. Now the regional directors will have full authority to act." Freed from most routine duties, the headquarters staff was better positioned to set an overall course and to advise Congress and other executive agencies on issues involving mineral resources.

This relatively decentralized structure lasted through the 1950s, with modest changes. Director John J. Forbes (1951–1955), who had worked his way to the top through his decades of service with the Bureau's mine-safety programs, decreased the number of regional directorates to five under a 1954 reorganization plan. As the Synthetic Liquid Fuels Act wound down in early 1955, the Fuels and Explosives Division was abolished. Separate Solid Fuels (later Coal) and Petroleum divisions took its place. Forbes's successor, Marling J. Ankeny (1956–1964), introduced new terminology in 1959: the modern-sounding language of "research centers" and "research laboratories." The Albany station became the Albany Metallurgy Research Center. Pittsburgh had a Coal Research Center, an Explosives Research Laboratory (renamed a Center in 1963), and a Health and Safety Research Testing Center; it also gained a Mining Research Center in 1964, after all work on coal mining was folded into the Bureau's general mining program. Morgantown had a Coal Research Center and a Petroleum Research Laboratory, while the Bartlesville and Laramie stations each acquired the designation of Petroleum Research Center.

But an inherent tension always remained between regionalism and service to national policy. Economic growth, the rise of the United States to a position of global power, and the Cold War placed great demands on the Bureau to meet the federal government's internal needs for data on mineral supplies and for technological innovations to address particular economic and national-security problems. There was pressure to focus on priorities set in Washington instead of by the regional directorates. In consequence, recentralizing tendencies soon appeared.

A prime example of power flowing back to Bureau headquarters was the administration of mine-safety activities. Enforcement of the federal mine-inspection law was a politically sensitive matter, crucial for maintaining good relations with the coal industry and the general public. This sensitivity had increased in 1952, when Congress authorized the Bureau to begin *requiring* the correction of major safety violations in large underground coal mines. Suddenly the Bureau's safety standards were no longer merely recommended best practices. They had acquired the force of federal administrative law. Inspectors could shut down noncompliant mines. Director Forbes moved to exert greater control over this new authority in 1954 by requiring all health and safety field offices to report directly to an assistant director at Bureau headquarters. In April 1967, Secretary of the Interior Stewart L. Udall created the new Bureau position of associate director for health and safety to monitor these activities.

The 1960 annual report noted a more sweeping reassertion of oversight from Washington: "To achieve greater efficiency in planning, programming, and coordinating research and development work at Bureau installations throughout the Nation, responsibility for these functions was centralized during the year, in headquarters Divisions of Minerals, Coal, and Petroleum." In 1963, the

The Bureau of Mines mainframe computer at the Denver Federal Center, 1969. (photo credit: Bureau of Mines publication).

regional directorates were abolished, leaving only an eastern administrative office in Pittsburgh and a western administrative office in Denver. More uniform management practices gradually came into use. For instance, the Bureau issued its first style guide for authors of its publications in 1962, created a central public-relations office in 1967, and acquired a mainframe computer in 1969 to handle automated personnel and payroll records.

A 1957 report found that the Soviet Union had five times more coal specialists than the United States.

An important external organizational change that affected the Bureau came in July 1960, when President Dwight D. Eisenhower signed legislation establishing the Office of Coal Research (OCR). This new agency was not part of the Bureau; it existed separately within the Department of the Interior. Nor did it conduct research. Rather, the OCR administered federal research grants to other government agencies, universities, trade associations, and private corporations to devise new uses for coal.

The OCR originated in concerns about geographically uneven economic development. Some regions of the country, including many coal-dependent areas, did not share in the general prosperity of the 1950s. Especially in the Central Appalachians, struggling coal-mining districts organized politically to seek assistance from the federal government. Few Americans, even if they lived in the troubled areas, favored open-ended federal subsidies, but there was greater support for using selective public investments in education, infrastructure, and new-business startups to spark regional economic growth.

Congressional delegations from coal-producing states insisted that spurring the transformation of coal into more valuable industrial products be a part of any such development plans. In August 1957, a special subcommittee of the United States House of Representatives issued a report lamenting the inadequacy of American coal research. According to these findings, the Soviet Union had five times more coal specialists than the United States did. A huge gap separated the coal industry's estimated $18.5 million in annual research spending from the petroleum industry's comparable expenditures of almost $146 million. Coal regions, the report concluded, had no hope of regaining competitiveness as long as such imbalances continued. The subcommittee proposed an independent federal coal research and development commission. Although President Eisenhower rejected that idea, placing the OCR within the existing Interior Department structure proved to be an acceptable compromise.

Throughout the 1960s, the OCR remained a small agency with a staff of not more than two dozen people. Its presence did, however, significantly expand funding for applied coal research at a time when few other public or private sources were engaged in this field. The OCR focused on industrial processes that might become large consumers of coal in the near future. That emphasis led it into domains where the Bureau of Mines had long been active, such as coal gasification and improvements to coal-fired boilers. Since the Bureau continued to do applied research through cooperative agreements (of which roughly 200 were in force each year), the OCR and the Bureau often found themselves on parallel tracks or collaborating on certain projects.

Another internal reorganization of the Bureau unfolded between 1969 and 1971. In July 1969, the Explosives Research Center and the Health and Safety Research and Testing Center at Pittsburgh were combined to form a unified Safety Research Center. The task of certifying explosives and mining equipment under the federal permissibility schedules was relocated to a new Health and Safety Technical Support Center, with offices in both Pittsburgh and Denver. These offices also provided technical assistance to mining companies about how to comply with increasingly strict federal and state regulations. Two deputy directorates, one for law enforcement and one for research and development, were established at the Bureau's headquarters in April 1970 to ride herd on these functions. And five experiment stations—Bartlesville, Pittsburgh, Morgantown, Grand Forks, and Laramie—were renamed yet again; all became Energy Research Centers as of 1971. The acronyms BERC, PERC, MERC, GFERC, and LERC quickly became familiar to Bureau employees and their clients.

Coal Science: The Ordinary and the Extraordinary

In its 1957 annual report, the Bureau explained that its coal research "was divided into two general categories": continuing efforts to make "well-established coal-mining, preparation, and utilization methods" more effective, and "exploration of wholly new approaches" to obtaining and using coal. This distinction held up well over the next fifteen years. Although the period was dominated by incremental, unspectacular extensions of work the agency had been doing for decades, there were also signs of profound change in mining practices and new applications for coal and coal science.

Mechanization and technological change advanced swiftly in American coal mining after World War II, and the Experimental Mine at Bruceton was no exception. In the early 1950s, a mule named Mac was still hauling loads at the mine. (photo credit: National Archives and Records Administration)

Bruceton's investigations into ignition, detonation, and combustion fed practical innovations beyond the coal industry, from safer fuel tanks and stove burners to the design of spacecraft.

The Bureau's core duties of promoting safety and productivity in mining continued. Both the Pittsburgh station and the Morgantown station participated in implementing federal mine-safety laws, which had been consolidated into the Coal Mine Safety Act of 1952. Besides regularly inspecting all active underground mines and strip mines in the country, the Bureau could now order operators of underground mines to remove hazards that might cause a mass-casualty accident.[1]* Most safety problems thus identified were quickly resolved, but between 1958 and 1963 the inspectors issued an average of 107 "withdrawal orders" per year to require complete or partial work stoppage in mines that had uncorrected defects.

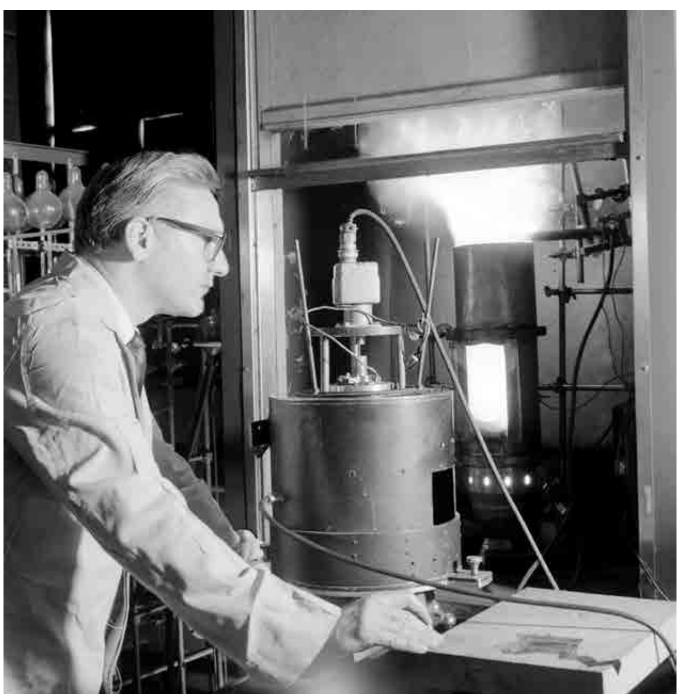
At Pittsburgh, Bureau scientists still focused on understanding and preventing mine explosions and fires. Explosives research proceeded under the capable leadership of the chemist Robert Wayne Van Dolah, who headed the explosives program from 1954 to 1978. Van Dolah received the prestigious Nitro Nobel Gold Medal in 1967 for devising a theory of how accidental initiations of liquid explosives began. The Bruceton explosives laboratories' state-of-the-art capabilities for investigating the phenomena of ignition, detonation, and combustion expanded in the early 1960s with the addition of equipment such as a flash X-ray system that could capture images in one ten-millionth of one second and electronic sensors to measure the velocities of explosive detonations. This basic research informed many practical innovations beyond the coal industry, from safer fuel tanks and stove burners to the design of spacecraft. Under contracts with the armed forces and the National Aeronautics and Space Administration (NASA), the Pittsburgh Explosives Research Center conducted projects during the 1960s on solid rocket propellants, safety procedures for handling liquid-hydrogen fuel, the behavior of explosives in conditions resembling the lunar atmosphere, and shielding to protect space vehicles against meteor impacts.

An important addition to the standards for permissible explosives was the requirement that all permissibles contain small amounts (around 10 percent) of sodium chloride. This change, fully implemented by 1969, grew out of years of research that demonstrated sodium chloride's effectiveness in making explosives less prone to ignite flammable dust and gases. In 1966, the triumph of permissibles seemed complete when the federal government finally outlawed the use of black powder in all underground coal mines. As conventional methods of blasting became less risky, however, the Bureau faced new problems with the growing popularity of liquid explosives and of explosives based on inexpensive, but potentially deadly, mixtures of petroleum and ammonium-nitrate fertilizer.

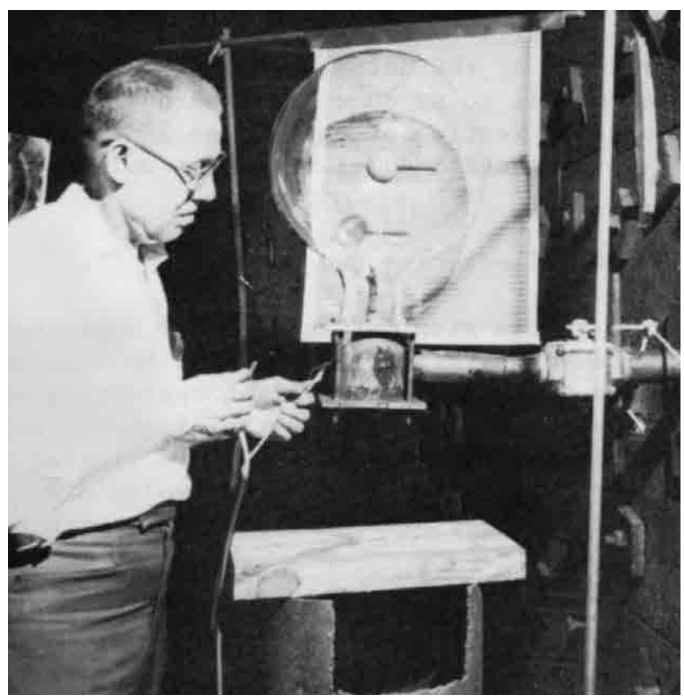
Learning how to extinguish fires was as important as learning how they started. The Pittsburgh station studied the use of chemical foams to put out under-

1* Between 1952 and 1966, this authority only applied to underground coal mines that regularly employed at least 15 people. Amendments to the Coal Mine Safety Act in 1966 extended the Bureau's regulatory power to all underground coal mines.

By 1955, permissible diesel engines had replaced mule power on the Experimental Mine's underground tracks. (photo credit: National Archives and Records Administration)



Using a rotating-film camera to photograph the ignition and combustion of mixtures of coal dust, methane, and air. (photo credit: National Archives and Records Administration)



A researcher at Bruceton tests small explosive charges in a high-vacuum environment to simulate the behavior of explosives in the thin atmosphere of the moon. (photo credit: Bureau of Mines publication) ground fires and to block off sections of mines or quickly change ventilation patterns in an emergency. It developed methods for stopping or controlling hundreds of blazes that smoldered in abandoned mines and in above-ground heaps of coal-mining wastes. Bureau engineers assisted NASA in developing fire-suppression systems for space vehicles. After a fire at Cape Kennedy killed three astronauts in the Apollo 1 disaster of January 27, 1967, Robert Van Dolah served on the official NASA review board that analyzed the causes of the tragedy and recommended safety improvements.

The Pittsburgh station also explored the revolutionary concept of methane control, which aimed to eliminate those hazards at the source.

Other hazards from electrical and mechanical equipment were evaluated at Pittsburgh. Reflecting the complexity that mechanization had wrought, the Bureau reported in 1960 that its permissibility approvals for that fiftieth-anniversary year included “17 continuous miners, 2 conventional mining machines, 13 conventional loading machines, 13 shuttle cars, 17 drilling machines, 2 power units, 1 utility truck, 2 rock-dust distributors, 6 distribution boxes, 3 air compressors, 2 mine pumps, 1 dust sampler, 1 fan, 7 diesel trucks, 1 diesel carrier, 2 flashlights, and 1 miniature methane-indicating detector.”

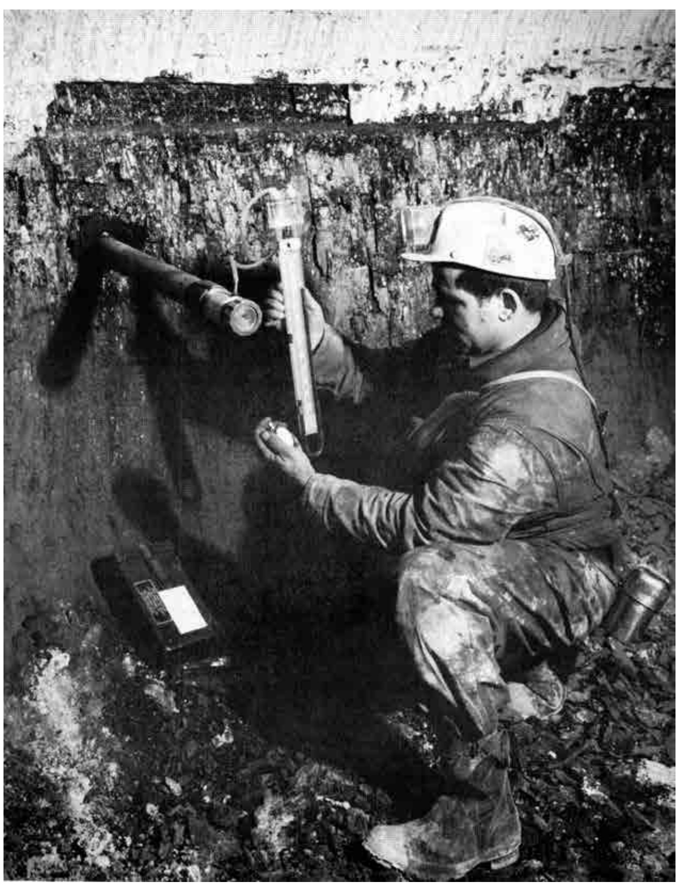
Bureau of Mines instructional materials to promote the use of health and safety equipment in mining. (photo credit: Bureau of Mines publication)

The miniature methane-indicating detector, a recent Bureau invention, was among the first fruits of a renewed campaign to tame the perils of methane. Technological change was heightening the risk of explosive gas concentrations in mines. As mechanization increased the speed and volume of coal production and as mine shafts plunged deeper into the earth, the amount of methane dislodged from coal seams rose, overloading mine ventilation systems. Engineers at the Pittsburgh station initially addressed the resurgent gas danger by harnessing postwar advances in electronics, such as transistors and computers, to improve the detection and dispersion of methane. A project launched in 1957 developed a network of sensors that could automatically cut off electrical power to any section of a mine where methane reached hazardous levels. By the end of the 1960s, several companies were selling methane detectors based on the Bureau’s designs.

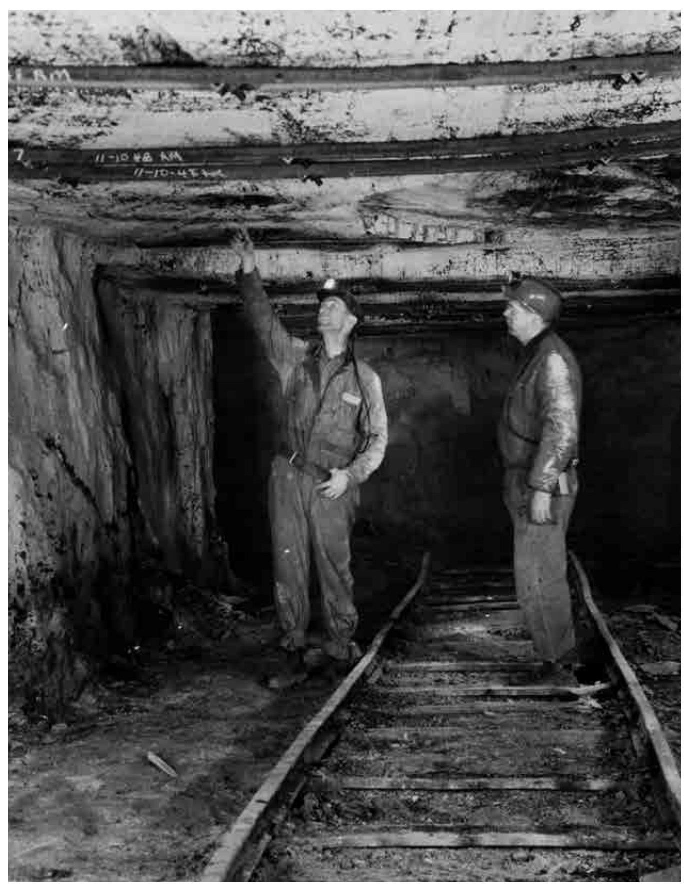
Not content with incremental progress in reacting to methane hazards, the Pittsburgh station also explored the revolutionary concept of *methane control*, which aimed to eliminate those hazards at the source. This approach emphasized fundamental questions: Why do coal seams contain methane? What factors affect the amount and the rate of gas emissions? How does gas travel through a mine? The answers would make it possible to forecast how much methane a new or expanded coal mine would generate and to predict likely sites of gas accumulation. Then the methane could be removed before it could endanger miners—perhaps even before mining operations began. Artificial methane drainage, in which carefully placed boreholes drew toxic gases away from a mine site and vented them to the atmosphere outside, was already used in Europe. In 1961, the Bureau initiated one of the earliest American methane-drainage experiments at the Pocahontas No. 4 coal field in southern West Virginia.

A far-reaching research program on methane control began at Pittsburgh in 1964. Over the next decade, scientists of the Mining Research Center’s Methane Control and Ventilation Group, such as Maurice Deul and M. G. Zabetakis, verified that methane was a ubiquitous byproduct of the biological and physical processes that formed coal. They invented techniques for measuring the methane that was stored in the pores and cracks of coal beds, and concluded that gas content depended primarily on the depth of the bed and the rank of the coal. They explained the flow of methane into mines as a consequence of the difference between atmospheric pressure in mine shafts and higher pressure in intact, gas-filled coal beds. When mining activity exposed the coal, gas migrated toward the low-pressure zone—the mine. Using specially designed drills at a test site near Morgantown, the researchers confirmed that it was feasible to vent methane by sinking vertical shafts into an unmined coal bed and then running long horizontal drainage holes from the shafts through the coal.

Other physical hazards in coal mining received much more attention after World War II than they had earlier. To reduce deaths and injuries caused by rock falls from collapsing mine roofs, the Bureau assertively promoted roof bolting, a procedure in which long bolts, spaced about four feet apart, were driven into the roof of a mine tunnel and then anchored and connected to form a support system. Growing awareness of chronic lung diseases among mine work-



Measuring the outflow of methane gas from a horizontal hole drilled into an unmined coal seam. (photo credit: Bureau of Mines publication)



Demonstration of roof bolting near the entrance of a coal mine.

ers prompted the Pittsburgh and Morgantown stations to examine the health impacts of silica and carbon particles in mine atmospheres. A new unit of the Experimental Mine at Bruceton, completely separate from the original section, had opened in 1955 and was exclusively dedicated to ventilation and dust studies. In cooperation with the Appalachian Laboratory for Occupational Respiratory Diseases, the Morgantown station began planning in 1969 for a unique dust-exposure chamber that would allow researchers to create artificial atmospheres in which dust concentrations could be precisely controlled and observed.

The ambition of reducing the dangers of coal mining through radically different, less labor-intensive mining methods endured. Based on its earlier experiments at Gorgas, Alabama, the Bureau concluded in 1959 that underground coal gasification was not commercially feasible in the United States. But other alternatives remained under study during the 1960s. One possibility was hydraulic coal mining, which used high-pressure jets of water to break apart coal beds. Describing a test of this concept at the Sugar Notch anthracite mine near Wilkes-Barre, Pennsylvania, a Bureau report noted in 1962 that hydraulic mining promised "superior safety" because it would avoid "such hazards as airborne coal dust and dislodged roof supports, as well as the danger of storing, handling, and firing explosives underground." The Bureau envisioned that coal would be not only cut but also transported by water (or possibly by compressed air), using hydraulic lifts to bring coal to the surface and pipelines to carry it to processing plants or directly to customers.

Of greater immediate significance were the growth of surface mining and the spread of longwall technology at underground sites. Open-cut strip mines, which had provided 19 percent of the total American production of bituminous coal and lignite in 1945, supplied 29.5 percent in 1960 and 40 percent in 1970. They yielded large volumes of coal quickly and cheaply, and since they operated

Reclaiming a strip-mine site by enriching the soil with power-plant fly ash, 1972. The treated section in the background is redeveloping into meadowland, while the untreated section in the foreground is still almost barren after fifteen years of reliance on natural vegetation alone. (photo credit: Bureau of Mines publication) entirely above ground, they eliminated the need for miners to enter dangerous confined spaces. The longwall method of underground mining accounted for about 3 percent of underground bituminous-coal production by 1973. By removing large slabs of coal under the protection of moveable roof shields and then allowing the controlled cave-in of the roof behind the mined-out areas, it required fewer workers and minimized the threat of unexpected roof falls.

Almost half of American bituminous coal output by the early 1970s thus came from unconventional mining techniques. The changes in technology presented many challenges to the Bureau, which had to define safe practices for these unfamiliar, rapidly evolving situations. Moreover, both strip mining and longwall underground mining raised environmental concerns because of the damage they did to land surfaces and water supplies. As early as 1963, the Pittsburgh and Morgantown stations began cooperating with state governments and the coal industry on environmental remediation at abandoned mine sites. The Morgantown Coal Research Center developed a method for reclaiming desolate strip-mined lands by using fly-ash waste from coal-burning power plants to make the soil wetter and less acidic so that new vegetation could take root.

Both Morgantown and Pittsburgh had cutting-edge capabilities for analyzing the physical and chemical structures of coals and other minerals.

No matter how coal was extracted, its effective use required much study and preparation. The Bureau's ongoing basic and applied research on various types of coal boosted increasingly sophisticated efforts to match specific coals to specific industrial needs. Both Morgantown and Pittsburgh had cutting-edge capabilities for analyzing the physical and chemical structures of coals and other minerals (including a few extraterrestrial specimens—see sidebar). Through spectroscopy, X-ray diffraction, electron microscopy, and other means, scientists probed the geological origins of coal and the differences in mineral composition that defined coals by rank and by grade.

A wet concentrating table for separating sulfur-containing pyrite from coal. (photo credit: National Archives and Records Administration)

An important goal of coal research was to obtain "clean coal," a term that, in the mid-twentieth century, simply meant coal that was relatively free from impurities. The coal that emerged from large-scale mechanized mining of any kind was intermixed with contaminants, including rock fragments and water, which had to be removed. Bureau of Mines studies during the 1950s and the 1960s helped to commercialize several processes for mechanically or chemically "washing" coal by separating it from other minerals.

In particular, there was demand for reducing the sulfur content of high-sulfur coals so that they could be used for industrial purposes without damaging equipment or interfering with chemical reactions. Experiments at Pittsburgh and Morgantown pointed toward improved methods for extracting pyrites (inorganic compounds of sulfur and iron), which constitute one major form of sulfur in coal. However, these methods were still incomplete and costly, and organic sulfur compounds—which were more tightly integrated into the molecular structure of coal—posed even greater unsolved problems.

Sulfur removal gradually acquired an environmental dimension during the 1950s and the 1960s as public concern about air pollution rose. Emissions of sulfur dioxide (SO_2) from coal-burning power plants were among many contributors to the smog problem. Faced with growing political pressure to take corrective action, officials of the coal and power industries needed to know if there were—or soon could be—technological solutions that would clear the air without driving up the price of coal-generated electricity.

Members of the Process Evaluation Group at the Morgantown station, 1967. From left to right: Bill Morel, Ken Plants, Sidney Katell, Lu White, Charles Jackson, and Paul Wellman.

Bureau chemists and chemical engineers, with their long involvement in purifying synthesis gas and other coal chemicals, were well poised to help answer this question. The United States Public Health Service and the Bureau began a joint study of desulfurizing industrial gas emissions as part of an air-pollution research program that Congress had authorized in 1955. Information Circular 7836, "Sulfur Dioxide—Its Chemistry and Removal from Industrial Waste Gases," which the Bureau published in 1958, established a baseline of knowledge. After reviewing several promising approaches to SO_2 control in Europe, Japan, and the United States, researchers at the Pittsburgh station chose to develop a method of their own called the alkalized-alumina process. An initial small pilot plant to test this process was set up at Bruceton in 1961.

Pilot plant at Bruceton for testing the alkalized-alumina process of removing sulfur dioxide from the flue gas of coal-burning boilers. (photo credit: National Archives and Records Administration)

In the Bruceton pilot plant, hot exhaust gas from a coal-fired furnace entered the bottom of a reactor and came into contact with tiny spheres of alkalized alumina, a solid material made from aluminum oxides and sodium. As the flowing gas heated them and carried them upward out of the reactor, these spheres absorbed SO_2 and other sulfur compounds from the gas. They were captured in a mechanical separating device and sent to a regenerator, which removed the sulfur compounds and prepared the solid spheres for recycling back into the reactor. Another set of chemical reactions then converted the sulfur compounds into pure sulfur. Theoretically, a power company could offset part of the cost of installing the pollution-control system by selling the sulfur, which was a valuable industrial chemical with potential markets in fertilizer manufacturing.

Three years of testing in the original facility, followed by the operation of a larger pilot plant beginning in the fall of 1966, demonstrated that the alkalized-alumina process worked. It removed most SO_2 from the waste gases that burning coal produced. It even won the approval of Sidney Katell. From his office in Morgantown, Katell, a founding member of the American Association of Cost Engineers, kept strict watch over cost discipline. His job was to evaluate the economic feasibility of Bureau-invented industrial processes once hard data about their performance became available. Comparing the alkalized-alumina process to two other SO_2-control processes that had reached the pilot-plant stage, Katell concluded in 1966 that the Bureau's design had the lowest capital investment costs and operating costs.

As the Bureau had witnessed many times before, however, technical feasibility was no guarantee of commercial success. The alkalized-alumina process did find industrial applications, but it did not become the dominant technology in the emerging field of *flue-gas desulfurization* (FGD). That status belonged to a different type of FGD process that used widely available pulverized limestone to capture and neutralize SO_2 from power-plant stacks. As United States electric utilities began implementing tougher air-pollution controls in the early 1970s, they selected limestone-based scrubbers. And because all early FGD methods proved to be costly and awkward when enlarged for full-scale commercial use, these innovations spread slowly. Engineers soon realized that cleaning up coal-burning power plants would be a long, difficult quest that might not be achievable without a deeper rethinking of how best to extract energy from coal.

Synthetic Fuels and Other Creations

Converting coal to liquid or gaseous synthetic fuels was a low priority for the federal government and private industry for over a decade after the Synthetic Liquid Fuels Act ended in 1955. Nevertheless, Bureau laboratories at Morgantown, Grand Forks, and Pittsburgh quietly pushed ahead with investigations in these areas.

One focus at Morgantown was low-temperature coal tar. The idea of coking coal at relatively low temperatures and recovering abundant liquids byproducts had never lived up to the enthusiasm of its early promoters. Only a handful of commercial low-temperature carbonization plants had ever been built in the United States. Yet low-temperature carbonization remained under serious consideration. It worked well for making coke from the low-rank and low-quality coals that predominated in many Western states, and it was still a potential backup source of liquid fuels and organic chemicals if petroleum output ever faltered. Several Bureau stations conducted research on the subject, and in 1955 Congress specifically designated funds for the establishment of a Low-Temperature Coal Tar Laboratory at Morgantown.

Founded to look for breakthroughs that might result in new industrial markets for coal chemicals, the laboratory posted a record of more modest accomplishments. Its early years were devoted mostly to identifying and analyzing the complex variety of chemicals present in low-temperature coal tar and developing a process for increasing the liquid yield from bituminous coal. By the late 1960s, its staff had demonstrated that the tar could be used to make alcohols, biodegradable detergents, and durable binders for industrial electrodes and coatings. In 1969, Richard L. Rice, Robert R. Lynch, and John S. Berber reported that they had devised a tar-based synthesis of carbon black, a form of carbon that had many uses in the manufacture of pigments and rubber products. Although all these chemicals were usually made from petrochemical sources, there was value in proving that the vast coal reserves of the United States could also supply them at need.

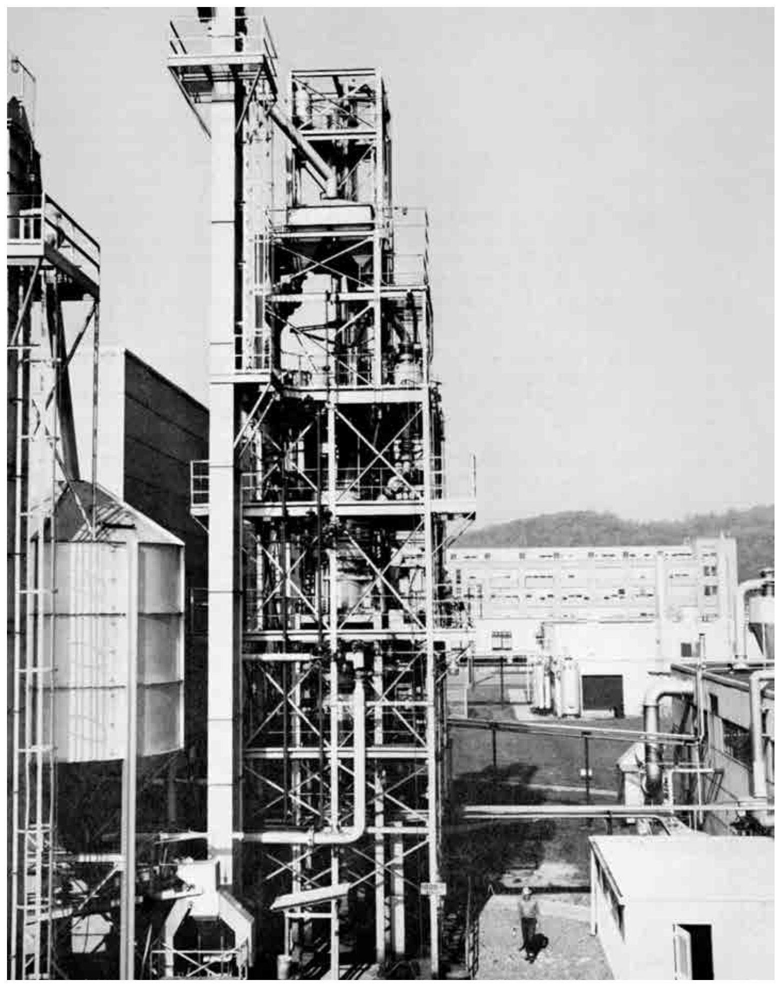
The centerpiece of applied coal chemistry at Morgantown and at the Lignite Research Laboratory in Grand Forks remained coal gasification, to which the Pittsburgh station also made important contributions. The search for cheap, versatile gasification methods and more efficient and reliable gasifier designs went on. Each of these three experiment stations had its own angle on the subject, reflecting local conditions and research priorities.

Grand Forks was the principal center of research and development on lignite for the Bureau and the nation. During the 1950s, it continued to study externally heated and internally heated variations on its original concept of using a ring-shaped Reyerson-Gernes reactor to gasify North Dakota lignite. A quite different approach took form in 1957–1958 with the construction and startup of a slagging fixed-bed gasifier (SFBG), which operated until 1965. This pilot plant had a cylindrical reactor in which a stationary bed of lignite reacted with oxygen and steam at temperatures high enough to form slag (molten ash). The liquid slag drained automatically through a taphole near the base of the reactor. An advantage of the SFBG was that it required less steam—and therefore less water—than did non-slagging gasifiers, making it potentially well suited for use in the arid states of the West.

At Morgantown, gasification research initially displayed much continuity with the Synthetic Liquid Fuels Act era. The station continued to pursue its original mission of providing inexpensive synthesis gas for coal-to-liquids conversion processes. Individuals who had helped to establish the gasification program during the mid-1940s held dominant positions well into the 1960s. Prominent among them were Lester L. Hirst, who served as the director of coal research

John S. Berber with an array of organic chemicals made from coal tar at Morgantown's Low-Temperature Coal Tar Laboratory.

Research Director James Paul McGee at Morgantown.



The modified Lurgi fixed-bed gasifier at Morgantown. (photo credit: Bureau of Mines publication) until his death in May 1963, and his successor, James Paul McGee, who held the position of research director until 1968. Initially, work at Morgantown concentrated on the pressurized, entrained-bed gasifier that had been under development there since 1951. Engineers tinkered with the layout and lining of the reactor and altered the coal feeder, seeking enhanced performance and an end to the erosion problems that had afflicted previous versions.

The Morgantown station had emerged as a national leader in the development of coal-fired gas turbines.

In 1963, however, the coal-gasification group set off in a new direction. It began planning another pilot plant that jettisoned key features of previous Morgantown coal-gasification projects. Instead of an entrained bed, this gasifier had a fixed bed. It did not use pure oxygen; rather, it combined air and steam with coal at slightly elevated pressure to yield what was called producer gas or fuel gas, which had a much lower heating value than conventional synthesis gas. Completed in 1968, the new plant was essentially a modification of the commercial Lurgi gasifier, a device that manufacturing industries used to make low-cost gas for fuel and chemical processing.

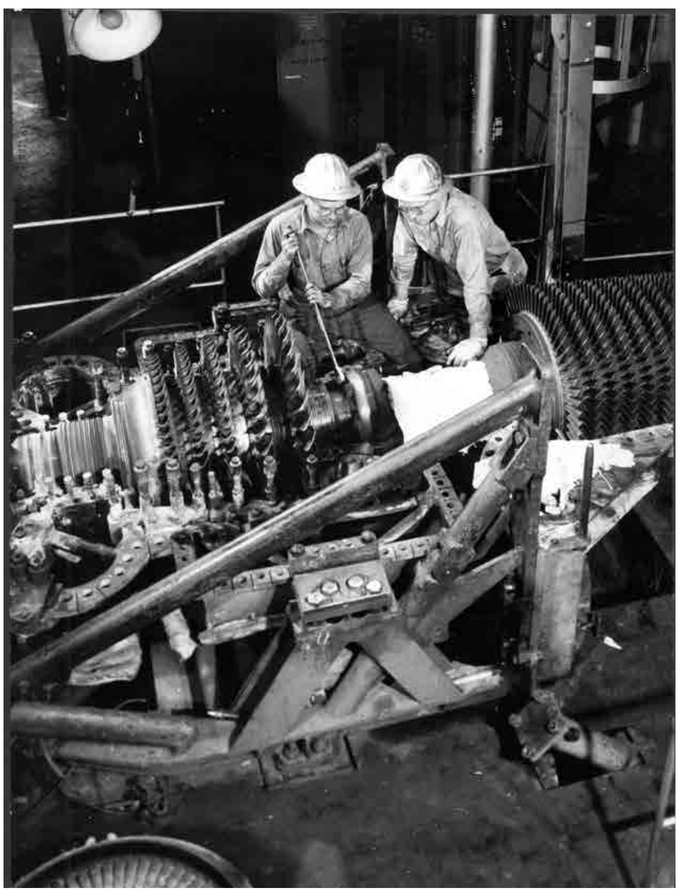
Several reasons informed the engineering choice of a simpler gasifier that generated a lower-grade gas. With no large-scale demand for synthetic liquid fuels on the horizon, officials at Morgantown calculated that what they needed most was a dependable source of gas that could be used for multiple purposes. The Lurgi fixed-bed technology was familiar, durable, and capable of operating with most kinds of coal. Its worst shortcoming, an inability to handle the many American coals that had strong tendencies to "cake" or agglomerate, was overcome by adding an agitator that kept coal inside the reactor from clumping together. Since it did not need costly pure oxygen, it was inexpensive to run. This gasifier was suitable for many tasks at the station, from analyzing fundamental coal-gasification reactions to pursuing two topics that had become pivotal to applied research at Morgantown: gas turbines and gas purification.

Very recently, and almost by chance, the Morgantown station had emerged as a national leader in the development of coal-fired gas turbines. The origins of its turbine program lay in the private sector. Back in 1945, a group of coal companies, joined by several railroads that received much of their freight business from coal hauling, had raised a question: Could coal-burning locomotives be made competitive with the newfangled diesel-electric locomotives that were rapidly displacing coal power on American railways? Bituminous Coal Research, Inc., a private organization serving the coal industry, had agreed to organize an investigation. The Locomotive Development Committee (LDC) was born.

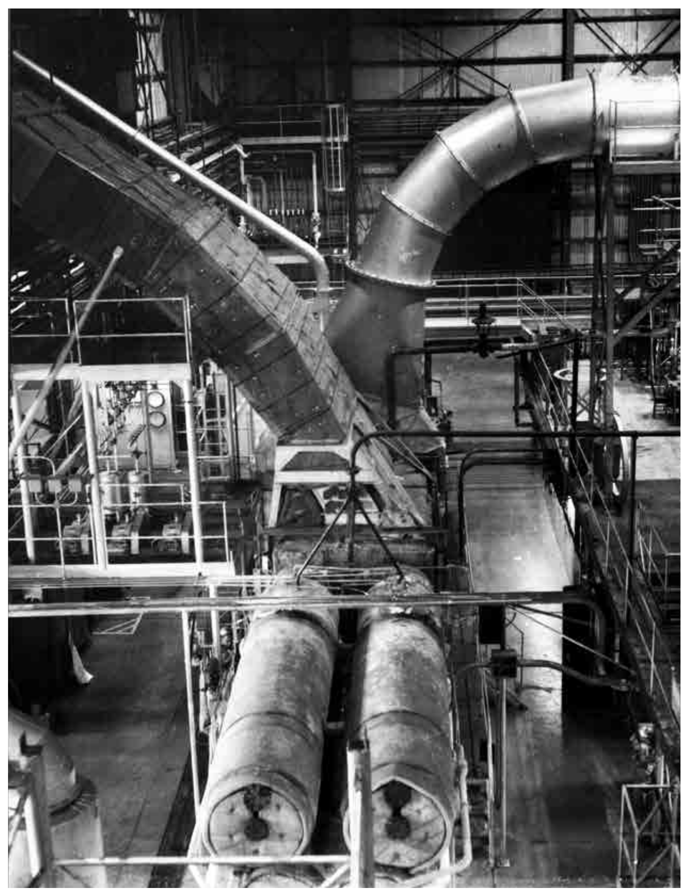
For the next fourteen years, the LDC explored the possibility of installing a coal-fired turbine engine in a railroad locomotive. A working prototype was built and tested at the LDC's facilities in the Lake Erie port city of Dunkirk, New York. In 1959, however, the LDC conceded that the forces of petroleum had triumphed over coal in the locomotive market. Proclaiming its locomotive turbine to be a technical success, but recognizing that the economics of the project were impossible, it offered to loan the prototype to the Bureau of Mines for further study. Bureau officials eagerly accepted.

The LDC turbine at Dunkirk was dismantled, shipped to Morgantown, and carefully reassembled. Its new overseers, under the direction of James Paul McGee, proposed to turn it into the nucleus of a high-efficiency stationary power plant. To do so, Bureau engineers had to solve a problem that the LDC had been unable to fix. The engine worked by burning a mixture of compressed air and pulverized coal to generate a stream of hot exhaust gas that rotated the turbine. But that gas carried ash and dust that severely eroded and fouled the turbine blades. The Morgantown researchers initially concentrated on reconfiguring the blades so that they were less vulnerable to this damage. Test runs that began on August 14, 1963, revealed substantial improvement, but ash deposits continued to keep the experimental turbine from coming anywhere near the standards of life expectancy that a commercial power plant would require.

Removing more of the dust and ash from the combustion gases before they hit the turbine was another logical step. In 1964, the gas-turbine project group installed what C. C. Shale, a research chemist at Morgantown, described as "the first electrostatic precipitator of semi-commercial size ever designed for operation at high temperature and high pressure." The principle of filtering solid particulates out of a flowing gas through electrostatic attraction had been known



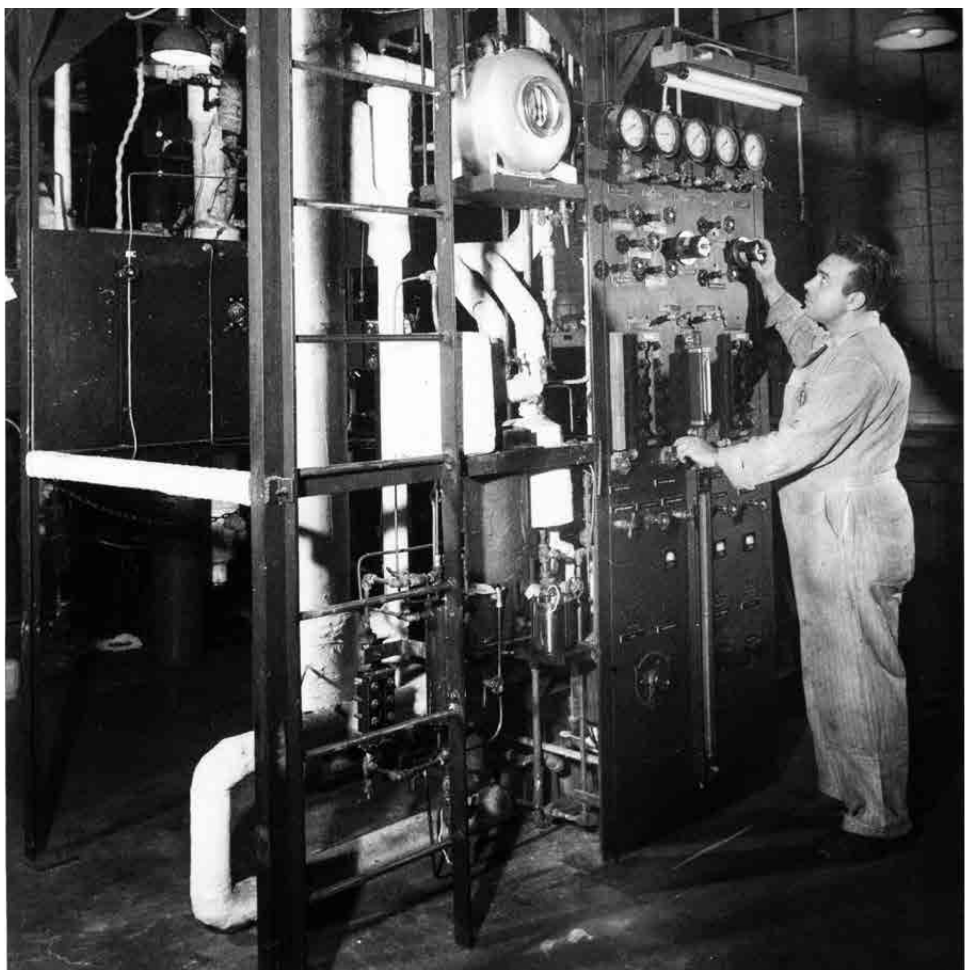
Close-up view of blades in the coal-burning gas turbine engine, 1964.



Overview of the gas-turbine installation at Morgantown.

since the early twentieth century, but existing precipitators for industrial use were not suitable for the harsh conditions in a gas-turbine power plant. Based on previous studies, the new precipitator design reflected the Morgantown station's program of research on methods of sampling and analyzing dust-filled gases and improving dust control.

Early in the turbine project, the Morgantown staff recognized that the problems with dust and ash might also be lessened by burning synthesis gas or fuel gas to power the turbine instead of burning pulverized coal directly. "Coal gasification or carbonization processes can be used to produce gases that are almost dust-free," McGee and his colleagues noted in a March 1963 article. Yet the turbine group hesitated to recommend this course of action due to a lack of confidence that linking a coal gasifier and turbine would be economically viable. The unfavorable cost differential between synthetic gases and natural gas or raw coal remained discouraging.



A fluidized-bed Fischer-Tropsch reactor at Bruceton, one of several devices used in early experiments with making substitute natural gas from coal during the mid-to-late 1950s.

These doubts faded as the engineers kept grappling with the logistics of getting from the original LDC railroad-engine design to a usable means of generating electricity in a stationary plant. An inexpensive source of gas from coal—such as Morgantown's modified Lurgi gasifier—came to be seen as a reasonable option. The General Electric Corporation, which was partnering with the Bureau on turbine development, thought along similar lines. By 1970, the Morgantown station was at work on a concept for integrating its coal-gasification, dust-removal, and turbine technologies.

The Pittsburgh Coal Research Center gained an international reputation for its basic research on the chemistry of coal-to-liquids conversion.

Growing concerns about the rising price and dwindling long-term supply of natural gas in the U.S. helped to make coal gasification more attractive. As early as 1962, forecasts from the American Gas Association and others hinted that the postwar era of abundant natural gas might be coming to an end. Supply was falling behind demand, and known domestic gas reserves might not last to the end of the twentieth century. The federal government and the gas industry began looking for alternatives in case a gas shortage emerged. These trends shaped the path of gasification research at the Pittsburgh station, which became the Bureau's leader in studying the production of substitute natural gas (SNG) from coal.

Chemically, natural gas and synthesis gas derived from coal are not very far apart, but their differences matter. Natural gas consists almost entirely of methane. Synthesis gas, composed primarily of carbon monoxide and hydrogen, contains some methane to begin with and can be almost entirely converted into methane through the process of *catalytic methanation*. The heating value of natural gas greatly exceeds the heating value of synthesis gas, meaning that equipment tuned to burn one efficiently will not perform properly when burning the other. In 1964, the Pittsburgh Explosives Research Center used its knowledge of combustion to determine what blends of synthesis gas and natural gas could be used without causing burner malfunctions and safety hazards in stoves and furnaces that were built to operate on natural gas. It found that the hydrogen content of any such mixture must remain below 37 percent.

Chemical engineers studied several SNG processes in the Bruceton synthetic-fuels laboratories. One of the earliest approaches involved a version of the Fischer-Tropsch synthesis called the hot-gas recycle process, which used gas circulation to cool the reactor. Bureau personnel noticed in experiments during the late 1950s that this process was adept at producing gaseous fuels as well as liquid ones. With the right catalysts, a hot-gas-recycle Fischer-Tropsch reactor could turn synthesis gas into nearly pure methane instead of into oil.

During the 1960s, Bruceton shifted to the development of two new gasification processes that were specifically designed to yield SNG. The Synthane process, an outgrowth of the station's Fischer-Tropsch research, derived a methane-rich synthesis gas from coal in four steps. A fluidized bed of pulverized coal was exposed to steam and oxygen at low temperatures in a pressurized pretreatment reactor, eliminating any tendency for the coal to "cake" unevenly.

Gasification was then completed in a second pressurized fluidized-bed reactor at much higher temperatures. After purification, the resulting synthesis gas went to a Bureau-designed methanator for final conversion into a high-Btu gas that could replace natural gas. In the Hydrane hydrogasification process, raw coal was changed to SNG-quality gas through hydrogenation with no need for added oxygen. Multiple reactors carbonized coal, combined it with hydrogen, and purified it to form methane.

These processes grew directly out of routine studies of coal hydrogenation and the Fischer-Tropsch synthesis at the Bruceton laboratories. Testing catalysts and evaluating different reactor designs proceeded continually on a small-scale basis. The Pittsburgh Coal Research Center gained an international reputation for its basic research on the chemistry of coal-to-liquids conversion and for its digests of relevant information, such as a 1968 bulletin that summarized the history and principal findings of coal-hydrogenation investigations worldwide.

By the early 1970s, the worsening natural-gas situation seemed about to lift the Bureau's work on synthetic fuels out of obscurity and into the limelight. The long-projected gas shortages were on the verge of becoming reality. Some natural-gas suppliers in the Northeast and the Midwest had stopped accepting new customers and were warning publicly that they might not be able to meet all their contractual obligations. Amid ominous talk of an energy crisis, the Office of Coal Research was funding half a dozen privately conducted SNG projects identified by bewildering names: HYGAS, BIGAS, COED. Coal research was once again acquiring a sense of urgency.

A Bartlesville engineer using field instrumentation to detect the flow of low-level radioactive tracers underground.

Going Nuclear

Alongside the Bureau and the OCR, a third federal entity joined in the post-1955 quest for more efficient production and creative use of fossil fuels: the Atomic Energy Commission (AEC). The AEC, founded in 1946 as an outgrowth of the wartime Manhattan Project, was the civilian agency that controlled the nation's supply of fissionable nuclear materials. It had already established a cordial working relationship with the Bureau on the development of uranium mining in the United States and on the rare-metals program at the Albany station. Beginning in the mid-1950s, as the federal government advocated peaceful commercial uses of atomic energy, the partnership widened to explore potential intersections between this newborn industry and the traditional energy sources of coal, petroleum, and natural gas.

Fossil-energy producers had long used high explosives to loosen tight sandstone or shale reservoir layers; it was logical to posit that a nuclear blast could accomplish the same task.

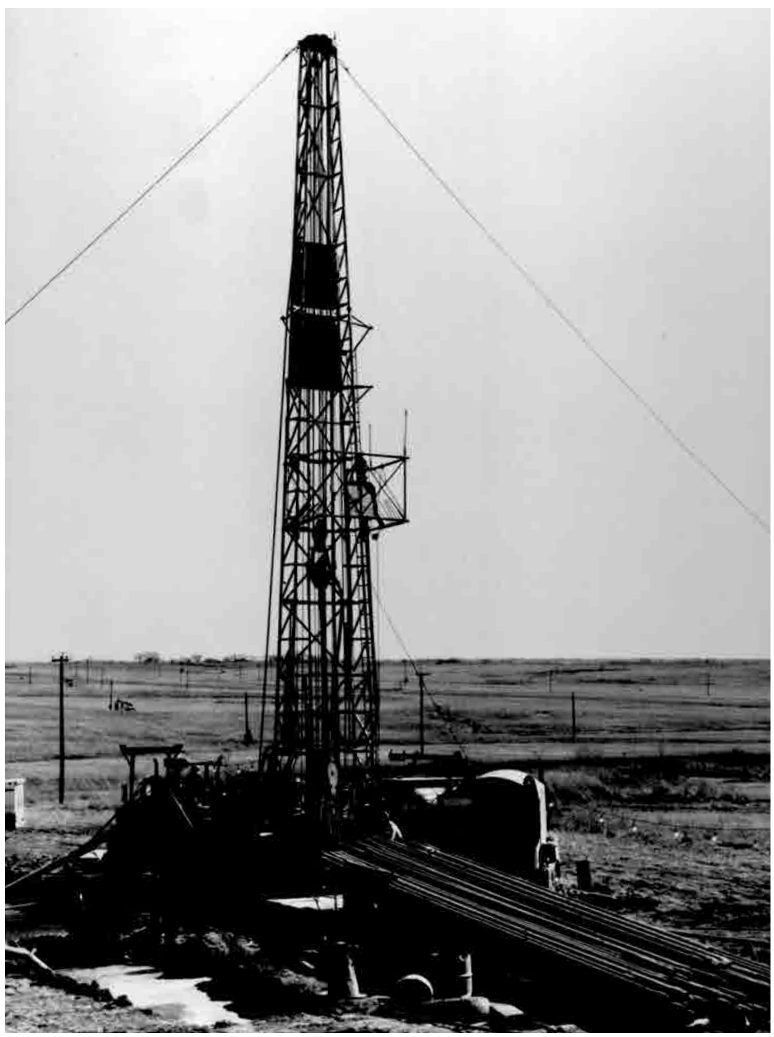
Atomic energy had several possible applications to the Bureau's fossil-energy research and development programs. It could make visible the normally hidden structures and flows of mineral resources. In the work of the Bartlesville station, radioactive tracers were helpful for tracking the underground movement of liquids and gases. Bartlesville had operated a radiochemical laboratory—a "hot lab"—since 1951 to prepare these tracers for use in waterflooding projects. The August 1968 edition of *The Research Reporter*, the Morgantown station's internal newsletter, noted that a team of researchers there was developing "a meter that could 'see' into . . . coal and give instant and continuous values for moisture and sulfur" by bombarding coal samples with neutrons and observing how the neutrons scattered and rebounded.

Heat for industrial processes might also come from nuclear reactions. In 1955, the AEC and the Bureau's coal-gasification section at Morgantown began investigating the possible use of nuclear reactors in coal gasification. A model developed between 1959 and 1964 used electricity to simulate the indirect transfer of heat from a small nuclear reactor to a gasifier via a stream of helium that circulated between the two. Evaluations of this scheme judged that it could work but was impractical with available technology.

But the most attention-grabbing elements of the joint AEC-Bureau of Mines research agenda involved nuclear explosives. In 1957, the federal government launched the Plowshare Program to demonstrate that nuclear bombs could have beneficial uses in civilian industries such as mining and construction. (The program took its name from a biblical verse (Isaiah 2:4) that prophesied the transformation of weapons into instruments of peace: "And they shall beat their swords into plowshares . . .") Stimulating the output of petroleum, natural gas, and shale oil became a major focus of this initiative. Fossil-energy producers had long used high explosives in attempts to loosen the tight sandstone or shale reservoir layers that held precious oil or natural gas captive or reduced its flow to an uneconomical rate. It was logical to posit that a nuclear blast could accomplish the same task, particularly in unusually stubborn underground rock formations that resisted conventional blasting techniques.

The idea of using nuclear explosives to liberate fluids from rock had gained enough plausibility by the late 1950s that J. Wade Watkins, a petroleum engineer at the Bartlesville Petroleum Research Center, began to study it seriously. After all, the AEC had detonated many nuclear bombs underground at its Nevada Test Site near Las Vegas since the end of World War II. No ill effects from those tests had been reported so far, so why not try something comparable that might benefit the petroleum and natural-gas industries?

It was not until 1962 that another engineer at the Bartlesville center, Charles H. Atkinson, suggested an actual demonstration of the concept in a natural-gas field. His proposal evolved into Project Gasbuggy, a component of the Plowshare Program. Calculations done in 1966 estimated that the use of nuclear explosives to shatter gas-bearing sandstone formations might increase the amount of recoverable natural gas by 317 trillion cubic feet. "This estimate,"



Derrick for Operation Gasbuggy, an underground nuclear explosion intended to fracture rock and release natural gas, near Farmington, New Mexico, 1967.

Atkinson said, "indicates that, if successful, nuclear fracturing could possibly account for reserve increases about equal to the present domestic proved gas reserve." If Gasbuggy worked, it might lead to hundreds of similar underground explosions that would revolutionize American natural-gas production.

Three private firms competed for the right to participate in Project Gasbuggy: Continental Oil Company, Austral Oil Company, and El Paso Natural Gas Company. By early 1967, only El Paso Natural Gas was ready to go at its site in the San Juan Basin of northwestern New Mexico; the other companies, with proposed sites in Colorado, were not prepared. On February 1, 1967, El Paso Natural Gas executives signed a contract with the Bureau of Mines and the AEC to provide roughly 37 percent of the estimated $4.7 million project cost.

Engineers and laborers spent the next three months drilling an exceptionally wide 18-inch-diameter gas well to a depth of over 4,200 feet through the Pictured Cliffs sandstone formation, 55 miles east of Farmington, New Mexico. Next came six months of testing the gas flow rates in the well to establish a baseline that the researchers could later compare to post-blast flow rates. A 29-kiloton nuclear bomb was lowered into place and sealed in concrete in mid-November, but the failure of a water pump in the bottom of the well caused a delay of several more weeks.

Finally, on December 10, 1967, detonation took place. The ground at the test site rippled in seven-foot-high waves radiating from a single point, like water running away from a pebble dropped in a pond. At a command tent two and a half miles away, Charles Atkinson of the Bureau, James E. Reeves of the AEC, and James Holcomb of El Paso Natural Gas were knocked off their folding metal chairs. Seismic measurements equated the rumble of the Project Gasbuggy test to the explosion of 26,000 tons of TNT, or 8 million quarts of nitroglycerin. The first nuclear blast ever sponsored by a public-private partnership had gone off without a hitch.

A feasibility study performed in 1965, based on the AEC's experience at the Nevada Test Site, had predicted that "the blast would vaporize the rock around it and create a subterranean chamber deep below the surface. The roof of the chamber would fall in, and a 'collapse zone,' or area of broken rock, would form above it to a height of about 350 feet and a width of about 130 feet. This would, in effect, create a large storage chamber into which gas would flow through innumerable fractions extending in all directions." When re-entry drilling was finished on January 10, 1968, these projections were confirmed. A collapse zone—called the chimney—about 333 feet tall was seen, and geologists estimated that the explosion had produced cracks extending out to approximately 440 feet in all directions. Natural gas that accumulated in the underground chamber was radioactive, but to a lesser degree than had been expected.

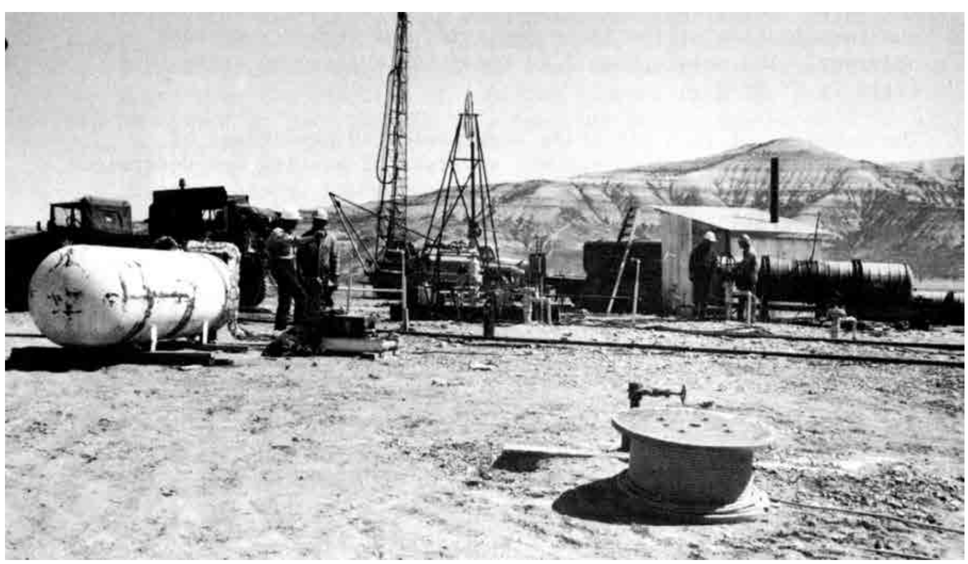
After further delays in obtaining funds for reopening test wells that had been placed 170 feet and 300 feet away from the epicenter of the explosion, solid numbers on the effects of Project Gasbuggy were in by May 1968. The news

The Bartlesville Petroleum Research Center celebrated its 50th anniversary in 1968. They held a logo competition; of the four entries, this logo was chosen by the employees to best represent the Bureau's work over 50 years.

was encouraging: Gas production from the Pictured Cliffs formation had greatly increased. "When the well was drilled before the shot, the flow of gas into it amounted to 12,000 to 15,000 cubic feet per day," explained Harry Gervertz, staff assistant to the director of exploration at El Paso Natural Gas. "Now, after the shot, the flow appears to be at the rate of 3.5 million cubic feet a day." Nevertheless, the company and the Bureau were cautious. "There is a long way to go between an experimental shot like Gasbuggy and economically feasible industrial use," Gervertz said, warning that the unorthodox well design used at the test site "would be economically prohibitive to industry."

Even more prohibitive was the refusal of El Paso Natural Gas's customers in California to buy the radioactive natural gas that Project Gasbuggy generated. Since there was no demand for it, virtually all the gas that emerged from the test wells over the next several years was vented or flared off into the atmosphere. Subsequent underground explosions modeled on the Gasbuggy precedent also stirred public concern about safety and environmental risks. In Project Rulison, the AEC and Austral Oil exploded a 43-kiloton nuclear bomb on September 10, 1969, in a natural-gas field just twelve miles from Rifle, Colorado, near the location of the Bureau's previous oil-shale experiments. A third test, Project Rio Blanco, simultaneously detonated three bombs totaling 90 kilotons elsewhere in Colorado's Piceance Creek Basin on May 17, 1973. All created gas that was too radioactive for sale.

The staff of the Bureau's Laramie Petroleum Research Center watched these events with interest because similar ideas were percolating in oil-shale research. Cooperation among the Laramie, Bartlesville, Pittsburgh, and Denver stations and the U.S. Navy on techniques for breaking up shale with high explosives had begun in 1964. A key goal of this work was to advance *in situ* ("in-place") retorting, which extracted oil from the shale without mining it.



Site of the first in situ oil-shale retorting test near Rock Springs, Wyoming, 1969. (photo credit: Bureau of Mines publication)

Resembling underground coal gasification, *in situ* retorting involved creating a network of fissures in an oil-shale deposit and then using them to set a controlled underground fire whose heat converted solid kerogen into oil and gases. If feasible, this process could slash costs by eliminating the problems of mining and transporting shale and disposing of waste rock. But oil shale was notoriously difficult to fracture and lacked the natural pores and cracks that offered starting points for underground gasification in coal seams.

By 1966, engineers at Laramie, led by J. L. Eakin, were anxious to try out a three-part approach that reduced oil-shale deposits to rubble through a combination of electrical currents (electrolinking), hydraulic fracturing, and liquid nitroglycerin explosives. The first full-scale *in situ* retorting experiment using this process took place in 1969 in the Green River Formation near Rock Springs, Wyoming. After a rubble zone was created, the broken shale was ignited and heated underground for six weeks. About 190 barrels of shale oil arrived at the surface via carefully placed wells. A second *in situ* test followed at Rock Springs in 1971.

A large block of spent oil shale after an above-ground retorting experiment, 1967. Light areas were oxidized during heating and combustion, while the dark center area still contains unreacted residual carbon. This block originally weighed about 650 pounds. (photo credit: Bureau of Mines publication)

Could nuclear explosives achieve the same or better results with less time and effort? The Bureau devoted much thought to this question. Findings from the Laramie station's laboratory research on the behavior of kerogen and shale oil suggested that an underground nuclear collapse zone would be a favorable environment for *in situ* shale-oil production. To simulate the conditions that they expected to find inside the collapse zone, the engineers constructed a 150-ton-per-day, above-ground retort for processing very large and irregularly shaped chunks of oil shale. Working with the AEC, the Bureau drew up plans in 1967 for Project Bronco, a proposed experiment to set off a 50-kiloton nuclear bomb in Green River Formation oil shale at a site in western Colorado.

But Project Bronco was never implemented, and enthusiasm for the concept waned as the realization sank in that nuclear explosives were no magic solution for expanding fossil-fuel output. Too much remained unknown about how shale formations responded to high explosives of any kind, and radioactive shale oil seemed likely to be as useless as radioactive natural gas was. During the early 1970s, follow-up studies of the Rock Springs shale-fracturing experiments and the Operation Plowshare nuclear detonations indicated that the underground cracks formed in these tests were not as extensive, interconnected, or productive as first thought. On balance, the prospects for greater oil and gas yields did not outweigh the costs of nuclear materials and the environmental hazards. The Plowshare Program quietly wound down in 1975, and efforts to pry fossil fuels out of "tight" rock turned to less exotic methods.

Clearing the Air

In 1948, a young mechanical engineer named Richard W. "Dick" Hurn had arrived at the Bartlesville station. Hurn, a self-described maverick, would chart his own path over the next few decades, achieving remarkable successes while ruffling a few bureaucratic feathers. His analyses of air pollution and his efforts to develop an emissions-control system for automobile engines provided another window on emerging relationships between energy research and concerns about environmental quality during the late 1950s and the 1960s.

Hurn's initial assignment in the Fuels Combustion Research group of the Chemistry and Refining Branch at Bartlesville was to study the combustion properties of diesel fuels, a continuation of work he had done at the University of Wisconsin to earn his master's degree. Diesel was assuming greater importance as railroads switched from steam power to diesel power and as increasing numbers of commercial trucks traveled the nation's expanding system of roadways. Hurn was given the engine laboratory that had been used to test aviation fuels during World War II to carry out his research.

To study the chemical reactions that created smog, Hurn and his colleagues developed one of the first "environmental smog chambers" in the world.

By 1951, Hurn had tired of the diesel studies and had become interested in the mysterious smog that was a growing problem in the atmosphere above the nation's big cities, especially Los Angeles, California. Although it was obviously tied in some way to the rapidly increasing number of automobiles that Americans were buying and driving, no one understood the chemical mechanisms by which smog formed from engine exhaust. Sources outside the Bureau were interested in the problem, and they had money to investigate it. Hurn proved to be adept in obtaining outside funding for his research; despite Bureau rules that research should be dictated by government directive and not the availability of outside funds, he was given some leeway in this matter. In the early 1950s, he and his colleagues developed a constant-volume combustion bomb calorimeter that would prove to be essential in thermodynamic studies of the properties of exhaust gases—a significant contribution to science.

By 1955, the Los Angeles smog problem had reached nuisance proportions and had attracted international interest. Hurn had the resources to attack the problem full time, but was handcuffed by other responsibilities. Chief among these was supporting a "regional exchange group" that had been established in World War II to ensure that various laboratories were using the same procedures and obtaining the same results in octane testing of fuels essential to the war effort. This octane testing was still a major function of the Bartlesville station ten years after the war ended.

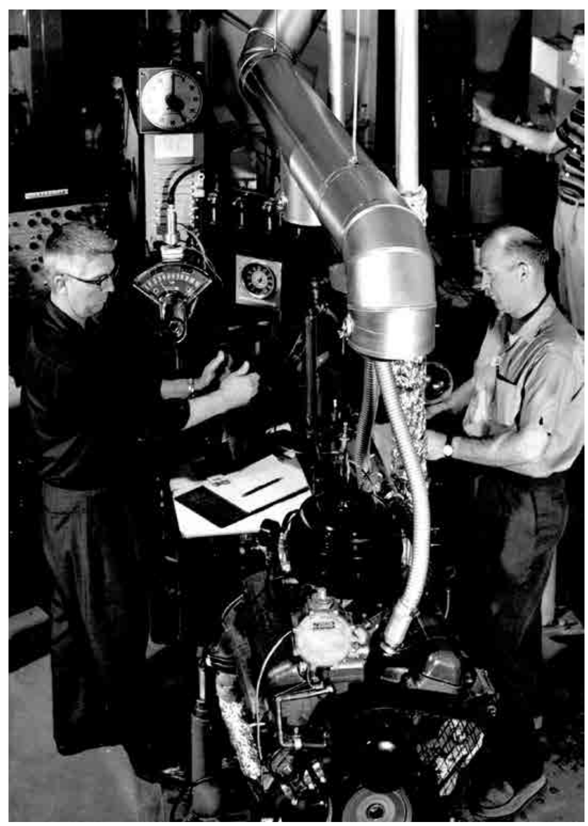
Hurn wanted to use the engines that were tied up with octane tests for his smog-testing activities. When he told Superintendent Harry S. Fowler that he was shutting down the exchange-group operation, Fowler replied that it was an institution at Bartlesville. Hurn countered that he had been hired to work, not to maintain institutions. This incident was just one example of Hurn's bold and brash approach to research that did not win friends, but did produce results. As Carlisle and Giebelhaus wrote in their Bartlesville history, "Few others at the center in the 1950s had his combination of abrasive independence of mind, energy, drive, and willingness to work closely with people in the regulatory agencies."

To study the mechanisms of the chemical reactions that created smog, Hurn and his colleagues developed one of the first "environmental smog chambers" in the world. Essentially an air-tight glass box surrounded by lamps to simulate sunlight, the smog chamber was filled with purified air, followed by a small amount of engine exhaust. The ratio of air to exhaust molecules was maintained at 1000 to 1. At this point, the chamber remained transparent. When the lamps were turned on to add sunlight to the mixture, the chamber soon filled up with the cloudy smog seen in the skies above major cities. This result showed that smog formation was a "photochemical reaction"—it required sunlight, which caused exhaust-gas molecules to react with atmospheric air to produce smog.

The smog chamber was equipped with sample ports through which the gases inside could be routed automatically to advanced analytical instrumentation outside. This instrumentation included the relatively new *gas chromatograph*, which could separate a complex mixture of gases into its individual components so they could be identified and quantified. By taking samples of the gases at intervals during the reaction process and analyzing them with the gas chromatograph and other instruments, the mechanism—the step-by-step pathway from reactants to intermediate chemicals to final products—of the smog reaction started to yield its complex secrets.

A January 1964 article in the *Bartlesville Examiner-Enterprise* summarized the findings: "Hurn said that tests show that smog is made from unburned and partly burned fuels of combustion and products formed in combustion coming into contact with the atmosphere in the presence of sunlight. Since the sun

Don Merckling and Patricia Simpson take a pressure reading on Hurn's smog chamber, 1961.



Engineers measure pollutants coming from an automobile engine.

will not shine in heavy fog or smoke, smog forms only in clear sunlight…. The exhausts go into the atmosphere, mixing with the oxides of nitrogen, which react with the fuel components and a photochemical reaction takes place, creating the haze known as smog." This explanation was a simplified one; the many chemical reactions involved in smog formation would take many more years of research to unravel. Still, the Bartlesville station was contributing to a growing pool of knowledge.

Richard Hurn's smog studies began drawing attention and funding from such groups as the American Petroleum Institute, the Public Health Service, and the California cities of Los Angeles and Sacramento in the early 1960s. This attention only increased when Congress passed the Clean Air Act of 1963. Newly arrived Director John S. Ball welcomed the attention and the outside funding that Hurn attracted to Bartlesville. In the spring of 1964, Ball separated the Fuels Combustion Group from the Chemistry and Refining Section, creating a new section with Hurn as the leader.

With his new freedom and Ball's sanction, Hurn next turned his efforts to preventing air pollution from automobiles. He decided to focus on the front end of the combustion process by developing a system that would lead to more complete burning of gasoline in the engine. Complete combustion of hydrocarbons such as those that comprise gasoline produces carbon dioxide and water, with no nitrogen oxides or carbon monoxide.

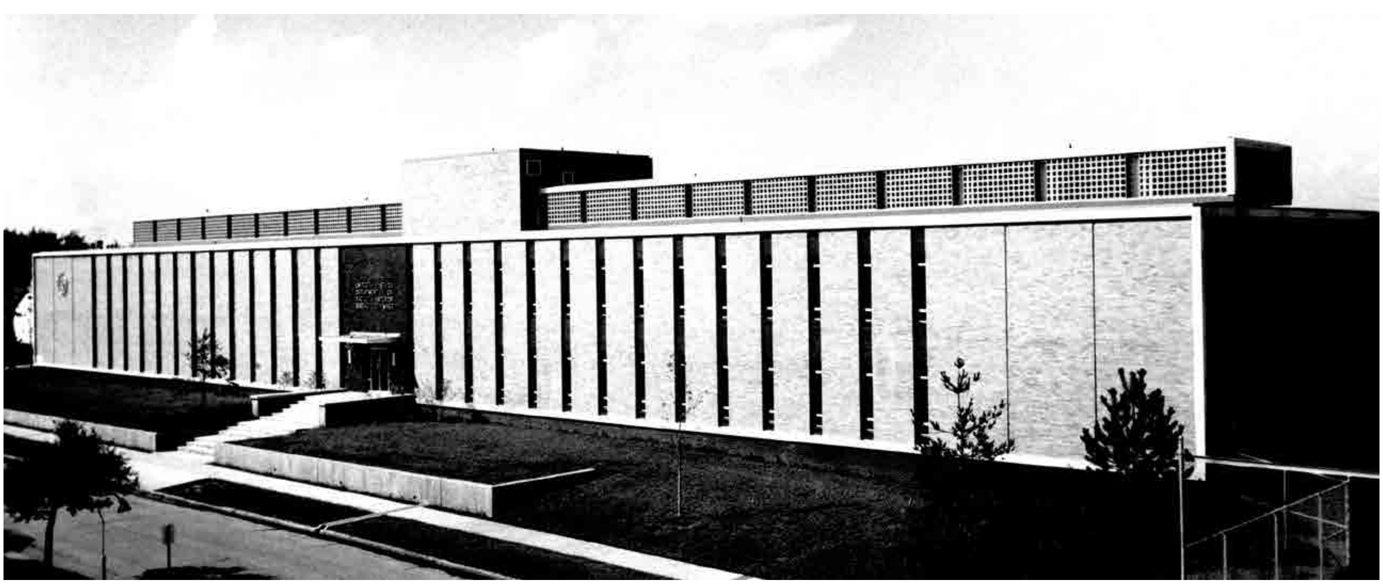
To understand the intricacies of automobile emissions, the scientists and engineers of the Fuels Combustion Research Section had to determine the type and concentration of automobile exhaust compounds under a wide variety of driving conditions. The quality of fuel, the driving speed, the frequency of stopping and starting, the ambient temperature, the ratio of fuel to oxygen in the carburetor—all these variables and more had to be studied. Hurn's team developed electronic controls that could be preset to put an engine through a range of driving conditions—an updated version of the data-gathering process that an earlier generation of Bureau researchers had conducted during the Holland Tunnels ventilation investigations of the early 1920s. The group also monitored the amounts of vapors evaporating from the carburetor and the fuel tank, because unburned hydrocarbons from any source could contribute to smog formation in the atmosphere.

Concurrently, Hurn worked with E.I. DuPont and Company to develop a device that would reduce the pollution coming from an engine. In 1967, he demonstrated the operation of his "exhaust manifold reactor," which took the normal exhaust gases and burned them a second time before exiting the tailpipe. The reactor consisted of two 4.5-inch-by-22-inch alloy-covered cylinders that covered the sides of a V-8 engine. Exhaust gases resulting from the first pass through the engine were intercepted and pumped through this reactor along with additional air, resulting in the burning of excess hydrocarbons, carbon monoxide, and nitrogen oxides. The exhaust from this second combustion pass then flowed out of the car's tailpipe.

Hurn's device did reduce emissions. When fitted to the engine of a 1966 Chevrolet Impala during tests conducted in 1967, the exhaust-manifold reactor decreased the amount of unburned fuel that was released into the atmosphere by a factor of nine, nitrogen compounds by a factor of two to three, and carbon monoxide by a factor of four. The remaining concentrations of unburned hydrocarbons and carbon monoxide were far lower than the target levels that the State of California had set for 1970. Only the nitrogen oxides failed to meet the California standard, which was 350 parts per million; the Bartlesville group was able to achieve only 400 to 600 parts per million. Walter R. Hibbard, the director of the Bureau, noted that this "work has refuted the pessimistic view that nitrogen oxides can be reduced below a certain level only if we are willing to accept higher levels of other contaminants."

The Bureau and Secretary of the Interior Stewart L. Udall were enthusiastic about the engineering concept that Hurn had demonstrated, viewing it as a significant step forward in the burgeoning field of research on the control of automobile exhaust pollution. But in the end, Hurn's manifold reactor lost the technological race to an alternative method developed by private industry: the catalytic converter, which cleaned up the exhaust stream by catalytic reactions just before it left the tailpipe. Catalytic converters began to appear on mass-produced motor vehicles in the mid-1970s and made a substantial contribution to reducing air pollution. Yet this achievement rested in part on the pioneering smog studies that Hurn and others had done at Bartlesville.

Other important petroleum-related investigations continued. In 1959, the Bartlesville station published a 181-page report detailing the properties of more than 3,000 crude oils worldwide. This document resulted from 40 years of research. Bartlesville had been involved since its inception in analyzing



The Bartlesville Physical Sciences and Engineering Building, 1963.

and characterizing samples of crude oils, first from the Mid-Continent region of the United States and then from elsewhere in the country and around the world. Its scientists were instrumental in developing analytical techniques that became standard throughout the petroleum industry.

In the space of thirteen days, the Albany station announced three scientific breakthroughs that gained international attention.

The thermodynamics program, led by Guy Waddington, John P. McCullough, and Don Douslin after H. M. Huffman's departure, continued to lead the world in this vital area of basic science. API Project 48 ended in 1966 after identifying 175 sulfur compounds in four different crude oils. The data it had generated assisted the petroleum industry in improving refinery processes and products. Financial support from the American Petroleum Institute (API) was crucial to the success of this program; indeed, the thermodynamics group at Bartlesville might have ceased to exist in the 1960s without the API's backing. During the mid-1960s, the institute entered into two new cooperative agreements with the Bureau: one to investigate high molecular weight compounds in petroleum (heavy ends), and another to examine thermodynamic properties of hydrocarbons and related substances. Renewed doubts about the nation's petroleum supply toward the end of the decade lent additional importance to such work.

After years of asking for more laboratory space, Bartlesville officials had finally gotten their wish when the federal General Services Administration approved the design for a new Physical Sciences and Engineering laboratory building in 1960. Groundbreaking was held on January 11, 1961, at the intersection of Virginia Avenue and Cudahy Street. The building was completed on August 15, 1962, and employees began to move in shortly thereafter. A formal dedication ceremony was held on April 9, 1963, at which a Dedication Plaque was unveiled. The plaque bore this fitting inscription: "The men and women who work here are the heart and soul of the research center."

Rare Metals at Albany

The Kroll Zirconium Process, the first great accomplishment of the Bureau's Albany Laboratory, was just the beginning of the many successes that station would have in developing methods to produce pure, rare metals. Further investigations showed that the Kroll process was applicable to more than zirconium and titanium. It turned out to be a very versatile and useful technique for obtaining other rare metals that were increasingly important in high-technology manufacturing industries. With this discovery and other innovations in rare-metals research, Albany quickly established a reputation as one of the foremost centers of metallurgical research in the country.

In 1956, Albany scientists were working with the mineral euxenite, which was known to contain the metals titanium, tantalum, and columbium. When boiling the mineral, titanium chloride distilled first, followed by a mixture of tantalum chloride and columbium chloride. The chemists developed a liquid-liquid extraction process to separate these latter two compounds from the mix, by first putting the mixture in an acid solution, and then adding organic solvents that selectively dissolved tantalum chloride or columbium chloride salts out of the solution. With tantalum and columbium now isolated in their chloride salts, it was simply a matter of finding a way of reducing the salts to the pure metal. Kroll, in his work with zirconium chloride, had already shown how to do so: add magnesium and then vacuum distill to produce pure tantalum and columbium. Other trace elements contained in euxenite, such as thorium and vanadium, were produced in pure metal form by the same method.

The metallurgist Frank Block described another method of purifying ores in an article that appeared on March 7, 1957, in the *Albany Democrat-Herald*. Because some metals are bound very tightly to the minerals that contain them, he explained, and because some of them react easily with air, they cannot be produced by ordinary smelting in a furnace. Block was the project coordinator of an effort to liberate rare metals such as molybdenum and vanadium by an explosive method called "bomb reduction."

"In a bomb reduction," Block wrote, "a metal is freed from its ore by reacting it with an even more active, but less costly, metal. In the process the active metal is consumed and is converted into a by-product slag. To conduct a reduction reaction of this nature, a special type of reactor is used which is usually called a bomb. These bombs are made in varying sizes depending on the scale of

Emil Anderson, a Bureau equipment mechanic, works on a reactor for the metal bomb reduction process.

Mass of molybdenum metal made using the metal bomb reduction process the operation and are constructed of thick steel cylinders because they must withstand great pressures."

For example, powdered magnesium--a cheap, easily available, and highly reactive metal--could be combined with the desired rare-metal ore inside a sealed steel cylinder. This procedure would cause an explosive reaction that produced temperatures of 5,000 °F and pressures of 5,000 psi. Heat was the key ingredient. "In bomb reduction it is necessary that the metal being produced as well as the by-product slag are heated until they melt in order that the metal can be made in massive form and separated from the slag," Block stated. The extreme heat could melt the steel cylinder, so the reactor had to be either lined with refractory materials or cooled by an external water spray. Another safety measure was to use a device that allowed the researchers to start the reaction by remote control. This precaution allowed them to stay far away from the concrete room that housed the bomb, keeping them out of danger if the bomb burst.

In the space of thirteen days during January 1959, the Albany station enhanced its leadership in the field of rare metals by announcing three scientific breakthroughs that gained international attention. The first of these achievements became publicly known on January 15. Robert A. Beall and his assistants Eugene D. Calvert and Stanley L. Ausmus reported that they had produced the world's first casting of molybdenum, a strong, lightweight metal that melts

(Left to right) R.A. Beall, E.D. Calvert, and S.L. Ausmus examine the first molybdenum casting ever made.

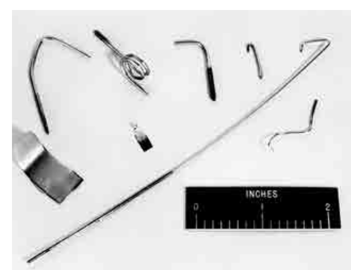
at the incredibly high temperature of 4,748 °F. Molybdenum's stability at high temperatures made it an ideal candidate for critical assemblies in extreme environments, such as the exhaust pipe of a rocket or missile.

Many attempts had been made to cast molybdenum into shapes before, but the high temperature of the molten metal destroyed any crucible that was used for casting. Beall and his colleagues finally succeeded by building incrementally on previous work at Albany over four years. Other researchers had used water-cooled copper crucibles to cast zirconium and titanium, metals with lower melting points; Beall's group just gradually worked its way up the temperature scale. "It was a big step ahead when we applied the technique to hafnium, which melts at 4,000 °F," Beall said. "It was just a matter of accumulating experience before we extended the casting to molybdenum."

Yttrium sponge (left) and ductile yttrium buttons first made at Albany in 1959.

To produce the small casting, which was a hollow cylinder only 4.5 inches in diameter and 8 inches long, the researchers melted 30 pounds of molybdenum using an electric arc in an inert atmosphere. When the molten metal reached the rotating, water-cooled, copper-lined crucible, the metal solidified on the walls of the crucible, forming the hollow cylinder. This small cylinder had large implications for the Cold War.

Because of its potential application to missile systems, the casting of molybdenum promised to advance the American position in the space race against the Soviet Union. Metallurgists believed that 90 percent of the molybdenum ore in the world was located in the United States, mostly in Colorado, thus putting the Soviet Union at a distinct disadvantage. In recognition of his research, Beall was given the 1959 Arthur S. Flemming Award for outstanding achievement by young people who worked for the federal government.



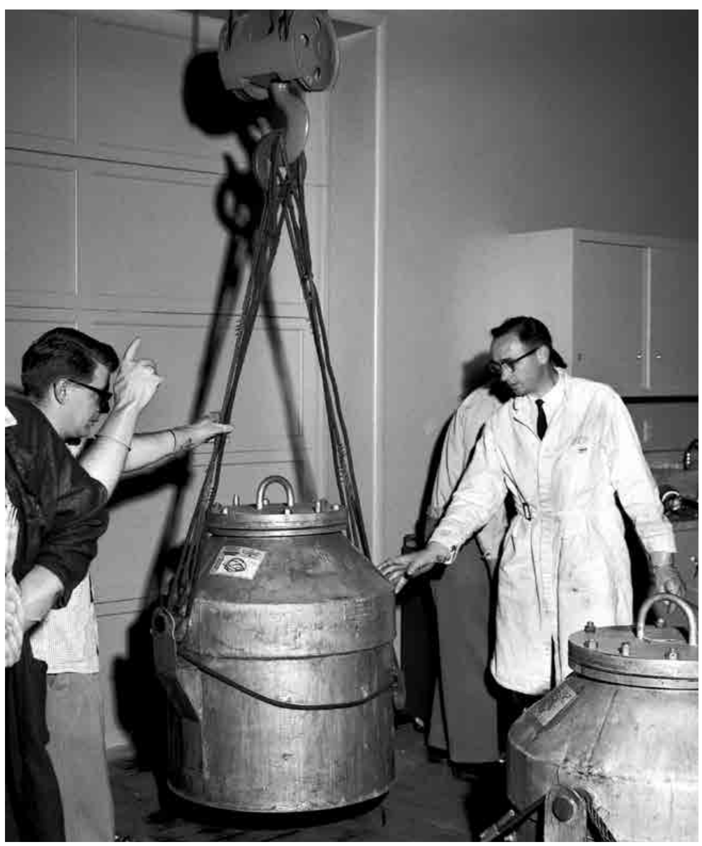
Samples of ductile chromium produced for the first time at Albany in the 1950s.

Just eleven days after the announcement of the molybdenum breakthrough, the Bureau trumpeted another development: the production of ductile yttrium metal at Albany. Following a year of research, Frank Block and his colleagues were able to make this brittle metal into a malleable form that could be readily shaped or even rolled into very thin sheets. Yttrium had long been desired by the atomic-energy industry for its low thermonuclear cross-section—its ability to let neutrons pass through to sustain a nuclear chain reaction. But few metallurgists thought it could ever become a structural material.

Block again built on previous research at Albany to devise a solution. William Kroll had established that removing impurities, even dissolved gases, from metals could improve their ductility; that understanding was one reason why he distilled zirconium and titanium under a vacuum. Using a process similar to Kroll's, Block was able to produce yttrium with a dissolved oxygen concentration of only 0.02 percent. The details of the process were withheld at the time because of the Atomic Energy Commission's desire for secrecy in breakthroughs involving atomic power. Like Beall before him, Block received the Arthur S. Flemming Award in 1960. In addition to his yttrium work, the award cited his "creation of a process now used by industry to separate columbium and tantalum, metallurgical 'Siamese twins' that long have defied conventional separation methods," and his "direction of research that led to a new process enabling industry to produce high-purity vanadium for less than half its former price."

The third achievement came two days after the yttrium announcement, on January 28, 1959. For the first time, metallurgists at the Albany lab had succeeded in melting thorium without contaminating it. Thorium had been hard to melt because it reacted with all the commonly used melting crucibles and became hard and brittle. "Bureau engineers found that the metal could be arc-melted in a water-cooled copper cup without affecting its purity," the *Spokane Chronicle* reported. "Until this melting method was developed…the atomic energy commission's 'breeder' reactor program was behind schedule for lack of high quality fuel elements."

Further intersections between atomic energy and Albany's metallurgical expertise emerged during the late 1950s and the 1960s. In June 1958, the Bureau revealed that high-purity chromium wire made at Albany had found an unusual medical application. Dr. William G. Meyers of the Ohio State University was investigating radioactive metals for implantation into tumors in an effort to extend the lives of cancer patients. Having discovered that the Albany center produced chromium that could be drawn into wires, Meyers looked up the half-life of radioactive chromium and found it to be 28 days—just the



Frank E. Block (in lab coat at right) directs the handling of the cask containing radioactive cobalt 60 rods in 1962.

right time span for cancer treatment. Chromium wires one-thirtieth of an inch in diameter were shipped to the AEC's Oak Ridge, Tennessee, laboratory and exposed to neutrons in a nuclear reactor there. The now-radioactive wires were then sent to Meyers, who inserted small quantities of them directly into cancerous human tissue so that the gamma rays the wires emitted could shrink the tumors. This research continued at the Argonne Cancer Research Hospital of the University of Chicago into the 1960s, with encouraging results.

Also in 1958, Albany's Research Director Mark White announced plans to build a radioactive Cobalt-60 "hot lab" on the site. Metallurgists hoped to use radioactivity to study how rare metals pick up and incorporate impurities. The project got underway in December 1961, with Frank Block serving as the project coordinator. By that time, Wright had been promoted to head Region 1 of the Bureau of Mines, and Alva H. Roberson, who had worked in the Bureau's metallurgy programs since 1935, was the new research director at Albany. Roberson announced that the purpose of the hot lab had changed: Researchers would use it to study the effects of gamma radiation on metals, chemicals, and fuels.

Scientist operates robotic arms to manipulate a rod in Albany's hot cell, 1962.

A radiation chamber was built in the former zirconium reduction building, with four-foot thick walls made of high-density concrete to prevent radiation leakage. Two windows, also four feet thick and made of leaded glass, allowed scientists to watch experiments and to maneuver materials inside the chamber using robotic arms. This facility would house 24 rods made of stainless steel and aluminum, each containing radioactive Cobalt-60. When not in use, the rods were submerged in a 17-foot-deep well of water, which rendered the chamber safe for humans. To start an experiment, they were raised out of the well on an electric hoist, allowing them to emit gamma rays that would interact with the material of interest. The rods would submerge automatically back into the well in case of emergency conditions.

In April 1962, the first lead-filled steel casks containing cobalt-60 arrived at Albany from the AEC's Savannah River plant in South Carolina. Eight cobalt rods were safely in place by early May, when the center held an open house for what was now being called the "hot cell." Alfred C. Jones, a writer for the *Capital Journal* in Salem, Oregon, was among the journalists who attended a preview on May 2. "It's an eerie feeling to walk into an irradiation chamber and look radioactive Cobalt-60 squarely in the face—through 17 feet of clear water," he wrote. He summarized the experimental process that would soon commence in the hot cell: "Cobalt-60 is heavier than normal Cobalt-59, having an extra electron in its outer orbit that makes it unstable or radioactive...When exposed to this strong radiation... metals and fuels may turn into something else. In other words, the radiation may knock electrons from the atoms of metal, causing them to join other atoms in chemical reaction and produce new alloys or metals."

The hot cell went live in July 1962, with 120,000 curies of radioactivity available. It was operated from 1962 to 1968, irradiating samples of many different metals and other materials. Despite the major investment and the initial optimism, however, few interesting results emerged from the hot-cell research, and the Cobalt-60 program was shut down in February 1968 for lack of funds.

A Change of Direction

Research plans at the Albany Metallurgy Research Center took a dramatic turn on November 12, 1965, with the announcement of a high-priority "crash project" to develop a method of preparing automotive scrap for use in steel production. This endeavor responded to the rising challenge of disposing of junked vehicles. Nearly six million automobiles were scrapped in the United States during 1965, and the numbers were rising. Junkyards had become such a visible and spreading blight on the land that President Lyndon Johnson's wife, Lady Bird Johnson, took a personal interest in the situation and urged that something be done to clean up the American countryside. Congress had passed the Solid Waste Disposal Act of 1965, and the Bureau of Mines took on the responsibility for developing a technical solution to the scrap-car problem. The project was assigned to the Albany center under the leadership of Lloyd Benning. Reflecting the political origins of the effort, Banning's team was playfully called "Lady Bird's Helpers."

The group built a structure to house a kiln for burning old cars. Filters on the kiln trapped the effluent gases and prevented air pollution. Scrap cars were purchased in the Portland, Oregon, area; their engines were removed for separate processing, and the cars were then crushed into small bundles that the kiln could handle. The goal, according to Research Director Roberson, was to develop techniques to smelt out the lead, zinc, tin, and copper. After these elements were removed, the remaining metal in the bundles would be mostly clean iron, which could be melted in an electric furnace and processed into new steel. The cast-iron engine blocks would be sent to foundries for recycling. In early December 1965, the first commercial-size steel ingot produced in this process, weighing about 700 pounds, rolled out of the Albany center. It was turned over to the Oregon Steel Mills in Portland for rolling into structural steel forms and testing of the mechanical properties of those forms.

But the development by industry of an "auto shredder" that was capable of chewing up an automobile into small pieces at the rate of one car a minute soon changed the project's direction. Steel could now be separated magnetically from non-magnetic scrap, so the smelting out of lead and other metals was no longer necessary. The resulting purer steel product was fed directly into an electric furnace in a mini-plant at the Albany Center to produce medium-carbon steel with low impurities. By 1970, as this form of recycling took hold, scrap automobiles that had been worth $16 a ton in the recent past were worth $50 a ton.

The metal-recycling project coincided with a change of leadership at the Albany center. Research Director Roberson retired on December 30, 1965, after six years in the position. His successor was announced on March 17, 1966: H. Gordon Poole, who was at that time the vice president and technical director of Oregon Metallurgical Corporation of Albany (OreMet). Poole had worked previously at the Albany station from 1951 to 1952 as the chief of the non-ferrous metallurgy branch. From 1954 to 1962 he was a professor and head of the department of metallurgical engineering at the Colorado School of Mines. He left the school to become the technical director of OreMet in 1962. His interests included metallurgical thermochemistry, chemistry of reactive metals, and high-purity metals. The appointment at Albany was effective April 4, 1966.

It was perhaps Poole's interest in thermochemistry that led to the transfer of the Bureau's thermodynamics laboratory at the University of California, Berkeley, to Albany in June 1967. Four employees and 45,000 pounds of laboratory equipment arrived as part of the transfer. Consolidation of thermodynamics research activities was cited as the reason for the move. In February 1968, Albany further expanded its capabilities by adding recovery of sulfur from industrial waste, superconductivity studies, and refining of beryllium to its program. Aircraft companies and NASA liked beryllium for its light weight and high strength.

The Albany Metallurgy Research Center celebrated its twenty-fifth anniversary with a dinner on June 15, 1969. Vin Hurley, who had been the president of the Albany Chamber of Commerce in 1944, was in attendance; he gave a speech about the origins of the Northwest Electrodevelopment Laboratory, as it was then called. Stephen Yih of Wah Chang Company, who had been instrumental in leading the transition of zirconium production from government to private industry, also attended. Dr. Earl T. Hayes, the acting director of the Bureau of Mines, gave a speech in which he said that "the original purpose of building a Bureau of Mines station here was to use surplus power [from the Bonneville Dam] when the war was over. That was a poor bit of planning… and thank goodness it was." Once the Bureau station was established in Albany, the benefits of surplus electricity had played no role in its plans or operation.

Soon after the anniversary festivities, however, a more troubled period began. Hayes returned to Albany on July 27, 1970, for some morale building. Still the acting director of the Bureau, he came to quell concerns about the possibility of the Bureau being reduced in size or even eliminated. "The 1972 Bureau budget was nearly eliminated in a maneuver by Under Secretary of the Department of the Interior, Fred J. Russell," the *Albany Democrat*-Herald reported. "Then after a hard fight in Congress, the budget was reinstated and an additional $1.5 million added, bringing the operating figure to over $100 million." The budget battles in the nation's capital had serious repercussions for Albany. In 1970, 30 percent of all Bureau jobs located in Oregon were transferred out of state. In the following year, the Office of Mineral Resources in Albany was closed, and the 17 employees of that organization were offered the choice of transfer to Washington, D.C., or termination. Remaining employees were assured that this reorganization involved only the economics and statistics end of the Bureau, not the research sector.

H. Gordon Poole retired on December 13, 1971, and was replaced by Rollien R.

(Ray) Wells, who had begun his Bureau career in 1942 as a metallurgist at the Salt Lake City location. Wells's first stint in Albany had lasted from 1948 to 1950, when he headed the ore dressing section of the lab. In 1951, he was named the Superintendent and Director of Metallurgy at the Bureau's Juneau, Alaska, station, where he spent nine years. He then moved to Washington, D.C., where he headed the Bureau's Division of Metallurgy before his appointment to Albany. Wells faced the unenviable task of steering the Albany center through the mounting economic uncertainties of the early 1970s.

"Bloodhounds" of Bartlesville

> *Wanted: Trained Noses. An Opportunity for Part-time Work as a member of a panel to sniff and judge diesel exhaust odors. Will require 2-5 hours per day, about 3 days per week, on an irregular schedule. The schedule will be known in advance. Desire 40-50 applicants for screening and training. Applicants first will be screened for odor perception. Further selection will be made in short qualification trials that involve odor identification and odor intensity rating. Who is Eligible? Anyone except heavy smokers and persons subject to asthma, hay fever, or severe respiratory difficulty. It is believed that housewives will be particularly interested.*
>
> *--Help wanted advertisement in the* Bartlesville Examiner-Enterprise,

Two Bartlesville women with highly sensitive noses evaluate the characteristics of diluted diesel fumes.

August 1, 1966

In the days following this advertisement, more than 100 people applied for the job at the Petroleum Research Center. They were mostly housewives looking to make a little extra money—about $5 for a two- or three-hour shift. Preliminary odor-sensitivity testing soon reduced this number to 30, of which 15 were eventually hired to evaluate the nature and strength of the odors of diesel exhaust fumes as part of the Fuels Combustion Research Laboratory projects under Richard Hurn.

Hurn had assembled a bank of engines that he would run on various types of diesel fuels under various conditions of oxygen concentration, engine speed, and ambient environment. Although he and his team had developed analytical techniques involving gas chromatography and other advanced laboratory instrumentation, they proved to be insufficient for the particular task of odor assessment. "At the present there is no known instrument capable of judging quality and intensity of odors as reliably as the human nose," said Hurn. "That's also one of our objectives in this experiment--to find some mechanical method of rating diesel odors as well as the human nose can do it….Until we find such a mechanical method of detection it will be very difficult to adopt any meaningful [emission] controls...."

To train the "sniffers," the researchers made sample bottles of the various fuel components that typically made their way into the exhaust stream. A series of bottles of increasing odor strength were prepared for each fuel component. These calibrated training bottles were labeled 'B' for burnt, 'O' for oily, 'P' for pungent and 'A' for aromatic, with numbers indicating intensity—'1' for weak, '2' for stronger, etc. After ten weeks of training, the women could pinpoint the type and strength of an odor in a blind smell-test to within one number.

At this point, the women, who were good-naturedly called "bloodhounds" or "human bird dogs" in local newspaper articles, were ready to rate the smells emanating from real diesel engines. Sitting in a room located above the engine laboratory, eight individual sniffing stalls were connected by piping to the exhaust from the eight test engines. "The women sit here with their knitting or magazines," Hurn explained, "until a buzzer sounds signaling them to take a sniff. They are well disciplined to take just one sniff at the tube, then write down their evaluation on a standard chart." For their safety, the exhaust gases were diluted with air at a ratio of 400 parts air to one part exhaust, similar to the concentration one might experience by following a diesel-powered bus. By 1968, approximately 50 women were working in the program.

Lunar Rocks at Morgantown

"The moon rocks have arrived!"

So began an article in the April 1970 issue of *The Research Reporter*, the in-house newsletter of the Morgantown Energy Research Center (MERC). A bit of clarification followed: The material that MERC had just received was not exactly rock. It was dust, "two 2-gram samples of lunar dust," brought back to Earth by the Apollo 12 voyage to and from the Moon in November 1969. People who had seen it described it as an outwardly unremarkable gray powder that resembled the fly ash from a coal-burning power plant. But this dust had extraordinary significance. Its presence at Morgantown evoked the wonders of outer

The Morgantown lunar materials team: Patricia A. Estep, seated; John J. Kovach, left; and Clarence Karr, Jr., right.

space, testified to the skill and courage of American astronauts, and highlighted the scientific competence that had led NASA to include the Bureau of Mines on the select list of research institutions that were authorized to examine the lunar materials obtained from the Apollo missions.

The similarity in appearance between the lunar dust and coal ash was apt, since MERC's ability to analyze lunar materials stemmed directly from its ability to analyze coal. In coal chemistry, knowledge of the internal physical and chemical structures of different types of coal and their byproducts was essential. Yet even after centuries of experience and study, much remained unknown about these structures. Scientists kept refining analytical methods to probe more deeply into the many organic and inorganic substances that coal contained. One of the most powerful tools for this purpose was electromagnetic spectroscopy, which used forms of electromagnetic radiation to identify the distinctive signature or "fingerprint" of each element or compound in a mineral.

MERC had developed a concentration of expertise in spectroscopy, particularly in the application of infrared radiation and ultraviolet radiation to coal research. To an unusual extent, the center was also engaged in infrared spectrometry, which integrated infrared spectroscopy with crystallography—the study of how atoms are arranged in solid materials. These capabilities had many practical uses in solving coal-utilization problems. For example, they led to better understanding of the various sulfur compounds in coal, which in turn aided the design of systems for purifying synthesis gas, desulfurizing power-plant flue gas, and recovering potentially valuable sulfur byproducts. Other MERC projects that were underway in the early 1970s used infrared spectroscopy and spectrometry to establish the mineral composition of fly ash from experimental advanced coal-fueled power systems to reduce air pollution.

These techniques were easily adaptable to the NASA lunar-materials program, which the Bureau entered under a contract with NASA. Of the dozens of groups around the world that received samples of rock and dust and from the Apollo moon landings, MERC's was the only one that employed infrared spectrometry. The lunar material analytical team at Morgantown was under the direction of Dr. Clarence Karr, Jr., and included Patricia A. Estep and John J. Kovach.

Estep, who was one of only two female chemists at MERC as of 1970, attracted much public attention at a time when few women were engaged in cutting-edge scientific research at the Bureau and other federal agencies. After graduating from West Virginia University in 1954 with a degree in chemistry, Estep had immediately joined the Bureau's Synthesis Gas Branch at Morgantown. She had played a key part in establishing the spectroscopic laboratory and training other scientists in spectroscopic methods. Her studies of coal-tar compounds were recognized as authoritative sources of data on that subject, and her early commitment to specialize in the emerging new field of infrared spectrometry made her a perfect fit for the lunar material program.

Examining specimens of material from the Moon was complex. When they received a sample from NASA, the team members had to prepare it for use, always handling it indirectly to avoid any possibility of contamination. “This involves working with rubber gloves that extend into a ‘dry’ box in which the samples are kept in a controlled environment,” *The Research Reporter* explained. Particles of the material were studied under a powerful microscope and selected for further analysis. Spectroscopic equipment then charted the mineral composition and structure of the specimens. Each stage of the process demanded great patience and care.

During the early 1970s, the Morgantown team studied dust or rock from three Apollo missions: Apollo 11, Apollo 12, and Apollo 14. Just as the Bureau of Mines paid close attention to regional variations in deposits of fossil fuels and other minerals on Earth, so NASA consciously dispatched its spacecraft to different areas of the Moon’s surface to assess diversity in the occurrence of minerals there. Apollo 11 and Apollo 12 samples came from lunar lowlands (the Sea of Tranquility and the Ocean of Storms, respectively), while Apollo 14 samples came from a hilly section called the Fra Mauro Highlands. The idea was that comparing and contrasting materials from different lunar regions would help scientists piece together the Moon’s origins and development.

According to Clarence Karr, the program succeeded in advancing human understanding of both the Moon and Earth. Karr reported his team’s findings that although lunar rocks and terrestrial rocks were often broadly alike, there were also significant differences in their compositions and structures due to the Moon’s very thin atmosphere and lack of moisture. Wind and moving water, two major sources of change in minerals on Earth, were absent on the Moon. Lunar rocks, Karr asserted, were valuable sources of information about what Earth might have been like in earlier phases of its geological history—and potential clues to the origins of Earth’s own mineral resources. The greatest benefit of that gray dust from another celestial body might thus be a deeper appreciation of the planet that we humans call home.

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

Chapter Ten: The Energy Crisis and the Creation of the Energy Research and Development Administration, 1973–1977


U S ENERGY RESEARCH
DEVELOPMENT ADMINISTR

Chapter Ten:

The Energy Crisis and the Creation of the Energy Research and Development Administration, 1973–1977

Demands and higher prices for petroleum and petroleum products are placing the Bureau's energy research activities at the top level of importance in State, national, and international affairs.
--Bartlesville Research Director John S. Ball in the December 22, 1973, edition of the Bartlesville Examiner-Enterprise

During the mid-1970s, a conjunction of events triggered an energy crisis that propelled energy research to the top of the national agenda. Mining-safety reforms and sweeping environmental laws placed new constraints on the production and use of coal. Shortages of natural gas hindered industrial activity and disrupted everyday life. Petroleum-exporting countries in the Middle East halted oil shipments to the United States in late 1973 and early 1974, resulting in closed gasoline stations, soaring fuel prices, and a long economic slump. In a time of intense political engagement and conflict, citizens expected their government to do more to ensure reliable energy supplies without compromising safety or environmental quality.

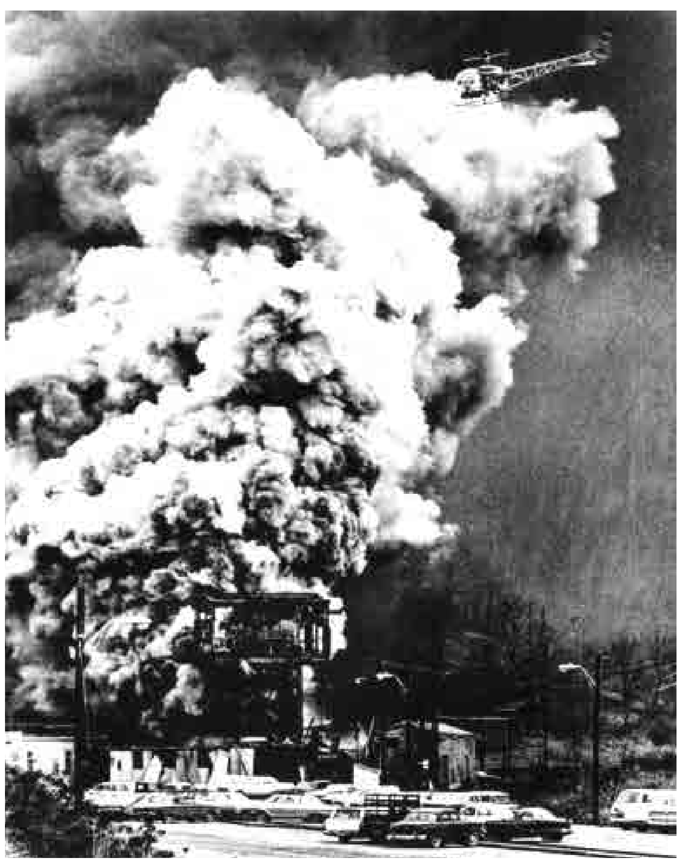
Energy Research and Development Administration sign at MERC, April 16, 1977. This picture was taken during a visit by U.S. Senator Jennings Randolph of West Virginia (fourth from left).

One consequence of the turmoil was a comprehensive reorganization of federal energy research. The Bureau of Mines lost most of its authority to oversee mine safety and its responsibility for energy-related programs and projects. An entirely new federal agency—the Energy Research and Development Administration (ERDA), created in 1975—gained control of the Bureau's Energy Research Centers. For only the second time since the 1910s, the Interior Department no longer housed a network of experiment stations to study fuels. Fossil-energy researchers at Pittsburgh, Morgantown, Bartlesville, Laramie, and Grand Forks now worked for the ERDA, while the metallurgy staff at Albany remained part of the Bureau's scope.

The substance of the fossil-energy investigations that the government conducted or sponsored changed too. As part of an urgent drive to extract more petroleum and natural gas from domestic sources, the Energy Research Centers deployed innovative methods of tertiary recovery and explored mysterious unconventional natural-gas reservoirs. The search for ways to use coal more cleanly and efficiently spurred renewed interest in venerable yet previously underappreciated technologies such as fluidized-bed combustion and coal gasification. Boosted by a powerful combination of economic, national-security, and environmental concerns and by a rising tide of public and private funding, federal energy research expanded and diversified in many directions.

Upheaval in Mine Safety

The political unraveling of the Bureau of Mines commenced where the agency's political formation had begun, in the treacherous coal fields of northern West Virginia. At 5:40 AM on November 20, 1968, an explosion tore apart the Consolidation No. 9 coal mine near Farmington, roughly five miles from the site of the Monongah mine disaster of December 1907 that had spurred the rise of the mining-safety movement. Multiple secondary blasts followed, and



Fire and smoke pouring from the Consolidation No. 9 mine after the November 1968 explosion (photo credit: Mine Safety and Health Administration, United States Department of Labor) fires blazed underground for over nine days until the mine was sealed with concrete. Although 21 miners escaped, 78 lost their lives. So complete was the destruction that no bodies could be recovered until October 1969, and 19 victims were never found despite years of methodical searching through the wreckage. Nor was the cause identified, although the Bureau suspected that methane buildup—long a known problem at Consolidation No. 9—was the prime culprit.

Like previous catastrophes, the Farmington explosion triggered a new round of recriminations and calls for reform. Fatal accidents on this scale had become unusual in American coal mining, thanks to mechanization and improved safety procedures; since 1950, both the total fatality rate and deaths from mine explosions had been at the lowest levels of the twentieth century. But the rarity of the event made it all the more disturbing. Farmington symbolized workplace dangers that seemed to be unnecessary, unacceptable remnants of a bleak past. It prompted criticism of the coal industry for tolerating unsafe conditions and criticism of the Bureau for not adequately supervising the industry.

In the weeks and months following the disaster, pressure to overhaul the Bureau and federal mine-safety laws mounted. Secretary of the Interior Stewart Udall convened an emergency conference on December 12, 1968, at which he stated, "Regrettably, I must report that the Bureau of Mines could have done more than it has done" to ensure mine safety. Several lawmakers and Ralph Nader, the leader of the growing consumer-protection movement, questioned whether the Bureau's inspectors had overlooked hazards at Farmington and elsewhere. Congress moved quickly to adopt a new Federal Coal Mine Health and Safety Act, which President Richard Nixon signed into law on December 30, 1969.

The 1969 law, often called simply the Coal Act, began to detach the health and safety mission from other Bureau activities. It authorized the transfer of mine-inspection and law-enforcement duties to a separate agency, the Mining Enforcement and Safety Administration (MESA), within the Interior Department. This change reflected perceptions that the Bureau's acquisition of mandatory mine-inspection and law-enforcement powers since 1941 had set up an unsustainable tension between protecting miners' safety and promoting growth in coal output and use. In the wake of the Farmington disaster, the Bureau stood accused of having favored industry at the miners' expense by allowing mine operators to delay or avoid safety improvements. Spinning off the inspection function was meant to resolve an apparent conflict of interest.

Other provisions of the Coal Act expanded the authority of the federal government over coal mining. The law brought strip mines under federal jurisdiction, required them to be inspected twice per year, and increased mandatory inspections at underground mines to four times per year. For the first time, willful violators of the safety standards faced criminal penalties as well as fines. Congress wrote certain standards for noise, dust levels, and safety equipment directly into the text of the statute rather than leaving the development of regulations solely to Bureau experts.

The Coal Act was controversial and slow to take effect. Mining companies complained that its requirements lowered coal production and would drive small mines out of business, while labor and consumer advocates charged that it did not go far enough to protect workers. The MESA did not formally come into being until May 7, 1973, leaving the Bureau of Mines to enforce the law for several more years. Bureau officials struggled with the need for more inspectors—the nationwide total rose to 1,314 by the end of the 1972 fiscal year—and with a deluge of new demands on their facilities. For example, from June 1970 to June 1971 coal-mine operators submitted over 280,000 mandatory dust samples to Bureau laboratories for analysis.

Political contention surrounding the legal changes contributed to instability at the top of the agency. Walter Hibbard, a former metallurgist with the General Electric Corporation who headed the Bureau from 1964 to 1968, had stepped down just weeks before the Farmington explosion. The next director, John F. O'Leary, was an economist who favored strong mine-safety enforcement. Although O'Leary gained wide public acclaim for his steady leadership during the passage and implementation of the Coal Act, his status as a Democratic holdover in a Republican administration after President Nixon took office in January 1969 put him at a disadvantage.

Nixon asked for and received Director O'Leary's resignation in February 1970 and set about finding a successor. No one wanted the position. Finally, Elburt Franklin Osborn of Penn State University—who had previously been offered the Bureau directorship twice during the 1960s and had turned it down—accepted the challenge in October 1970. A geochemist by trade, Osborn had risen to become the university's vice president for research. He had no close ties to either the coal industry or the labor and consumer side of the reinvigorated mine-safety movement. His low-key impartiality helped to rebuild confidence in the Bureau during his tenure, which lasted through 1973.

By mid-1973, the Bureau was no longer a law-enforcement agency and no longer regularly inspected coal mines. Subsequent events sharpened the emerging organizational distinction between research on health and safety issues in mining and research on minerals and energy. The Federal Mine Safety and Health Act of 1977 merged coal-mine regulation with oversight of all other types of mining under the new Mine Safety and Health Administration (MSHA), a successor to the short-lived MESA. Tellingly, Congress placed the MSHA in the Labor Department rather than the Interior Department, signaling that mine safety would henceforth be aligned more with labor and occupational-health issues than with natural resources and economic development.

The 1977 law also assigned the National Institute for Occupational Safety and Health (NIOSH) to monitor health conditions among miners, prepare health standards for recommendation to the MSHA, and take over the responsibility of certifying permissible respirators and devices for measuring hazardous gases. Research on mine explosions and collapses remained the province of the Bureau's Pittsburgh Mining and Safety Research Center, but the transfer of functions to other agencies diminished the role of the Bureau in the health and safety field. Daily life at the Pittsburgh and Morgantown stations changed too, since the sites were now physically divided among three federal departments—Labor, Interior, and Health, Education, and Welfare (to which NIOSH belonged)—that had differing missions and organizational cultures.

Underlying these restructurings was a sea change in political outlook. The Organic Act of 1910 and other founding documents of the Bureau had embodied the assumption that safety, industrial productivity, and the fuller development of mineral resources were mutually compatible and reinforcing goals that formed a unity of purpose. A single agency, in this view, could advance the well-being of miners and industry alike with the aid of science and technology. By the 1970s, however, that basic assumption had come into question. Experience and shifting public expectations highlighted conflicts and tradeoffs among safety, productivity, and development objectives. The Coal Act and the Mine Safety and Health Act reflected a different perception of miners and industry as distinct and sometimes clashing interests that were best represented by separate agencies.

The Energy Crisis and the Creation of the ERDA

Similar arguments that research on fossil fuels and energy should be split off from the rest of the Bureau's work on mineral resources gained support as anxiety mounted about the future of the energy industries. "In the 1970s, the Nation faces an energy crisis," the Bureau stated in its 1972 annual report. That crisis stemmed from "rapidly increasing energy demands, decreasing indigenous reserves of petroleum and natural gas, increasing dependence upon foreign sources . . . and the public's insistence on protection of the environment." Almost everywhere in the country, across economic sectors and across geographical regions, energy markets were in disarray. The idea of a specialized federal department to concentrate on this economically, strategically, and socially crucial set of issues had compelling power.

Events during 1973 illustrated the country's pervasive, interlocking energy problems. Natural gas remained in tight supply. Its rising price encouraged industries to switch to fuel oil, but there was not enough petroleum to meet the demand for both fuel oil and gasoline. In Texas, electrical service was disrupted in cities such as San Antonio as power plants experienced cutbacks in natural-gas and fuel-oil shipments. A reporter for the *Pittsburgh Post-Gazette* predicted in July that the Pittsburgh area would run short of fuel oil by autumn. Hard-pressed petroleum suppliers increased their reliance on imported crude; for the year, petroleum imports surpassed one billion barrels per day and accounted for 28 percent of U.S. petroleum consumption. Bituminous-coal producers complained that air-pollution regulations discouraged consumers from using coal as an alternative fuel. Even the hydroelectric plants of the Pacific Northwest faltered as low rainfall reduced water flow and electricity production.

Then international rivalries turned this volatile situation into an emergency. On October 17, 1973, the governments of several Middle Eastern nations declared a ban on petroleum shipments to the United States. Their embargo, which lasted until March 1974, had its proximate roots in the Arab-Israeli conflict but also reflected long-brewing economic tensions between petroleum-exporting and petroleum-importing countries. Many exporters had formed a cartel, the Organization of Petroleum Exporting Countries (OPEC), to affect the global market by coordinating their levels of production. OPEC had already decided that it would use its power to limit output and drive petroleum prices up. The embargo thus built upon preexisting trends toward costlier fossil energy and the emergence of new power centers capable of challenging American economic and political influence.

Signs like this one were common sights at gasoline stations across the country during the 1973–1974 oil embargo. (photo credit: Bettman/Corbis)

These events inflicted a damaging "oil shock" on the U.S. economy and initiated a new era of higher, unstable petroleum prices. The world-market price of crude petroleum more than tripled during the embargo, touching off inflation that continued for years. It seldom returned to pre-1973 levels thereafter, despite frequent wide swings. Through the winter of 1973–1974, Americans endured the unwelcome experiences of gasoline rationing and long waiting lines at service stations. Businesses scrambled to cut their energy expenses and find alternative sources or substitutes for fuels whose cost and availability had become unpredictable.

The embargo and the actions of OPEC also dramatized the national-security threat that dependence on imported petroleum created. Ever since World War I, energy analysts at the Bureau of Mines had been fretting about insufficient domestic petroleum reserves and the possibility that the United States could lose access to foreign sources of liquid fuels in times of international strife. Now the possibility had become reality. The time had evidently come for a national strategy to counteract this danger.

The Nixon administration responded by advocating a more unified, centralized approach to energy policy and federally sponsored energy research and development. As early as 1971, President Nixon had called for a new Cabinet-level "Department of Natural Resources" to integrate dozens of energy-related agencies and programs that were scattered across the government. Congress gave low priority to this idea, so as the situation in the energy markets worsened during 1973, Nixon moved on his own to establish a mechanism within the executive branch for coordinating energy policy. He set up a Special Energy Committee and a National Energy Office, whose functions were combined by executive order in June 1973 to form the Energy Policy Office.

After the petroleum embargo was declared, the government adopted more forceful measures. The president announced on November 7, 1973, that the United States would pursue what he called "Project Independence," an initiative to end reliance on petroleum imports by 1980 (the deadline was later extended to 1985). This campaign would include reducing energy consumption; expanding domestic energy production; and rebalancing the country's energy mix toward coal, nuclear, and renewable sources. To manage the immediate petroleum shortage, Congress authorized a temporary expansion of price, production, and marketing controls through the Emergency Petroleum Allocation Act of November 27, 1973. The Federal Energy Office (FEO), created by executive order in December to replace the Energy Policy Office, had broad authority to set priorities for apportioning scarce petroleum supplies to refineries, distributors, and consumers.

Bureau analysts had long fretted about the possibility that the U.S. could lose access to foreign sources of liquid fuels in times of international strife. Now the possibility had become reality.

The following year brought even more sweeping changes to federal energy policy and practice. Congress transferred the duties of the FEO and several Interior Department offices to the new Federal Energy Administration, which began functioning in May 1974. Five months later, on October 11, 1974, President Gerald R. Ford signed the Energy Reorganization Act into law. The act authorized the formation of the Energy Research and Development Administration (ERDA), an independent executive agency, to be the federal government's hub of scientific and technical expertise on all forms of energy.

Under the Energy Reorganization Act, five separate research programs merged. The Atomic Energy Commission (AEC) was dissolved, and its system of National Laboratories, which primarily supported the U.S. nuclear-weapons program, shifted to ERDA control. The ERDA also took over work on solar energy and geothermal energy that the National Science Foundation had previously supported, and took responsibility for a small Environmental Protection Agency program of research on methods of reducing air pollution from automobiles. Finally, two components of the Interior Department were transferred

President Ford signing the Energy Reorganization Act. (photo credit: U.S. DOE) to the ERDA: the Office of Coal Research and the five Bureau of Mines Energy Research Centers at Pittsburgh, Morgantown, Grand Forks, Bartlesville, and Laramie.

The ERDA officially came to life on January 19, 1975, with President Ford proclaiming that it would take the lead in devising "the needed technology to assure that the United States will have ample and secure supplies of energy at reasonable prices." Heading the organization was Administrator Robert C. Seamans, Jr., who had previously served as a deputy administrator of NASA, as the secretary of the Air Force, and as the president of the National Academy of Engineering. Seamans promptly turned his encyclopedic knowledge of recent civilian and military technological development to the task of creating a national plan for energy research in support of Project Independence.

For employees of the former Energy Research Centers, the creation of ERDA was bittersweet.

For the employees of the former Bureau of Mines Energy Research Centers, the moment was bittersweet. On the one hand, the idea of comprehensive energy planning, which had often found a sympathetic home at the Bureau, seemed to be vindicated with unprecedented public respect and support. The ERDA promised opportunities for cross-fertilizing scientific inquiries across disciplinary, institutional, and industrial boundaries. Project Independence, which many Americans in the mid-1970s compared hopefully to other science-driven achievements such as the moon landings, generated a sense of joint participation in a great national cause. "These are exciting times for Bartlesville," Research Director John S. Ball of BERC told the local Downtown Kiwanis Club in July 1975. "To be working on energy-related problems, as most of us in Bartlesville are at this time, is inspiring, and our research engineers and scientists are caught up with a zeal for accomplishment. We're literally working at it day and night around the clock."

On the other hand, cherished traditions had been abruptly broken. The reorganization had fragmented the Bureau's network of experiment stations, which had evolved continuously within the Interior Department since the 1910s except for the Commerce Department interlude from 1925 to 1934. Most stations, including the Albany Metallurgical Research Center, remained with the Bureau under the leadership of Director Thomas V. Falkie (1974-1977). But the five that had been spun off to the Fossil Energy Division of the ERDA were now part of a challenging project to forge a single new corporate culture from parts of multiple agencies.

The ERDA was principally shaped by the uneasy coexistence of two distinct and unequal legacies of the past: the National Laboratories, inherited from the Atomic Energy Commission, and fossil-fuels research programs, inherited from the Bureau of Mines. In terms of resources and political clout, the National Laboratories dominated. They accounted for over two-thirds of the ERDA's budget and personnel. Their heritage of concentration on nuclear energy and nuclear weapons had given them a centralized organizational structure and a focus on serving national policy goals. By contrast, fossil-fuels research was much smaller in scale, more diverse, and more decentralized. Oriented toward several different industries, the Energy Research Centers and former Office of Coal Research contracts reflected cooperative relationships with the private sector and sensitivity to regional variations in mineral resources. Each of the former Bureau of Mines centers had possessed its own budget and its own carefully nurtured relationships with local elected officials and communities.

Integrating these different traditions was often difficult. Changes in personnel and operating procedures led to confusion and conflict. Bureau of Mines veterans worried about being overshadowed by the larger and more prestigious National Laboratories. Multiple formerly independent research programs had to be redefined and reorganized in accordance with the ERDA's emerging overall plan.

Official seal of the Energy Research and Development Administration.

Working in favor of the new agency, however, was the fact that National Laboratories researchers and Bureau of Mines researchers were not complete strangers to one another. They had cooperated before the merger on projects involving nuclear materials. And the two sides had complementary strengths. The National Laboratories possessed unrivaled resources of cutting-edge laboratory equipment and human expertise in the physical sciences—capabilities that, when not in use for the nuclear-weapons program, could provide new insights into civilian energy problems. The former Bureau of Mines centers contributed their voluminous knowledge of the nation's fossil-fuel resources and their skills in outreach to industry and the American public.

Rapid increases in federal funding for energy research also eased the strains of the consolidation. The transformation of budget priorities as the energy crisis deepened was remarkably sharp. During the early 1970s, the Nixon administration had repeatedly floated proposals to reduce federal support for the Energy Research Centers and abolish the Office of Coal Research. The centers had faced job reductions, program cancellations, and even—in the cases of Bartlesville and Morgantown—threats of outright closure. Congressional resistance, particularly from the West Virginia delegation under the leadership of Senator Robert C. Byrd and the irrepressible synthetic-fuels advocate Senator Jennings Randolph (who had returned to Congress as a senator in 1958), scotched those moves. Appropriations for fossil-energy programs began to rise again during the 1973–1974 fiscal year and then jumped spectacularly. Between 1973 and 1976, total federal spending on energy research more than doubled, and the fossil-energy component increased more than tenfold from 1974 ($143 million) to 1979 ($1.41 billion).

There was one catch in the budget increases: Much, if not most, of the additional money had to be spent on partnerships with private companies, associations, and universities rather than on in-house activities at the ERDA's own facilities. Congress accompanied the additional spending with strict limits on the number of employees that the ERDA could have on the federal payroll. So the practice of contracting out, long familiar to the Bureau of Mines in the form of cooperative agreements, grew in importance. Portable trailers multiplied at the Energy Research Centers to accommodate contractors who were working onsite.

The transition to ERDA control coincided with a generational shift in leadership. People who had firsthand recollections of the Synthetic Liquid Fuels Act period were leaving the scene. New circumstances demanded new management skills that were not always available within the ranks of career Energy Research Center employees. Research directors at Morgantown, for example, had traditionally worked their way up inside the Bureau of Mines organization; James Paul McGee (1964–1968), James W. Eckerd (1968–1972), and William Eckart (1972–1975) had all followed that pattern. But in 1975, Augustine A. Pitrolo, who previously worked for General Electric, became the first research director at Morgantown who had not been previously associated with the Bureau. That same year witnessed the arrival of another talented outsider, Sun W. Chun, who came to the Pittsburgh Energy Research Center from the research and development arm of Gulf Oil and who would quickly rise to become the center's director in 1979.

By the end of 1973, it was apparent that the embargo would be a boon to the local economy of Bartlesville and to BERC.

Expanding Petroleum Supplies

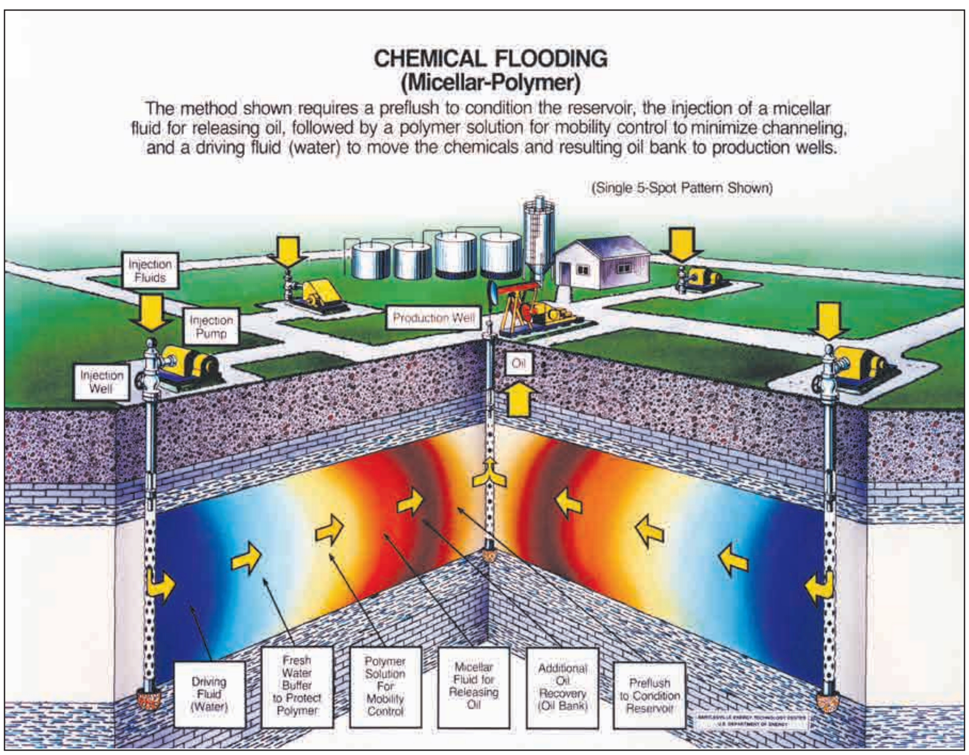
Even before the October 1973 petroleum embargo struck, getting more domestic petroleum out of the ground was one of the federal government's highest priorities. The Bureau of Mines headquarters in Washington shifted BERC's research emphasis in May 1973 to phase out many fundamental studies and replace them with applied research projects that might yield near-term results. These projects included exploiting heavy petroleum deposits, improving waterflood recovery, stimulating petroleum and natural-gas production through explosives, delineating the extent of hydrocarbon deposits from the surface by measuring natural radioactivity, and utilizing the "heavy ends" of petroleum—the leftover thick oils and tars that were difficult to turn into useful products.

Two-thirds of the petroleum in known, producing wells remained underground.

By the end of that year, it was apparent that the embargo would be a boon to the local economy of Bartlesville and to BERC. The Bureau was inundated with funding, and requests for new cooperative agreements to explore various ways of increasing petroleum output abounded. The December 22, 1973 edition of the *Bartlesville Examiner-Enterprise* carried the front-page headline, "Bureau of Mines Research Given Priority." The accompanying story reported that Research Director Ball had announced that BERC would have the vital role of helping to develop the technologies that would get an estimated 400 billion barrels of yet-undiscovered domestic crude to the surface of the earth and into the production pipeline. Ball specifically mentioned the need to develop the petroleum resources of Alaska's North Slope and offshore locations as a means to reach energy self-sufficiency.

Robert T. Johansen, the supervisor for petroleum production at BERC, announced in January 1974 that Congress had awarded the station an additional $1.3 million in funding, $525,000 of which was to be used for in-house research and the remainder for contract research. He was clear about where the money should go. "Oil recovery efficiencies are disappointingly low for most fields," Johansen noted. "Our national average is only about 32 percent." So two-thirds of the petroleum in known, producing wells remained underground. To improve on this percentage, research was needed in three areas: underground formation fracturing, enhanced recovery by fluid injection, and recovery of heavy oil and oil from tar sands. Fracturing would create more avenues for petroleum to escape. Fluid injection would force more of this free petroleum to the surface. Plans for recovering heavy oil and developing tar sands focused on the Sol-Frac process, a formation-fracturing solvent injection method that BERC had developed.

A series of field tests was soon underway, involving joint investigations between BERC and petrochemical companies in a cost-sharing arrangement. For the first of these investigations, announced in March 1974, the B & N Oil Company provided 10 acres of a low-producing petroleum reservoir in the Delaware-Childers Field near Nowata, Oklahoma, as a site for *micellar-polymer flooding*. This two-step, tertiary oil-recovery method involves first flooding the reservoir with a solution of micelles, which are chemicals that have one end that is hydrophilic (water-loving) and one end that is hydrophobic (water-fearing). In the reservoir, the hydrophilic ends of the chemical chains orient themselves toward the water, while the hydrophobic ends surround petroleum molecules. This process frees up some of the petroleum that sticks to the walls of the rock reservoir. The polymer step is essentially the introduction of a plug of water thickened by a polymer to push the micellar solution through the reservoir and out through the production well.



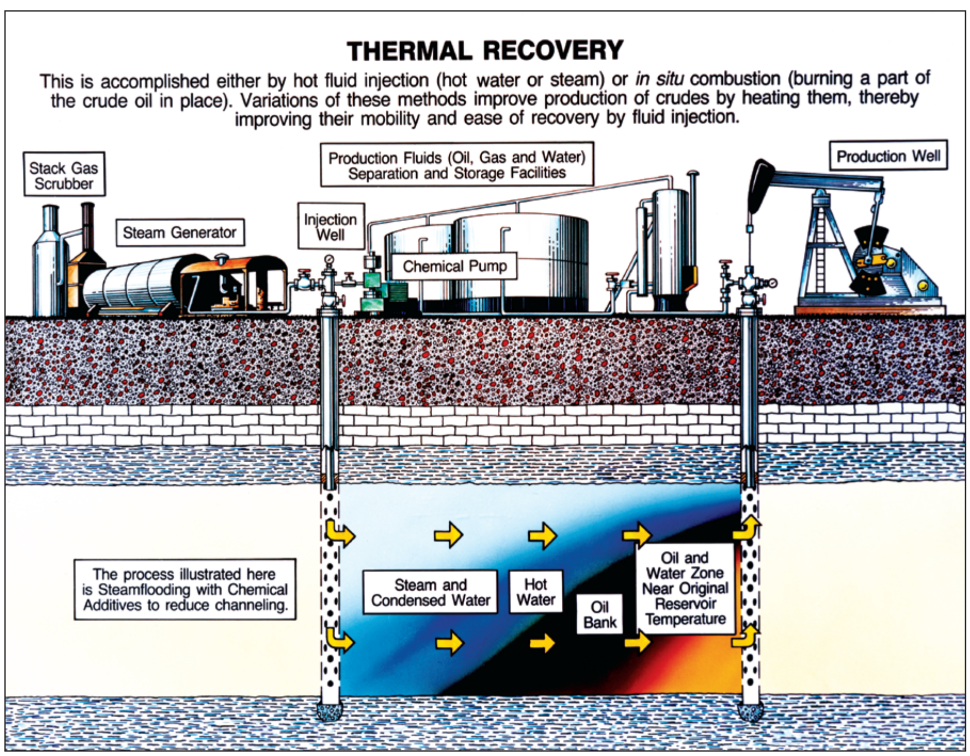
Schematic showing the micellar-polymer flooding process of tertiary oil recovery, 1974.

Many other micellar-polymer projects followed. For example, in May 1975 the ERDA and Phillips Petroleum entered into a cost-sharing agreement to flood a 90-acre tract of the North Burbank Unit in Osage County, Oklahoma, using the micellar-polymer technique. Phillips had been waterflooding this field for 25 years, resulting in 113 million barrels of petroleum. Still, the company estimated that successful micellar-polymer flooding could produce as many as 600,000 more barrels from this small tract over five years. If the treatment were extended to the entire North Burbank Unit, then the volume of tertiary petroleum recovered could be as much as 50 million barrels.

The test site was yielding 163 barrels of oil a day, compared to 60 before the start of the tertiary recovery program.

The North Burbank operation began in August 1976, and the payoff became publicly known on April 13, 1977. Under the headline "Micellar-Polymer Flood Ups Output at Osage Oilfield," the *Tulsa Daily World* announced, "Production has more than doubled after nearly two years of work on a government-industry enhanced recovery project in an Osage County oilfield." The test site was yielding "163 barrels of oil a day," compared to "60 before the start of the tertiary recovery program," and was "expected to peak at about 800 barrels of oil daily"—on track to meet the Phillips estimate of obtaining 6000,000 barrels of additional petroleum.

In 1975, the ERDA requested proposals for the first commercial-scale micellar-polymer flooding test covering 200 acres or more. Marathon Oil won the bid to run this demonstration project on a 400-acre tract of land in the Robinson Field in Illinois, with William D. Howell of BERC to serve as the accompanying

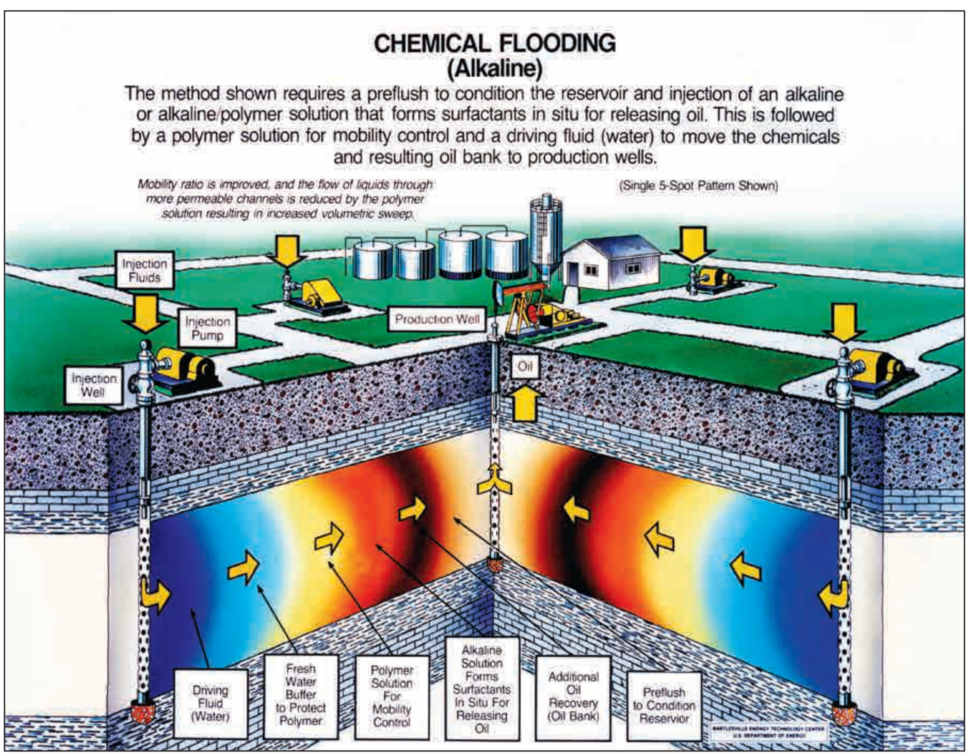


Schematic showing the thermal recovering, or fireflooding, process of tertiary oil recovery.

ERDA technical officer. The company drilled 176 wells on a 2.5-acre spacing and 69 wells on a 5-acre spacing. Micellar injection began in March 1977, and by May 1978 the "M-1 Project," as it was called, was producing petroleum at an average rate of 132 barrels per day in the 2.5-acre-spaced area and 67 barrels per day in the 5-acre-spaced area. Total output after one year was 42,472 barrels. The demonstration was a success.

Another tertiary-recovery technique was *fireflooding*, or *thermal recovery*, which involved heating petroleum underground to make it thinner and easier to pump to the surface. "In a fireflood," the *Bartlesville Examiner-Enterprise* explained on January 30, 1975, "part of the oil in the deposit is ignited, and underground burning is controlled by injecting varying amounts of air. Heat and pressure combine to thin the oil and push it to a producing well." BERC entered into an agreement that month with the Husky Oil Co. to use fireflooding to recover heavy crude that was too thick for conventional pumping. The test field was the Paris Valley field near San Ardo in Monterey, California, where an estimated 10 million barrels of thick petroleum sludge was located.

BERC scientists and engineers announced a project to test a third tertiary- recovery method in August 1978: caustic flooding. The plan was to inject large volumes of a dilute sodium hydroxide (caustic) solution into the Long Beach Unit in the Wilmington Field, Los Angeles County. "Two different caustic oil recovery mechanisms—entrapment and entrainment—have been proposed to be tested in combination for the first time at Wilmington," the *Examiner-Enterprise* report-



Schematic showing the alkaline (caustic) chemical process of tertiary oil recovery.

ed. Entrapment involved trapping particles of petroleum by surrounding them with caustic molecules; entrainment involved carrying these suspended, trapped particles along in a flowing stream to the surface. The injection was scheduled for completion in 1981, after one year of entrapment and two years of entrainment. In June 1981, the *Oil and Gas Journal* reported that the results of this effort were discouraging, possibly because the fine-grained nature of the rock resulted in a "tight" structure with low porosity that made flooding difficult.

In addition to tertiary petroleum-recovery methods, BERC scientists also began exploring new ways to fracture the reservoir rock to release more petroleum or natural gas. The Appalachian Basin was the focus of two new ERDA ventures along these lines in 1975. Always on the lookout for better fracturing processes, the ERDA contracted with Physics International Co. of Leandro, California, to combine flooding with downhole bore explosions to fracture oil- or gas-bearing formations. This approach was a modification of the hydraulic-cracking method, which used high-pressure water to induce cracking. Adding an explosives force was expected to improve the results. The work was to be supervised by the Morgantown Energy Research Center (MERC).

A second Appalachian project, the West Virginia-Kentucky Gas Co. project, investigated *directionally deviated* well-drilling techniques to enhance petroleum and natural-gas recovery. Instead of drilling a well vertically, this technique involved drilling into formations at angles of up to 60°. It was hoped that the angular drilling, followed by hydraulic fracturing, would result in longer well penetration and the release of more petroleum and natural gas than traditional vertical drilling.

In October 1975, the ERDA and the El Paso Natural Gas Co. announced a joint attack on tight reservoirs in the Green River Basin in Wyoming with a technique called *massive hydraulic fracturing*. Whereas conventional hydraulic fracturing used 25,000 to 100,000 gallons per well level, massive hydraulic fracturing required 200,000 to 500,000 gallons per well level, putting the well under extreme pressure from water alone.

Enhanced recovery of natural gas using *chemical explosive fracturing* was also tested in the mid-1970s. In this method, desensitized nitroglycerin was injected into a reservoir to penetrate the small cracks of the formation and then ignited to form an explosion that fractured the reservoir rock. However, the first three trials in a natural-gas field to the north of Fort Worth, Texas, were deemed to be dismal failures. The first resulted in no change in gas flow, the second caused a casing failure in the well that precluded further testing, and the third increased production by only 27 percent. Charles H. Atkinson, the ERDA's project engineer, initially expressed disappointment but was willing to try again. He reported at an Enhanced Recovery Symposium in September 1976 that success might yet come from a better understanding of the rocks that the BERC team was attempting to fracture. Despite occasional setbacks, the ERDA was not willing to give up on any technique that might have value for increasing petroleum and natural-gas yields. In mid-1976 came the announcement of nine new cost-sharing contracts in which representatives of government and industry would further investigate massive hydraulic fracturing and chemical explosive fracturing.

Finding appropriate sites to drill for petroleum had always been a hit-or-miss proposition, but in 1977 scientists and engineers at BERC attempted to introduce a scientific technique that might improve the odds. Rings of hydrocarbons in surface soils, called "halos," were detectable from aerial and ground-based magnetic surveys and appeared to be promising well sites. Tom Wesson was the ERDA technical officer for Project Halo, which had officially begun in 1972. By April 1977, the ERDA had performed surveys to locate three halos in Greenwood County in southeastern Kansas. The researchers analyzed gases that rose from the soil and took almost 600 soil samples from depths up to nine feet for laboratory analysis. Test wells were drilled at the halo sites: two wells at locations where soil magnetism was high and one where it was low. Results reported on July 17, 1977, indicated that hydrocarbons were found in all three wells, but that the well drilled in the magnetic low was most promising. The "purpose of the test holes was not to make producer [wells] but to get data and relate what we find at the surface with what we find as we go down," Wesson explained. "The gas [from the soil] comes from somewhere and we try to predict from where."

A long-term strategy for finding new sources of natural gas took shape, focusing on supplements to traditional gas prospecting and drilling.

BERC also made progress on the heavy-ends problem of what to do with thick petroleum residues. As early as January 1974, scientists at a meeting of the American Petroleum Institute (API) in Bartlesville reported on the development of the first method capable of analyzing and characterizing the heavy ends of a sample of crude. This accomplishment was a result of API Project 60, a joint investigation supported by BERC, the Laramie Energy Research Center (LERC), and North Dakota State University. The new ability to determine the chemical composition of heavy ends would help refiners get the most value out of their petroleum-processing operations.

Expanding Natural-Gas Reserves

Similar efforts were directed toward increasing the country's natural-gas supply. Natural gas, the cleanest-burning fossil fuel, held great promise to help industries comply with the Clean Air Act. But American natural-gas production fell during the mid-1970s, dropping from 22.6 trillion cubic feet in 1973 to 19.3 trillion cubic feet in 1978. Known reserves also declined, despite increased exploration. Soaring prices and constraints on use, such as local bans on new residential and industrial connections to natural-gas lines, expressed the continuing imbalance of supply and demand. During the bitterly cold winter of 1976–1977, shortages of gas forced temporary shutdowns of factories and schools across the Northeast and the Midwest. Even the Morgantown Energy Research Center (MERC) ordered nonessential employees to stay home for several days in February 1977 as a gas-conservation measure.

At MERC and other components of the ERDA, a long-term strategy for finding new sources of natural gas took shape. This strategy focused on supplements to traditional gas prospecting and drilling. Scientists had already identified four seldom-explored geological settings that might yield natural gas in large quantities: shale formations in the Appalachian Mountains and the Midwest; “tight” sandstone under the Rocky Mountains and the Great Plains; methane-bearing coal seams; and geopressurized underground aquifers along the Gulf of Mexico. Collectively known as unconventional natural-gas reservoirs, these resources were hard to reach and costly to exploit. Companies hesitated to invest in them without good information about their locations and potential gas output. The ERDA could aid private industry by helping to acquire the data and develop the technical means that would make extracting unconventional natural gas a practical proposition.

Early in 1976, MERC launched the five-year-long Eastern Gas Shales Project to map ancient, gas-bearing rock formations beneath the Appalachians and parts of Illinois and Michigan. These formations, called Devonian shales, are deeper than coal seams and most petroleum and gas wells; some lie over 8,000 feet below the surface. In the 1970s, little was known about their geology. Drillers who occasionally tapped into them had found that wells sunk into the Devonian shales produced substantial amounts of gas, although usually at a slower pace than conventional shallower wells did.

The Eastern Gas Shales Project set out to create a comprehensive portrait of these potential gas resources. Through dozens of contracts with universities and private companies, MERC arranged for test wells to be drilled in every state where Devonian shales were present. Analysis of core samples from these sites provided knowledge of the rocks’ physical and chemical characteristics and how much natural gas they contained. This information was correlated with surface maps and geological maps to detect regional variations in the shales and to chart patterns of underground fractures through which gas could move.

Energy companies particularly wanted to know whether the hydraulic fracturing, methods used in the petroleum industry could be used to increase gas output from Devonian shales. MERC and its contractors planned a series of field experiments to evaluate different fracturing techniques that might boost gas flow by artificially fragmenting the shales. Several National Laboratories—including Los Alamos, Lawrence Livermore, and Sandia—agreed to participate by setting up instrumentation to monitor these experiments and designing computer models of fracturing processes.

Building on earlier work at Bartlesville and Laramie and in industry, a similar Western Gas Sands Project crystallized around the problem of extracting natural gas that was locked in dense sandstone rock beneath many Western states. Breaking up these “tight” rock formations to release the gas had been the goal of the Bureau of Mines experiments with underground high explosives, including nuclear explosives, during the late 1960s and the early 1970s. High costs and unacceptable environmental risks had discredited those controversial tests, so the ERDA favored a more modest approach that emphasized conventional fracturing techniques.

The first tight-sandstone projects had begun in Colorado during 1974, and in 1977 the program expanded. ERDA and private firms shared the costs of these tests. A key focus of attention was massive hydraulic fracturing. Specialists at Bartlesville and the National Laboratories studied the physics of interactions between fluids and rock and developed sensors to measure the progress and results of underground fracturing.

A third potential source of unconventional natural gas was methane drainage from coal beds. Originally, the methane-control program that the Bureau of Mines had conducted since 1964 had focused on getting explosive gases out of the way of mining operations. Justified as a way to improve mining productivity and safety, it had not emphasized capturing and using the methane that escaped through vent pipes. But the natural-gas shortages of the 1970s led the researchers to reconsider their strategy. Bureau scientists had noted that the methane drawn from coal mines often closely resembled natural gas. The coal deposits of the United States contained an estimated 700 to 800 trillion cubic feet of methane. Why not salvage this gas and put it to work in nearby cities and industries?

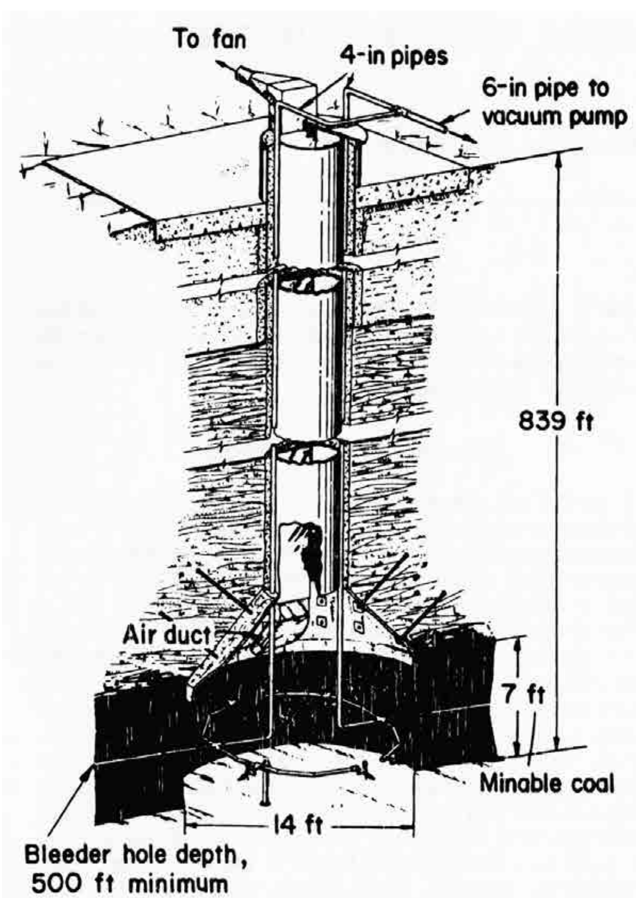
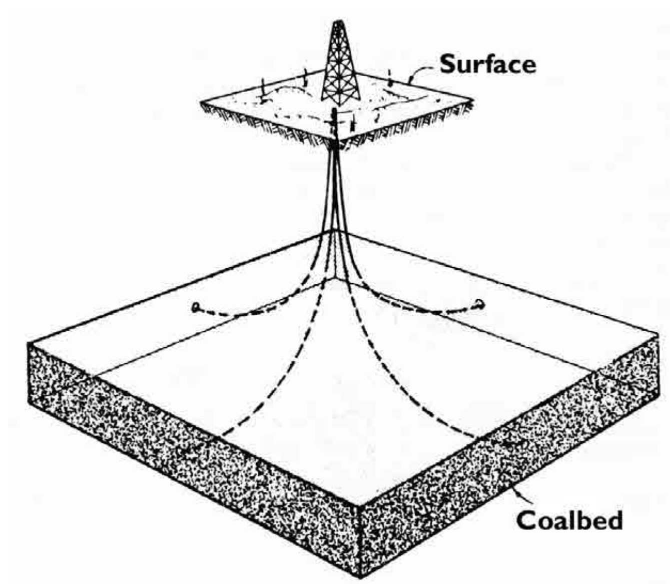


Diagram of a vertical borehole used to drain methane gas from coal beds near Pittsburgh. (photo credit: Bureau of Mines publication)



Directional drilling allowed multiple holes to be drilled on slanted paths from a single well site, improving the effectiveness of methane drainage. (photo credit: Bureau of Mines publication)

The ERDA inherited a substantial body of knowledge about methane control from the Bureau of Mines. In Pennsylvania, West Virginia, Alabama, and Oklahoma, the Bureau partnered with coal companies in methane-drainage tests. These projects proved the effectiveness of vertical boreholes and horizontal piping systems in removing methane from coal beds before or after mining. Most of the extracted gas was vented or flared away, but at a few sites, such as the Federal No. 2 Mine near Morgantown, small amounts of it were sold to local natural-gas suppliers. Experience convinced the Bureau's engineers that recovering coalbed methane was technically feasible and could be economically profitable. After the split between energy research and mine-safety research in the mid-1970s, the Bureau continued to study the safety aspects of methane control, while the ERDA took responsibility for promoting the commercial development of coalbed methane.

Innovations in drilling technology played a role in transforming coalbed methane from a waste product to a viable source of natural gas. The petroleum industry's recent strides in directionally deviated drilling, which allowed wells to follow slanted or even horizontal paths, were applicable to methane control as well. Engineers at MERC also contributed to this development; in 1976, Joseph Pasini III and William K. Overby, Jr., of the MERC staff received a U.S. patent for their work on adapting directional drilling to coalbed-methane recovery. This method improved productivity by permitting greater use of long horizontal drainage shafts, which could collect large amounts of methane at relatively low cost. Moreover, it allowed multiple shafts to radiate through a coalbed from a single point on the surface.

The final type of unconventional natural-gas reservoir the ERDA committed to investigating was a zone of geopressurized aquifers found beneath the coast of Texas and Louisiana. In this area, groundwater compressed under layers of sediment contains dissolved methane. Classified as a geothermal resource, the geopressurized zone was a mystery in the 1970s. No one knew how much methane it held or whether deep drilling to recover the gas was commercially workable.

Early research on unconventional natural gas was full of risk and challenge. Would unorthodox reservoirs yield enough gas to reverse the declining trend of U.S. natural-gas supplies, or would they amount to little more than a minor sideshow in the quest for new sources of energy? The answer was far from obvious, but the question was clearly central to the future of domestic natural-gas production.

Synthetic Fuels Underground

However much enhanced recovery of petroleum and drilling for unconventional natural gas might ultimately contribute, there was consensus in the mid-1970s that coal and oil shale would soon play larger roles the nation's changing energy mix. The Project Independence goal of achieving energy self-sufficiency by 1985 spurred renewed interest in liquids and gases made from these solid hydrocarbons. One consequence was a revival of underground coal gasification, a technology that had been dormant in the United States since the Bureau of Mines and the Alabama Power Company had shuttered their pioneering experimental site at Gorgas, Alabama, in 1960. Similar work on retorting oil shale underground accelerated under the sponsorship of energy companies and the ERDA.

Bureau of Mines engineers at Morgantown and Laramie had quietly resumed studying underground coal gasification in the late 1960s. With the aid of satellite imagery and a better understanding of the natural fissures that run through coal beds, they could pinpoint optimal locations for drilling boreholes and opening passageways to guide controlled subterranean fires. The same directional-drilling methods that aided enhanced petroleum recovery and the capture of coalbed methane also offered a new way to create precise linkages among the boreholes at an underground-gasification site. In 1972, the Laramie Energy Research Center (LERC) had begun a new series of field tests at Hanna in southeastern Wyoming. The first experiment there ran continuously from September 1973 through February 1974, producing a low-BTU fuel gas by burning and gasifying subbituminous coal.

For both economic and environmental reasons, underground coal gasification looked promising during the turbulent 1970s. It could produce synthesis gas that might partly replace natural gas in power generation and chemical manufacturing. It required less energy and caused far less disruption to the land than conventional coal mining and use did. The ERDA established an underground coal gasification branch within its Division of Oil, Gas, and Shale Technology in 1975 to oversee two initiatives: further testing at LERC's Hanna site and the implementation of a parallel MERC site at Pricetown in northern West Virginia. Another ERDA component, the Lawrence Livermore National Laboratory, chipped in to launch a third underground-gasification facility at Hoe Creek, Wyoming, in 1976.

View of the underground coal gasification test site near Hanna, Wyoming. (photo credit: U.S. DOE)

The results from these demonstration projects were encouraging. Hanna II, the second set of test runs at the LERC site during 1975–1976, was the most productive and thermally efficient underground coal gasification experiment on record. It gasified over 7,350 tons of coal with no detectable gas leaks and no significant failures of equipment or processes. At the much smaller Pricetown project, which got underway in 1975 but was not fully operational until 1978, researchers from MERC and several private contractors found that a new technique called a longwall generator could effectively gasify Appalachian bituminous coal underground. This approach used a series of directionally drilled horizontal wells to inject air, steam, and an ignition source into the coal bed and to withdraw produced gas. The Lawrence Livermore site at Hoe Creek became a laboratory for proving the concept of Controlled Retraction Injection Point (CRIP) technology, another method based on directional drilling.

At LERC, the analogous idea of obtaining synthetic crude oil by heating oil shale while it was still in the ground had been under investigation since the early 1960s. The Laramie station had maintained its status as one of the foremost centers of research on oil shale and shale oil in the world. As it had done under the Synthetic Liquid Fuels Act, it kept seeking to improve the quality and lower the cost of synthetic fuels derived from shale. And turning rock formations into giant underground reactors for oil production had definite cost-saving potential. There would be no more need to cut the shale, crush it, and haul it along steep paths to a processing plant. Disposing of waste rock would cease to be a problem. Instead, an underground fire would do all the work of liquefying the shale's kerogen content while the rock stayed put.

View of the underground coal gasification test site near Pricetown, West Virginia.

The first underground oil-shale retorting tests under Laramie's supervision, performed near Rock Springs, Wyoming, in 1969, had a disappointingly low rate of oil recovery. During the early 1970s, LERC ran a second field test at Rock Springs and conducted above-ground experiments and computer simulations to determine how recovery yields could be increased. This work expanded after the ERDA took over the program. The new agency established cost-sharing contracts with several private firms to test alternate types of fracturing and retort development.

Underground retorting was part of the federal government's renewed drive to reestablish a commercial oil-shale industry in the United States. By the mid-1970s, knowledge of retorting and refining had improved enough that the widespread commercialization of oil shale finally appeared to be possible. Several private organizations had built—or were ready to build—demonstration plants; among them was a consortium of 17 energy companies that had leased and reactivated the old Bureau of Mines facility at Anvil Points, Colorado, to test the Paraho process, which was based on the Bureau's gas-combustion retort technology.[1*] ERDA proposed to have two such plants completed by 1985. The Federal Prototype Oil Shale Leasing Program, authorized in 1971 and begun in 1974, set rules for establishing commercial oil-shale plants on selected tracts of public land in the West.

Geographic and economic obstacles remained, however. Although the ERDA investigated significant oil-shale resources in Eastern states such as Michigan, the Green River Formation remained the principal magnet for oil-shale development. But that region would need massive investments in physical infrastructure to transport shale oil and to support new businesses and residents. Water was scarce, and water pollution was a serious concern. Experience had already shown that underground oil-shale retorting, like underground coal gasification, could contaminate groundwater and nearby streams. Since it belonged to the highly regulated Colorado River Basin, on which downstream cities such as Las Vegas and Los Angeles depended for their water supply, the Green River Formation had little margin for error on water-quality issues.

The cost differential remained as well. Even under the most favorable conditions, shale oil was still more expensive than natural petroleum. Rising petroleum prices during the 1970s narrowed the gap, but investors could not be sure that this trend would continue over the long lead time required to build an oil-shale industry. The question of federal subsidies for synthetic liquid fuels was just as controversial as it had been a quarter-century earlier; in 1975, Congress turned down a proposal to make the construction of oil-shale works

1* Paraho Oil Shale Demonstration, Inc. obtained its lease on Anvil Points in 1972 and began operating the Underground Quarry and a processing plant there two years later. During 1975 and 1976, the consortium produced over 10,000 barrels of shale oil there, the largest volume of synthetic oil that the U.S. had seen since the expiration of the Synthetic Liquid Fuels Act. The U.S. Navy, the U.S. Air Force, and the participating companies tested shale-oil products in military aircraft, in a freighter that carried iron ore across the Great Lakes, and in power-station boilers.

eligible for public funding. Faced with economic uncertainty, many oil-shale developers put their projects on hold or moved ahead slowly, weighing the promise of new technologies against the risks of making commitments.

Cleaner Coal

A key assumption behind Project Independence was that Americans could substitute domestic coal for imported petroleum in power generation and other industrial uses. The ERDA advocated expanding coal production and switching power plants from fuel oil to coal. Yet this call for greater reliance on coal collided with public insistence on higher environmental quality. Any sustainable increase in coal's share of the market for industrial fuels would depend on reducing coal's contributions to air pollution.

Under the Clean Air Amendment of 1970, the U.S. Environmental Protection Agency (EPA) established the first national standards for the amounts of particulates, sulfur dioxide, and other hazardous pollutants that newly built boilers and stationary engines could discharge into the atmosphere. Existing power plants were exempt, but only because Congress was optimistic that they would soon be replaced with cleaner, more efficient designs. The law created incentives for new or enlarged power plants to burn natural gas, which emitted far less pollution than coal did. But that course of action contradicted both the goal of promoting coal use and the reality of persistent natural-gas shortages during the 1970s. Consequently, the development of new methods for cleaning up coal shot to the top of the ERDA research agenda.

One approach was to emphasize types of coal that were either naturally low in sulfur or easy to desulfurize through known washing and preparation procedures. Many power-plant operators initially used low-sulfur coals to meet the EPA air-quality standards. This solution, however, had an economically and politically significant regional dimension. Low-sulfur coals predominate in the West, especially in the vast Powder River Basin of southeastern Montana and northern Wyoming. By contrast, much of the coal that lies east of the Mississippi—including the seams beneath Pittsburgh and Morgantown—has high sulfur content. Rising demand for low-sulfur coals thus tilted the geography of coal production westward, rekindling old rivalries between Eastern and Western coal interests. The federal government was sensitive to appeals from coal producers and coal users in the Eastern states for help in keeping locally abundant high-sulfur coals economically viable.

Changes in boiler design could allow power plants to keep burning high-sulfur coals while still cutting air pollution. An especially attractive technology for this purpose was *fluidized-bed combustion*. In the furnace of a fluidized-bed boiler, particles of crushed coal are lifted and suspended on jets of air that give the solid particles a rolling, fluid-like motion as they burn. This behavior promotes complete combustion by improving the distribution of heat through the coal. It also allows the boiler to work efficiently at relatively low temperatures that limit the formation of nitrogen oxides, which are acidic gases that contribute to smog. If particles of crushed limestone are added, the limestone absorbs sulfur compounds that are given off by the burning coal, thus reducing the creation of acidic sulfur-dioxide pollutants as well.

The ERDA's program on fluidized-bed combustion brought together several lines of inquiry that had separate origins in two predecessor agencies: the Bureau of Mines and the Office of Coal Research. Since the 1920s, when the basic principle of fluidizing solid materials had been worked out in Europe and the United States, the Bureau had taken an interest in this subject; in fact, the engineer W. W. Odell of the Pittsburgh station had taken out one of the earliest patents on fluidization in 1929. Most initial applications of the concept had involved the design of reactors for chemical manufacturing. Engineers at both the Pittsburgh station and the Morgantown station had repeatedly experimented with fluidized-bed gasifiers, converters, and coal feeders for synthetic-fuels production. During the mid-1970s, MERC used a fluidized-bed combustor to evaluate how various types of coal—from lignite to anthracite—behaved in this combustion process.

Elsewhere in the Interior Department, the Office of Coal Research had taken a different approach. The agency had established a public-private partnership during the mid-1960s with Pope, Evans, and Robbins, Inc., an American engineering company that was building upon British research to develop fluidized-bed boilers for power plants. This firm had constructed small prototypes, culminating in a pilot plant at Alexandria, Virginia, that began operating in 1967. By the early 1970s, it was ready to attempt a much larger version that

Rivesville Station, site of the first industrial-scale demonstration of fluidized-bed combustion in the United States.

would represent an intermediate stage between the prototypes and a full-size commercial plant. The Office of Coal Research agreed in 1972 to fund the company's installation of a fluidized-bed boiler at the Rivesville Station of the Monongahela Power Company in northern West Virginia.

The Rivesville demonstration project was the first industrial-scale fluidized-bed boiler ever operated in the United States.

The Rivesville demonstration project, which fell under MERC's supervision after the creation of the ERDA, became the flagship of a campaign to push fluidized-bed combustion rapidly toward commercial use. It was the first industrial-scale fluidized-bed boiler ever operated in the United States. Begun in 1975, completed in November 1976, and officially dedicated on August 26, 1977, the project added a state-of-the art Pope, Evans, and Robbins 30-megawatt, multicell boiler unit to a vintage power plant that had served continuously since 1919. This boiler began supplying electricity to the regional power grid on September 30, 1977, and remained in use until it was shut down in 1981.

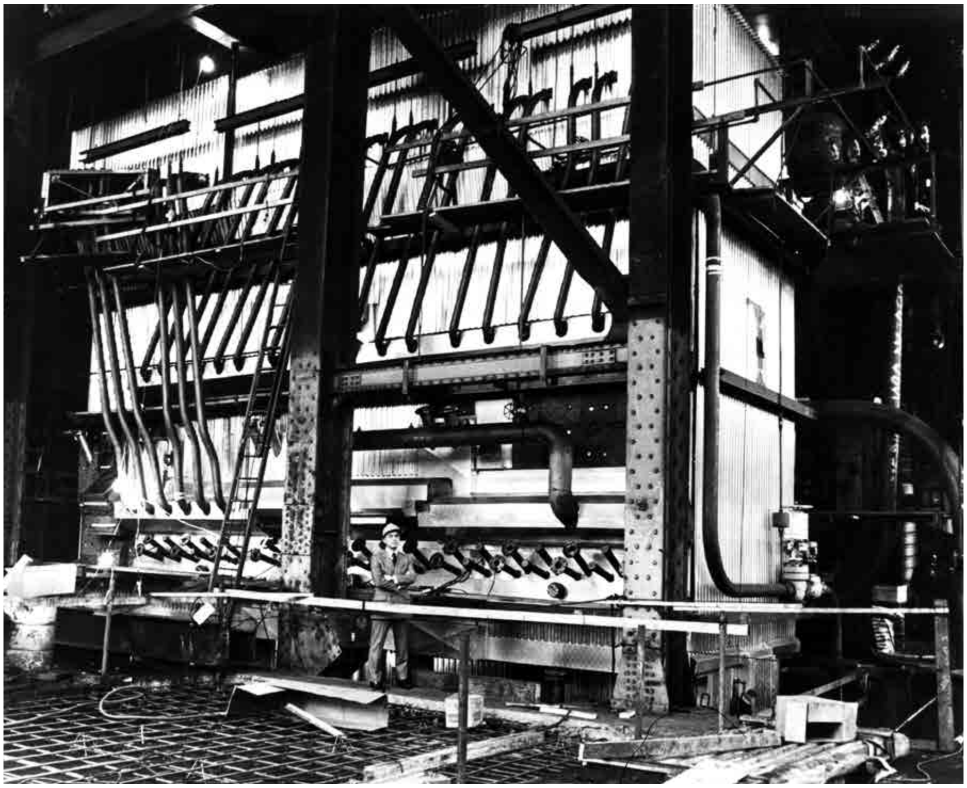
Although the project had many flaws that undermined its reliability, lessons learned from it directly encouraged and influenced the adoption of fluidized-bed combustion elsewhere in the country. Engineers who gained their first experience with this technology at Rivesville went on to design and operate other fluidized-bed boilers. Successors, such as a unit that began providing steam for heating and air conditioning at Georgetown University in 1979, were modified in response to feedback about what went right and what went wrong in the pioneering Rivesville demonstration.

MERC emerged as one of the leading American centers of research on integrated gasification combined cycle technology.

Another way to make high-sulfur coal a more environmentally acceptable fuel was to gasify the coal first rather than burning it directly. The chemical transformation of coal during gasification liberates organic sulfur compounds, which can be removed with gas-purification methods. Then the resulting low-sulfur synthesis gas can be used as a fuel for boilers and turbines. Before the 1970s, chemical engineers had cared about desulfurizing synthesis gas primarily because sulfur damaged equipment and interfered with other chemical reactions in which the gas was used. Now, thanks to the Clean Air Act and the economic concerns of the coal industry, the environmental rationale for coal gasification and gas purification became equally compelling.

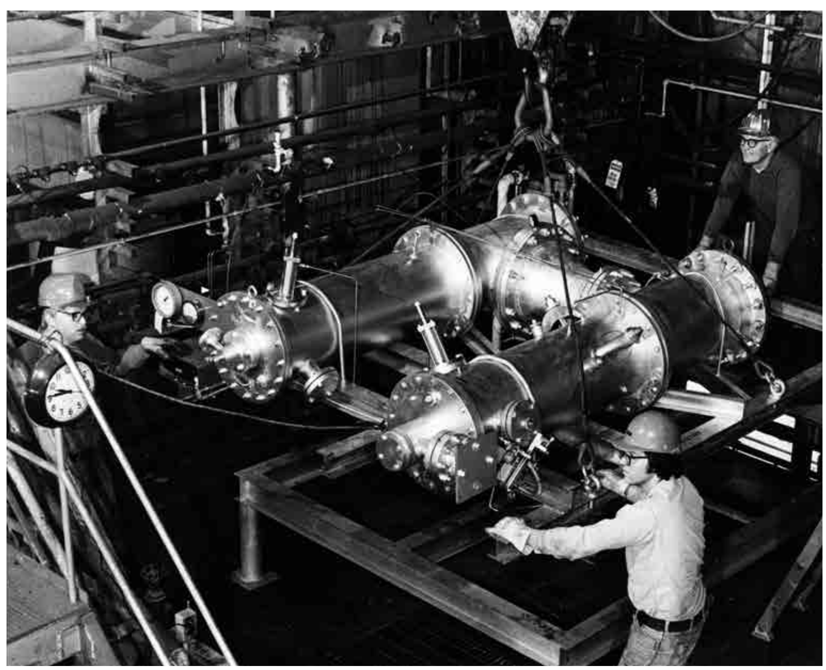
At MERC, the vision of combining coal gasification, gas-cleanup systems, and turbine engines to create the next generation of coal-fueled power plants advanced toward realization. MERC emerged as one of the leading American centers of research on *integrated gasification combined cycle* (IGCC) technology. In an IGCC plant, purified synthesis gas drives a turbine generator to produce electricity. Recovered heat from the combustion of this gas makes steam to power a second turbine generator that produces additional electricity. Cleaner and more efficient than the conventional method of burning pulverized coal to raise steam, IGCC appeared to offer the best long-term hope for the continuing use of coal in the American electric-utility industry.

A cooperative agreement between MERC and the General Electric Corporation in 1976 laid the groundwork for further improvements in coal-fueled gas turbines that could be used in IGCC applications. General Electric engineers



The experimental fluidized-bed boiler at Rivesville Station.

The fixed-bed coal gasification pilot plant at Morgantown by night.



Installing the General Electric turbine combustor, 1976.

visited Morgantown that spring to install a prototype of a combustor that the company had designed specifically to use low-BTU synthesis gas. This combustor was linked to MERC's faithful fixed-bed coal gasifier on one end and to a turbine on the other. It allowed company and ERDA researchers to study how burning synthesis gas affected turbine performance, with special attention to the perennial problem of slowing the erosion of the turbine blades.

Synthane transformed the Pittsburgh station and had a lasting influence on synthetic-fuels research.

The more exotic field of magnetohydrodynamics (MHD) offered a third possible path to using high-sulfur coal in an environmentally friendly manner. An MHD power plant can generate electricity directly from the hot gases released by burning or gasifying coal. Electrical current is created as these gases are converted into electrically conductive plasma and passed through a magnetic field. As in an IGCC plant, leftover heat can then be used to operate a steam-driven turbine. The Pittsburgh Energy Research Center (PERC) conducted laboratory-scale experiments with MHD.

To promote increased use of coal in the near term while innovations such as fluidized-bed boilers, IGCC, and MHD matured, the Pittsburgh Energy Research Center (PERC) studied improvements to existing pulverized-coal combustion processes. PERC's experimental coal combustor was the only publicly accessible testing facility in the United States large enough to simulate conditions inside the furnace of a commercial power-plant boiler. Capable of burning up to 500 pounds of coal per hour, this unique device could run controlled experiments to test the impact of changes in the air-to-fuel ratio, air temperature, size of the coal particles, and other variables on combustion efficiency and air pollution. The results indicated that emissions of harmful nitrogen oxides could be significantly decreased with modest changes in boiler design and operation.

Fueling power plants with a combination of pulverized coal and fuel oil was another option that PERC investigated. Mixing coal and oil was not a new idea; it had been tried as an emergency conservation measure during World War II. It could potentially reduce demand for fuel oil without requiring the costly, time-consuming complete overhauls that would be necessary to convert petroleum-burning boilers entirely to coal firing. Using a small commercial boiler, PERC ran initial tests on the combustion of coal-and-oil slurry and reported in 1977 that there was little difference in performance between the slurry and fuel oil alone. A much larger experimental boiler with better instrumentation entered service in 1978 to collect more data on the behavior of such mixtures, including the pollutants they emitted.

Synthane and Synthoil

As disruptions of the country's natural-gas supply intensified during the mid-1970s, so did interest in substitute natural gas (SNG) and synthetic liquid fuels made from coal. The ERDA continued a host of SNG and coal-liquefaction demonstration projects that the Office of Coal Research and the Bureau of Mines had begun. An important part of its SNG program was the Synthane process that PERC had developed. Although it ultimately failed to reach commercial viability, Synthane transformed the Pittsburgh station and had a lasting influence on synthetic-fuels research.

The Bureau of Mines had made a commitment in 1970 to build a demonstration plant that would test Synthane's ability to deliver quality SNG on a large scale. Preparing a site for this plant required the most sweeping physical changes to PERC's facilities at Bruceton since the original synthetic-fuels laboratories had been developed there in the late 1940s. Along Wallace Road to the south of the existing Bruceton campus, a steep valley was cleared, filled, and leveled to create about 40 acres of land (later known as Plateaus Four and Five) suitable for large structures. Construction of the Synthane plant and its supporting facilities at the western end of this addition began in 1973 and was completed in 1975.

Ironically, the natural-gas shortage, which hit Pittsburgh's southern suburbs hard, complicated the plant's inauguration. The local supplier of natural gas to Bruceton would not accept new hookups. PERC made alternative arrangements to use fuel oil as the startup energy source. On November 5, 1975, ERDA Director Robert Seamans presided at the dedication ceremony, and full operation commenced in July 1976.

Designed and operated by CE Lummus, a private engineering contractor, the Synthane demonstration plant could turn up to 72 tons of coal per day into 1.2 million cubic feet of SNG. The *Pittsburgh Post-Gazette* observed that this amount of gas would be "enough to heat 2,100 homes through a hard winter,"

The Synthane demonstration plant under construction at Bruceton, December 1973.

although none of the plant's output was actually used for that purpose. Not all of the coal was gasified; about one-third of it formed a solid char that could be recycled into the main Synthane reactor, burned as fuel, or employed as a feedstock for other synthetic-fuels processes.

The plant operated until September 1978, when it was shut down and placed in standby condition. It was technically quite successful. The Synthane process worked with any type of coal, including strongly caking, high-sulfur Eastern and Midwestern coals that were difficult to use for other purposes. It generated a hydrogen-rich synthesis gas that had few liquid byproducts, thus reducing the need for additional equipment to remove liquids and prepare the gas for methanation. Despite the usual problems with components that broke and instruments that failed, the demonstration plant was reasonably reliable.

A flurry of innovations was pushing coal-to-liquids technology beyond the limits of the conventional Bergius-I. G. Farben hydrogenation process and the Fischer-Tropsch synthesis.

The Synthane program was also included in the federal government's first systematic collection of data on how coal gasification affected the environment. In July 1976, the ERDA launched an environmental assessment of all SNG projects that it conducted or sponsored. With assistance from the Environmental Studies Institute at Carnegie Mellon University, it compiled documentation based on multiple tests of the quantity and chemical composition of the effluents from SNG production. Even noise pollution was tracked; a report in 1977 found that noise from the Synthane demonstration plant at Bruceton could be heard in downwind neighborhoods up to a mile away. These data indicated what environmental considerations the ERDA and any future SNG industry would have to take into account.

Economics, however, remained the stumbling block. Synthane's mix of costs and benefits ultimately proved to be relatively unattractive in comparison to several other, competing SNG processes. And SNG in general remained relatively unattractive in comparison to natural gas. Easing the gas shortage by bringing new sources of natural gas to market still seemed to be more economically feasible than massive investments in SNG were. Federal energy policy, expressed in the Natural Gas Policy Act of 1978, concentrated on promoting exploration for gas and removing government regulations that tended to limit interstate gas shipments. By the end of the 1970s, supply of and demand for natural gas were edging back into balance, and enthusiasm for SNG waned.

PERC continued to study other advanced SNG concepts, such as dilute-phase hydrogasification—an outgrowth of the center's earlier Hydrane process—and alternative methods for converting synthesis gas to methane. Solid byproducts from coal gasification, such as Synthane char, were burned in the station's experimental coal combustor to test their suitability as industrial fuels. Fundamental research on the nature of coal, and on catalysts for transforming synthesis gas into methanol, ethanol, and other useful chemicals, carried on the Pittsburgh tradition of excellence in coal chemistry.

Coal liquefaction also remained a PERC specialty. A flurry of innovations was pushing coal-to-liquids technology beyond the limits of the conventional Bergius-I. G. Farben hydrogenation process and the Fischer-Tropsch synthesis. Seeking an inexpensive way to produce low-sulfur synthetic fuel oil, PERC operated several liquefaction pilot plants during the mid-1970s. These plants refined traditional methods and tested novel approaches that had been developed in the station's laboratories. Experimental processes aimed to cut costs through simplification. For example, one pilot plant demonstrated hydrogenation with a "disposable catalyst"—a catalytic material that was discarded after a single use, thus eliminating the time and effort involved in recycling spent catalysts. Another method, COSTEAM, obtained liquids by reacting coal with synthesis gas and steam instead of hydrogen. It did not require any added catalyst. Rather, it achieved catalytic effects by relying on minerals that are naturally present in coal.

The flagship of the coal-to-liquids program at PERC was Synthoil. Launched under Bureau of Mines control in 1969, Synthoil belonged to a class of processes called *solvent extraction*. It worked by dissolving coal in a reactive liquid. A slurry consisting of pulverized coal and a solvent—usually a form of oil obtained from coal during previous runs or from other liquefaction methods—was pumped into a reactor that held a catalyst specifically designed to remove sulfur. Some hydrogen gas was added, and the mixture was heated at pressures between 2,000 and 4,000 psi—considerably less than the pressures in conventional hydrogenation. After cooling and the removal of gases and solids, the resulting liquid coal extract was separated from the solvent. This extract was low in sulfur and suitable for use as fuel oil.

With the energy crisis of the 1970s and the transition to the ERDA, hopes for the future of Synthoil soared. PERC had started out with a small Synthoil pilot plant that could liquefy about 5 pounds of coal per hour and had progressed to a half-ton-per-day pilot plant. In 1975, however, work began on a Process Demonstration Unit (PDU) that would dramatically scale up the Synthoil process. The PDU was located on the new Wallace Road extension of the Bruceton campus, just east of the Synthane site. It would be able to process up to 10 tons of coal per day. If this project succeeded, the ERDA proposed to develop a 500-tons-per-day Synthoil demonstration plant. Given that influential private companies such as the Gulf Oil Corporation and Hydrocarbon Research Inc. were conducting similar research on solvent extraction, the prospects for commercial applications seemed bright.

The Grand Forks Energy Research Center (GFERC) in North Dakota also contributed to the resurgence of synthetic fuels. Lignite, GFERC's specialty, benefited from the energy crisis. As the prices of other fuels rose, demand for this cheap, low-rank coal increased in areas of the Midwest that had access to lignite deposits. Because lignite contains little sulfur and is easy to liquefy and gasify, synthetic-fuels developers found it very attractive despite its relatively high output of other pollutants.

The experimental slagging fixed-bed gasifier that had operated at the Grand Forks station during the late 1950s and the early 1960s was restarted in 1976 to collect further data on the gasification of lignite. This research program, which continued until 1982, focused on environmental issues. GFERC analyzed wastewater and solid wastes from the gasifier to help develop better methods of pollution prevention and control and evaluate health hazards that workers in a future coal-gasification industry might encounter. Laboratory-scale experiments created synthetic oil from lignite and other low-rank coals by combining the coal with carbon monoxide and steam.

GFERC also advised private industry on how newly constructed lignite-fueled power plants could meet Clean Air Act requirements. Engineers at Grand Forks used several experimental furnaces and combustors to suggest improvements in boiler design and to evaluate new methods of flue-gas desulfurization. Because the center had forged strong relationships with mining companies, regional electric utilities, and academic scientists, it was well positioned to disseminate advances in technical knowledge quickly. It co-sponsored the Biennial Lignite Symposium at the University of North Dakota and conferred regularly with a Lignite Advisory Council that represented industry, organized labor, and the general public. These activities illustrated the ongoing value of the arrangements for public-private cooperation that the ERDA's predecessor agencies had established and nurtured over many decades.

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

Chapter Eleven: The Department of Energy and the Era of Project Management, 1977–1995

Overview of the main Pittsburgh Energy Technology Center campus at Bruceton in the 1990s. The original buildings constructed via the Synthetic Liquid Fuels Act in the 1940s are surrounded by recent additions.

Chapter Eleven:
The Department of Energy and the Era of Project Management, 1977–1995

We are well on the way to having the option of using our technology for a more secure energy future. That route can steer us away from the oil fields of the Middle East and allow us to rely on our own domestic fossil fuel reserves.

--Sun W. Chun, Director,
Pittsburgh Energy Technology Center, 1991

In 1977, the year that the United States Department of Energy (DOE) was established, the Morgantown Energy Research Center looked much as it had at the time of its dedication 22 years before. Most of its buildings had received little more than regular maintenance and an occasional coat of paint. But major changes were afoot. Over the next fifteen years, new laboratories replaced the outmoded original facilities. Plans for a building to provide more space for administrative and project-management functions at Morgantown became reality with a groundbreaking in October 1988; this project was completed in 1992.

Similar physical transformations unfolded at the Pittsburgh center during the 1980s and the early 1990s. The long shift of activities from the grand old Central Experiment Station on Forbes Avenue to suburban Bruceton culminated in 1985 with the sale of the Forbes Avenue site to Carnegie Mellon University. At Bruceton, now the hub of the DOE's Pittsburgh operations, buildings that had formerly housed synthetic-fuels demonstration plants were converted into office space for government employees and contractors. New structures arose to accommodate burgeoning specialized research on coal preparation and coal combustion.

These examples of physical modernization were outward expressions of a fundamental shift in the way that federally supported energy research was conducted. After the DOE replaced the Energy Research and Development Administration as the government's central hub for energy programs, the trend of greater reliance on outside contractors accelerated. Although the Energy Research Centers—now known as Energy *Technology* Centers—still had vigorous on-site research and development capabilities, their principal role was increasingly to oversee and manage contracts with private companies, universities, research institutes, and state and local governments that bore primary responsibility for project implementation. The shift played out differently at each location. Morgantown and Pittsburgh remained government-owned, government-operated laboratories that flourished under the new system. Bartlesville, by contrast, was converted to a government-owned but privately managed facility. And in 1983, Laramie and Grand Forks became DOE project offices linked to Morgantown, with their sites and much of their research activities transferred to separate, nonprofit organizations.

During the first two decades of DOE control, integration was the watchword in federal fossil-energy research. Common themes spanned programs and agencies: increasing domestic production of petroleum and natural gas, developing the next generation of technologies for producing electrical power cleanly from coal and natural gas, and fostering a renaissance in synthetic liquid and gaseous fuels. Although not yet a part of the DOE during this period, the Albany Metallurgy Research Center played an important role in crafting materials that could help the energy industries meet national goals for energy security, economic growth, and environmental protection.

The Birth of the Department of Energy

The creation of a new Cabinet department within the executive branch of the federal government is a rare event. On August 4, 1977, it happened for the fourteenth time in American history when President Jimmy Carter signed legislation authorizing the establishment of the U.S. Department of Energy (DOE). An executive order dated October 1, 1977, officially activated the department.

President Carter signing the Department of Energy Organization Act, August 4, 1977. (photo credit: U.S. DOE)

James Schlesinger, the first Secretary of Energy, came to the DOE from a distinguished career in national security; he had led the strategic-studies program at the RAND Corporation and had been the Secretary of Defense from 1973 to 1975 under Presidents Nixon and Ford. His appointment illustrated the deeply held, bipartisan strategic concerns that had prompted Congress to elevate energy issues to representation at the highest level of federal public administration. Not since the 1940s had energy been more obviously central to national defense and economic prosperity than it was in the tumultuous mid-1970s.

Not since the 1940s had energy been more obviously central to national defense and economic prosperity than it was in the tumultuous mid-1970s.

Activities that had originated in some 50 different federal agencies were reshaped and consolidated within the DOE. The department took over all the research and development work of the now-defunct ERDA and the emergency petroleum regulations of the Federal Energy Administration. It encompassed a Federal Energy Regulatory Commission to supervise pipelines and electrical power systems, and an Energy Information Administration to integrate all federal data-gathering on energy production and use. Control of the Naval Oil Shale Reserves moved to the DOE, as did responsibility for the sale of electricity generated at the Bonneville Dam and other federal hydroelectric facilities. Forty-four Bureau of Mines employees who had been working at the Pittsburgh station on methods of increasing productivity in coal mining were also transferred to the new department. The Carter administration sought to coordinate these assembled powers and programs in support of an integrated national energy strategy that would include increased production, greater conservation, and the rapid deployment of alternative sources in the form of synthetic fuels and renewable energy.

Changing the name on the administration building at Morgantown.

For workers at the former ERDA Energy Research Centers, DOE jurisdiction brought an intense and sometimes bewildering flurry of changes. The centers were renamed, becoming Energy Technology Centers. Now there was a new set of acronyms to master: Pittsburgh Energy Technology Center (PETC), Morgantown Energy Technology Center (METC), Bartlesville Energy Technology Center (BETC), Laramie Energy Technology Center (LETC), and Grand Forks Energy Technology Center (GFETC).

Moreover, the internal operating procedures at these sites underwent a transformation as the balance of in-house work and outside contracting tilted further toward contracting. During the late 1970s, the DOE decentralized responsibility for managing research and development projects from its headquarters in Washington, D.C., to field offices such as the Energy Technology Centers. Continuing restrictions on federal hiring also obliged the centers to turn many functions over to private companies; for example, METC hired its first site-support contractor for administrative services in 1978.

These innovations meant that center personnel had to acquire skills in project management and program management. Funding for energy research increasingly passed through the centers to universities, private companies, and other contractors that did much of the work, often at distant offsite locations. Federal employees devoted much of their effort to monitoring the contractors and evaluating the results. Project-planning meetings, contract awards, and reviews of contractors' performance made heavy demands on staff time.

Historians Rodney P. Carlisle and August W. Giebelhaus later described how new administrative practices that had begun during the ERDA period and expanded under the DOE altered the work experience at Bartlesville. To coordinate large contracts under which the government and private companies shared the costs of enhanced petroleum-recovery investigations, BETC officials set up "matrix management groups." Such groups "ranged in size between four and six, drawing on the skills of different types of technical people—chemists, petroleum engineers, production specialists, and reservoir analysts." By 1980, the center had adopted a modern, mission-focused, systems-analysis approach to planning its research program. It expected its staff to participate in setting priorities for its remaining internal research activities within the context of national energy goals and the current and likely future needs of the petroleum industry.

The changes were initially disruptive and elicited mixed reactions. "Men and women hired as researchers were now cast increasingly in the role of administrators," Carlisle and Giebelhaus observed. Not everyone was comfortable in that role. A DOE survey of the Energy Technology Centers in 1979 noted that adjustments were continuing. PETC, for instance, was still "going through a process of educating itself" in preparation for its expanding project management duties. In the long run, however, many employees welcomed the challenges and responsibilities of the new system. The era of project management increased opportunities for constructive interaction among government, private industry, and the academic world.

Total federal funding for energy research and development kept rising during the early years of the DOE. It almost doubled again between 1976 and 1980, with particularly strong gains in the areas of fossil fuels, energy conservation, and renewable resources. Following the Carter administration's policy guidance, the DOE concentrated on supporting technological solutions that appeared to have good prospects for rapid commercial adoption. Progress toward the Project Independence target of national energy independence in the mid-1980s remained the touchstone.

Federal funding for energy research and development almost doubled between 1976 and 1980, with strong gains in the areas of fossil fuels, energy conservation, and renewable resources.

The value of reducing American reliance on imported petroleum was reinforced when the Iranian Revolution of 1979 and the beginning of the Iran-Iraq War in 1980 triggered another spate of real or potential interruptions in the global petroleum supply. Waiting lines briefly reappeared at gasoline stations. The OPEC cartel took advantage of the situation to impose higher petroleum prices, which fed already-soaring inflation and pushed the U.S. economy into a slowdown. Coming so soon after the previous crisis of 1973–1974, this second oil shock was so alarming that Congress adopted the Energy Security Act of 1980 to speed the development of American synthetic-fuel industries. That law did what preceding measures, including the Synthetic Liquid Fuels Act of 1944, had always stopped short of doing: It offered public subsidies to private developers of commercial synthetic-fuel plants.

Provisions of the Energy Security Act established the Synthetic Fuels Corporation (SFC), an independent federal agency. The SFC was empowered to purchase synthetic fuels, guarantee prices for them, and guarantee construction loans. With these tools, it instituted a subsidy program that somewhat resembled what European governments had done to promote coal-to-liquids production before and during World War II. The corporation also had the authority to make loans, to enter into joint ventures with private companies, and to own and operate as many as three synthetic-fuels manufacturing facilities itself. But it never exercised those more dramatic forms of intervention.

While the SFC was getting organized, the DOE received funding for an interim program of supporting private synthetic-fuels ventures during the early 1980s. Three projects received promises of federal assistance: two oil-shale processing facilities in Colorado and a coal-gasification plant in North Dakota. Sixty-three

Motorists waiting in line for scarce gasoline in Rockville, Maryland, on June 16, 1979.

other proposals reached the SFC in time to meet a March 1981 deadline for the first round of competitive project selection, and in 1982 five of them were chosen to receive SFC aid. The United States appeared to be on its way toward a national synthetic-fuels program that would far exceed all previous attempts and ambitions.

The transition to the Reagan administration's austere stance toward federal energy programs encouraged the idea of privatization.

However, the Energy Security Act's embrace of direct federal subsidies crossed a politically sensitive line at what turned out to be an inopportune moment. Soon after the legislation took effect, energy prices began to fall. Demand for fuel and power dropped as the U.S. economy went through back-to-back recessions in 1980 and 1981–1982, and as businesses and households found ways to conserve. Worldwide supplies of petroleum and natural gas began to expand because the price spikes during the 1970s had attracted new producers into the marketplace. Once again, as in the 1920s and the 1950s, the improving outlook for conventional fossil fuels made energy companies less interested in committing private capital to synthetic fuels. Several firms that had submitted applications to the SFC later withdrew them from consideration.

The SFC concurrently became a rallying point for a strong conservative opposition movement that viewed it as an example of governmental overreach and unjustified interference in energy markets. After President Ronald Reagan—who had won the 1980 election on a platform that called for cutting federal spending and abolishing the DOE —took office in 1981, political backing for synthetic-fuels subsidies declined. Even the underlying concept of coordinated public action to promote energy independence attracted less sympathy now that the sense of acute crisis had faded. Decisions about which types of energy research and development merited ongoing federal support became more cautious and market-driven.

Transforming Federal Petroleum Research

While engineers and scientists at Bartlesville were exploring every possible way to get more petroleum and natural gas out of the ground in the late 1970s, organizational changes big and small began to alter the functioning of the station. Research Director John S. Ball decided to retire on October 5, 1978. He was replaced 11 days later by Harry Johnson. Despite official assurances that the mission of the newly renamed Bartlesville Energy Technology Center (BETC) would not change, the role of federal research on petroleum was being questioned at a time when private industry appeared to have all the resources necessary to carry out similar investigations at its own expense. Talk of closing BETC or transferring it to private ownership became more frequent.

The transition from the expansive energy agenda of the Carter administration to the Reagan administration's more austere and skeptical stance toward federal energy programs encouraged the idea of privatization. Real changes were in the air by 1981. A December 27, 1981, headline in the *Tulsa World* insisted that the "End of DOE Won't Halt Area Research." But four months later, the only promises being made were that the DOE would not lay off any employees before the end of 1982. The DOE clearly hoped to sell the BETC site to private investors. When Secretary of Energy James Edwards visited Bartlesville in July 1982 to present a plaque to outgoing Director Harry Johnson, who was about to be succeeded by Acting Director Ed Lievens, he remarked that a privately owned BETC would operate more efficiently.

In December 1982, the DOE announced that it would solicit proposals from private, nonprofit organizations interested in competing for the right to manage BETC. The winner of this competition was the Chicago-based IIT Research Institute (IITRI). The contract, signed on September 17, 1983, by IITRI's President Dr. David Morrison and a branch chief in the DOE procurement office, stipulated that the federal government would still own the research complex and fund some research. IITRI would be allowed to do research for outside customers, including states and oil companies. BETC would now be called the National Institute for Petroleum and Energy Research (NIPER, pronounced "nipper"). This new company was to receive $35 million in federal funding over five years and contribute $15 million of its own resources. The federal funds were seen by the government as seed money for basic enhanced oil recovery research to get the private enterprise started while it tried to establish a base of industrial customers.

The change from BETC to NIPER was initially an unwelcome one for Bartlesville residents, who were proud to have been the home of a prominent national laboratory since 1918 and who thrived on the jobs and the money the federal

Bill Steele of Bartlesville setting up a thermodynamics experiment using the rotating bomb calorimeter in the 1980s.

BETC became the National Institute for Petroleum Research (NIPER) in 1983.

government brought to the community. BETC employees were directly and tangibly affected; 114 of them received "reduction-in-force" notices, and of that number, three retired, and five resigned. Fifteen federal employees remained at the Bartlesville site as a separate entity called the Bartlesville Project Office. These personnel, under the direction of Tom Wesson, managed the federally funded components of NIPER's research program. IITRI offered jobs to the remaining 91 people. By June 1984, NIPER had hired 90 more employees, bringing the total at the site to 240.

NIPER had success with microbe-enhanced oil recovery, which used microbes injected into oil wells to reduce the viscosity of the oil and make it easier to pump to the surface.

NIPER aggressively marketed its services by giving more than 250 presentations to prospective customers in six months. Its targets fell into three main categories: major oil companies; large independent operators that had no laboratories of their own to support their field work; and small independent companies that could band together in a particular geographical area to solve problems specific to that region. The June 25, 1984, issue of the *Oil & Gas Journal* noted, "NIPER… has negotiated more than $1.2 million worth of proprietary research with 19 clients, including oil companies, refiners, a foreign non-government company, and several DOE agencies."

NIPER's fortunes rose and fell, just as those of the federal laboratory had done over the years. Funding cuts threatened by the president were usually restored by Congress, bad years followed good ones, and the possibility of a shutdown always loomed. In 1987, the DOE put NIPER on its list of properties to be auctioned off because the company could not prosper under the existing budget constraints. Around the same time, the Reagan administration announced that it wanted federal employees out of NIPER within 18 months. In the end, DOE extended NIPER's contract for one year, from September 30, 1988, to the same date in 1989.

The laboratory remained relevant to the petroleum industry. "With the price of oil down drastically from its $30-a-barrel level of the early 1980s, research at many of the nation's oil and gas companies has been reduced or eliminated," the *Tulsa Business Chronicle* reported on January 30, 1989. "The companies, however, still need research data. To get it, many now are relying on NIPER." Jim Deterding, the director of NIPER, noted that NIPER had advantages such as a thermodynamics laboratory that was second to none in the world. The data generated by the thermodynamics lab was crucial to improving the refining and processing of crude oils. He also discussed the success NIPER had been having with microbe-enhanced oil recovery (MEOR), which used microbes injected into oil wells to reduce the viscosity of the oil and make it easier to pump to the surface. General interest in oil-eating microbes had been generated by the cleanup of the March 24, 1989, *Exxon Valdez* oil spill, in which microbes had been used to help remove some of the 10.9 million gallons of crude that had poured into Prince William Sound, Alaska, as a result of that accident.

In January 1992, when Michael McElwrath was Director of NIPER and Dexter Sutterfield was Director of Fuels Research, MEOR continued to yield promising results. Thomas Burchfield, Director of Energy Production Research, described the process to the *Tulsa World* in detail: "Single-celled, living microbes are pumped into an injection well along with molasses… The microbes live off the molasses and multiply until the food source runs out. Then they die, leaving water and a detergent behind that pushes the oil to the well where it is pumped out, [Burchfield] said." The technique had improved the yields in some fields by 13 percent.

With these capabilities, NIPER did well enough to have its contract extended through 1993—its tenth anniversary. During the traditional recompete process

NIPER Core Analysis Lab: Rick Schatzinger at the Gamma Ray Machine, 1990.

Daryl Doughty operating instrumentation in NIPER's nuclear magnetic resonance lab, 1990.

NIPER Reservoir Characterization Group, 1990.

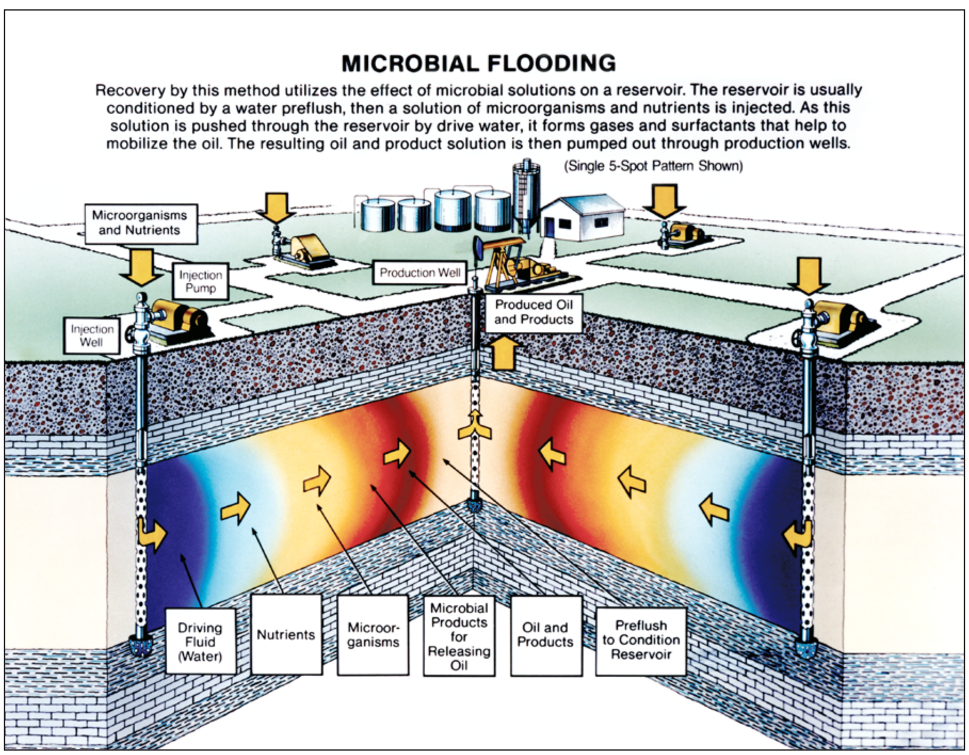
Susan Jackson and Alan Brinkmeyer examine magnified images of petroleum reservoir rock samples using a petrographic analyzer.

that year, a company called BDM-Oklahoma, a subsidiary of BDM-Federal, won the contract to replace IITRI as the manager and operator of NIPER beginning January 1, 1994. Bennie DiBona was president of BDM-Oklahoma. The five-year contract called for BDM to coordinate the implementation of DOE's Domestic Natural Gas and Oil Initiative, with the University of Tulsa as the principal subcontractor.

BDM-Oklahoma began its management of NIPER at a tough time in the cyclic petroleum business. American dependency on foreign oil had reached its highest level since the mid-1970s. The domestic petroleum industry had lost more than 400,000 jobs in the last decade, domestic production was at a 35-year low, and crude oil prices were at a 20-year low. DiBona of BDM-Oklahoma and Wesson of the Bartlesville Project Office worked together to try to help independent domestic oil producers during this tough time.

The most important technological solution that NIPER could offer to independents continued to be MEOR. By April 1994, 47 microbe-injected wells on a 520-acre test site in Rogers County, Oklahoma, had increased production by 20 percent after three years. Dr. Rebecca Smith Bryant, senior biologist and manager of chemical and microbial advanced oil recovery at NIPER, had approximately 65 workers involved in EOR, with about 14 in chemical/MEOR, and four devoted entirely to microbes.

Genetic engineers working elsewhere continued their efforts to develop a "superbug" that could survive the pressures and temperatures of an oil well thousands of feet deep. Microbes were easily found in the environment and



Schematic showing the microbial enhanced oil recovery (MEOR) process, 1992.

multiplied rapidly, making MEOR a cost-efficient form of enhanced oil recovery. Besides secreting surfactants to release oil from the underground rocks they clung to, microbes made polymers that thickened the water (similar to the micellar-polymer process), and they produced gas that could repressurize a well to force more oil to the surface. Bryant's group maintained a culture bank of 300 different strains of bugs, although only 10 to 20 different strains were used routinely in their MEOR work.

On December 9, 1994, BDM-Oklahoma and the University of Tulsa revealed plans for a joint U.S.-Russia center for oil and gas research. This center would give Russian firms access to American technology while providing Americans with information about the expanding petroleum and natural-gas industries in Siberia. Five days later, Bennie DiBona was replaced as President of BDM-Oklahoma by Dr. Lowell Smith, a 30-year veteran of the oil industry who was formerly the manager of production research at Aramco Production Co. in Tulsa.

Smith's tenure got off to a rough start in 1995, as Energy Secretary Hazel O'Leary unveiled a Strategic Alignment and Downsizing Initiative on May 3 of that year. The plan was to cut employees and expenditures at METC, PETC, and NIPER, including the possible consolidation of one of these centers into the remaining two. In late May, four DOE representatives traveled to Bartlesville to meet with NIPER and Bartlesville Project Office officials for seven hours, in what was called an "information gathering mission." "There's some threat that NIPER may be downsized or closed," Smith reported at the end of the meeting.

Ron Grigsby performs an analysis in BDM-Oklahoma's mass spectrometry lab, 1994.

Dr. Rebecca S. Bryant of BDM-Oklahoma studies a video screen showing a microscopic view of microbial cells used in microbe-enhanced oil recovery.

Wesson said the best-case scenario was a 75 percent reduction in Bartlesville's activities.

The summer of 1995 was a particularly tense time for Bartlesville as Congress moved toward making deep cuts in the DOE's fossil-energy research budget. Several legislators secured passage of amendments to restore much of the funding and to retain all petroleum research at NIPER, but Congress had changed its mind before. The issue was finally settled in August 1995, when Energy Secretary O'Leary announced that NIPER would be saved, but that it would be completely privatized during 1996. According to the initial plan, the 27 federal employees of the Bartlesville Project Office would be offered transfers to the Office of Energy Efficiency and Renewable Energy (EERE) in Golden, Colorado.

Research on other fossil fuels from the late 1970s to the early 1990s fell into two categories: activities above the earth's surface and activities below it.

Meanwhile, the Russian-American Oil and Gas Technology Center opened for business in Tyumen City, Siberia, in September 1995, as a collaborative effort of the DOE, the U.S. Agency for International Development, the Russian Ministry of Fuel and Energy, the Tyumen Regional Administration, and the University of Tulsa. "The opportunities for industry are tremendous, and they go both ways," said Tom Burchfield, director of Petroleum Program Integration for BDM-Oklahoma. "Some of the Russian technologies show great promise for our oil and gas industry." This initiative illustrated the growing trend of international cooperation in efforts to solve energy problems.

The Unconventional Underground

DOE research on other fossil fuels—coal and coal products, oil shale, and natural gas—from the late 1970s to the early 1990s divided logically into two categories: activities above the earth's surface and activities below it. The Office of Fossil Energy's Oil, Gas, and In Situ Coal Division, which handled subterranean projects, faced a situation rich in accomplishments and possibilities. Public and private investments in unconventional underground energy sources were starting to pay off. Several novel technologies that were capable of enlarging U.S. fossil-fuel reserves had reached the threshold of commercialization.

In its Underground Coal Conversion Program, the DOE set a goal of demonstrating a practical process for the underground gasification of Western coals by the 1985–1987 timeframe. It came very close to doing so. Further field tests at sites managed by LETC, the Lawrence Livermore National Laboratory, and private contractors during the late 1970s and the 1980s clarified the geological conditions that favored sustainable combustion and gasification of coal beds. Both LETC's linked vertical wells technology and Lawrence Livermore's Controlled Reaction Injection Point (CRIP) technology were effective, although CRIP had important advantages of controllability. Underground coal gasification's relatively low costs and ability to access valuable coal deposits that traditional mining could not reach were points in its favor.

The Rocky Mountain 1 project at Hanna, Wyoming, cosponsored by the DOE and the Gas Research Institute, was the largest field test of underground coal gasification that had ever been conducted anywhere outside the Soviet Union. From November 16, 1987, to February 26, 1988, it converted 15,710 tons of Wyoming bituminous coal into low-grade fuel gas. The two basic methods, linked vertical wells and CRIP, were both used simultaneously to compare and contrast their operation. Results from Rocky Mountain 1 and other tests convinced DOE engineers that there were no longer major technical obstacles to the commercial use of underground gasification.

The Rocky Mountain 1 project at Hanna, Wyoming, was the largest field test of underground coal gasification ever conducted anywhere outside the Soviet Union.

Still, underground gasification had limitations and risks that private industry found unattractive at a time when energy prices were low and abundant coal for conventional strip mining was available. Site selection was crucial; the process worked properly only in locations that had certain characteristics, such as coal beds that lay at moderate depths. Groundwater contamination was a significant issue that investigators at Rocky Mountain 1 and other sites spent much time investigating. The evidence indicated that although underground gasification definitely polluted nearby groundwater, the problem could be managed by carefully venting, cooling, and flushing the burned-out cavities that the process left behind. Fouled water could be restored by pumping it to the surface and treating it before allowing it to reenter the site.

The verdict on underground coal gasification in the 1980s was not much different than it had been twenty years earlier: This technology was important and feasible, but would not likely become common in the United States anytime soon. Over time, the DOE scaled back the Underground Coal Conversion Program. LETC ceased to be an independent organization after 1983, when it became a projects office of METC and responsibility for the federal research portfolio on the unconventional underground energy resources was centralized in Morgantown. The Western Research Institute (WRI), an affiliate of the University of Wyoming, moved into the former LETC buildings at Laramie and established several cooperative agreements with METC, including contracts

Cross-section of the Rocky Mountain 1 underground coal gasification site, showing the channels created for injecting reactants into the coal seam and withdrawing fuel gas. (photo credit: U.S. DOE) for environmental cleanup at the Hanna test site and the creation of a database containing the results of underground-gasification tests. METC continued to do laboratory-scale work on modeling underground coal gasification and exploring potential applications of lessons learned in the West to Eastern coal beds.

Underground retorting of oil shale followed a more dramatic trajectory. The late 1970s and the early 1980s witnessed the greatest oil-shale bubble since the original World War I-era boom. Lured by high petroleum prices and the availability of public funding, dozens of energy companies proposed new retort designs and laid plans for dotting the Green River Formation with pilot plants. The frenzy peaked after the DOE announced federal support in 1981 for two large commercial oil-shale developments in western Colorado: the Colony Oil Shale Project and the Parachute Creek Shale Oil Project. Several of the many oil-shale ventures that began during this period used, or proposed to use, in situ retorting.

The DOE energy research program, through LETC and METC, took a keen interest in developing in situ methods of extracting liquid oil from shale. In addition to LETC's own in situ retorting experiments at Rock Springs, Wyoming, which continued through 1979, the department participated in several cooperative demonstration projects with private developers. One of these ventures, which had started in 1976 under the ERDA, paired federal researchers with Geokinetics Inc. to build and operate an in-situ oil-shale retort at a site nicknamed "Kamp Kerogen" near Vernal, Utah. Between 1977 and 1984, 26 separate underground retorting chambers were blasted into oil-shale deposits at this site, and 20 of these chambers were set afire to produce shale oil. Some of the output from the Geokinetics project went to the U.S. Air Force, which was evaluating shale oil as a source of jet fuel for military aircraft.

But the oil-shale boom soon collapsed. Petroleum prices dropped so far and so fast during the 1980s that shale oil and other synthetic liquid fuels had no prospect of competing. On May 2, 1982, a date that would be remembered with sorrow throughout the Green River Formation, the Exxon Corporation announced the shutdown of the massive Colony Oil Shale Project. Other companies withdrew as their opportunities for profits dwindled, and by 1989 the Parachute Creek Shale Oil Project was the only commercial oil-shale plant still operating in the region.

Although this rapid meltdown discouraged further private investment in the oil-shale industry, DOE officials remained confident that oil shale had an economic future in which in situ retorting would play a significant part. The demonstration projects had shown that in situ retorts (or modified in situ retorts, which combined limited mining with underground retorting) were advantageous for large-scale extraction of oil from thick deposits of shale. Controlled fracturing of the rock was still very difficult, however.

In 1984, the DOE revised its Oil Shale Program. The new version established a ten-year agenda for basic and applied research managed by METC, which had become the lead center for the program after the Laramie laboratories were privatized. Much of this work went back to basics: studies of the physical and chemical properties of oil shale, kerogen conversion, and shale oil. Findings from the Oil Shale Program were expected to help private firms develop concepts for the next generation of retorts and prepare for an eventual turnaround in the oil-shale industry's fortunes.

The Unconventional Gas Recovery Program showed steadier progress. American coalbed-methane production reached a milestone in 1984 with the first commercial sale of gas from a set of wells that had been purpose-built solely to collect usable methane from unmined coal. Many energy companies were still reluctant to think of methane gas as a valuable commodity in its own right, rather than as merely an unwelcome byproduct of coal mining. There were other obstacles, particularly the need to build new physical infrastructure and settle questions about who owned the gas. But with the aid of federal tax incentives and regulatory changes, coalbed methane became a significant addition to the country's natural-gas supply by the early 1990s.

1984 saw the first commercial sale of gas from a set of wells that had been built solely to collect usable methane from unmined coal.

In close cooperation with the Gas Research Institute (GRI), which represented the natural-gas industry, the Energy Technology Centers worked on identifying areas that were rich in coalbed methane. The Central Appalachians, the Black Warrior Basin in Alabama, the Arkoma Basin in Oklahoma, the San Juan Basin in New Mexico, and the Powder River Basin in the Rocky Mountains were among the regions best suited to this novel form of gas production. Engineers with the DOE and the GRI encouraged state governments and private firms to view coalbed methane as a long-term business proposition, urging careful attention to issues such as well spacing and proper wastewater disposal.

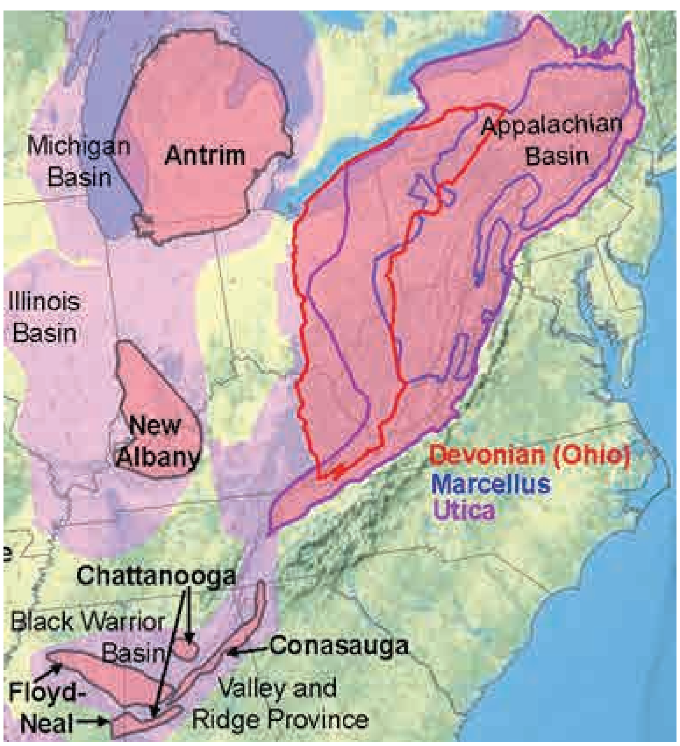
Extraction of natural gas from the deep Devonian shales of the East and the tight sandstone formations of the West also moved ahead. The Eastern Gas Shales component of the Unconventional Gas Recovery Program built upon what the ERDA had begun, vesting METC with the lead role in promoting increased exploration and development of the gas that was locked inside these ancient rocks. A key part of this effort involved constructing the first comprehensive inventories of the Devonian shales. Results from the program's core samples and test wells, historical records of gas production, and geological information were correlated to identify the most favorable locations for prospecting. Maps, atlases, and electronic databases made the resulting data available to the energy industries and the general public.

In addition to learning where Devonian shale-gas reservoirs were, the researchers wanted to know how drilling and fracture-stimulation methods could best be applied to get the gas to the surface. It was soon recognized that directional drilling would be essential. The main problem with the shales—besides inaccessibility—was their impermeability, the shortage of spaces through which fluids could move. Wells that slanted across a shale deposit or passed through it horizontally would maximize contact with whatever natural pores and fissures did exist. METC and its contractors set up more test sites in the Central Appalachians during the late 1980s and the early 1990s to experiment with angled and horizontal wells. Hydraulic fracturing and a new technique called tailored pulse loading stimulated the flow of gas.

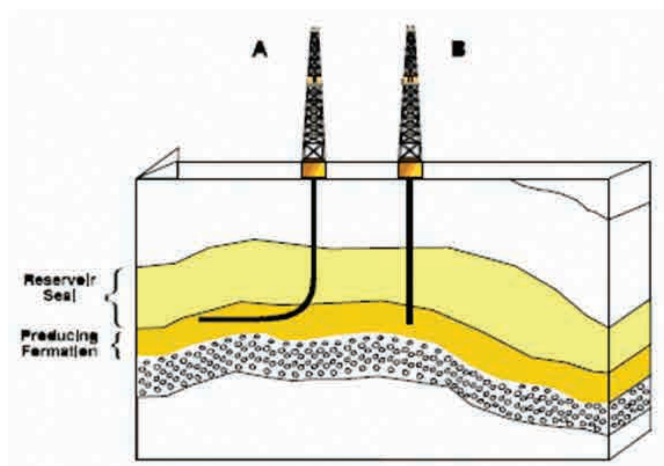
Computerization greatly benefited the Eastern Gas Shales Project. The late 1970s and the early 1980s witnessed an electronic revolution in engineering practice. Microcomputers put unprecedented computing power in the hands of individuals. Sophisticated software allowed researchers to track the performance of gas wells over time and to build mathematical models that simulated reservoir behavior. One element of the project was the creation of a software program called the Drilling Decision Tree System, completed in 1984, which provided step-by-step guidance for making choices about locating and drilling gas wells in the Devonian shales.

"Tight sands" were generally better known and easier to reach than the Eastern gas shales were, but developers usually ignored them in favor of less demanding opportunities.

In the West, the similar Western Gas Sands Project explored hard, impermeable, but gas-rich sandstone formations such as the Mesaverde Group in western Colorado and eastern Utah. These "tight sands" were generally better known and easier to reach than the Eastern gas shales were, but because extracting gas from them was so difficult, developers had usually ignored them in favor of less demanding opportunities. As natural-gas prices kept rising during the late 1970s and the early 1980s, however, the gas industry took another look. The Gas Research Institute and private contractors joined the DOE—represented by METC, Sandia National Laboratory, and Lawrence Livermore National Laboratory—in a systematic assessment of the tight-sands formations.



Map of Devonian shale formations that are major reservoirs of natural gas in the eastern United States .(photo credit: Energy Information Administration, U.S. DOE)



Horizontal drilling placed a well in greater contact with a petroleum or natural-gas reservoir than vertical drilling did, an advantage that was especially important in the difficult context of impermeable shale formations. (photo credit: Energy Information Administration, U.S. DOE)

Early attempts to break up the tight sands with conventional fracture-stimulation techniques yielded disappointing results, so the researchers concluded that two things were needed: better understanding of the rock and better fracture-stimulation techniques. These objectives, in turn, required improved means of measurement and analysis. The partners in the Western Gas Sands Project designed computer models of tight-sands gas reservoirs. They set up thoroughly instrumented test sites, the most notable of which was the Multi-Well Experiment field laboratory near Rifle, Colorado, from 1981 to 1990. At the Multi-Well Experiment site, three vertical wells and a directionally drilled horizontal well were used to study the geology of the sandstone and to assess the results of different fracturing methods. The resulting data were used to update estimates of tight-sands gas reserves and point toward the most promising areas for commercial development.

Although DOE-sponsored research made useful information about tight-sands gas available, the future of these resources ultimately depended on the willingness of private investors to accept the cost and risks of development. The pieces of the tight-sands puzzle finally came together during the 1990s in north-central Texas, where the Barnett Shale formation runs beneath metropolitan Fort Worth. Independent natural-gas companies, led by Mitchell Energy, figured out how to release large amounts of natural gas from numerous small directional wells drilled into the Barnett Shale. By the end of the twentieth century, a tight-sands gas boom was underway.

Gary Covatch, a petroleum engineer at METC, using a computer program to monitor and analyze the results of fracturing experiments in a natural-gas field.

Site of the Multi-Well Experiment with natural gas in tight-sands formations near Rifle, Colorado. (photo credit: U.S. DOE)

The final component of the Unconventional Gas Recovery Program, methane trapped in underground reservoirs of water or ice, remained the least understood. Under the DOE, responsibility for investigating the methane-bearing geopressured aquifers along the Gulf of Mexico coast shifted to the Division of Geothermal Energy. But in 1983, METC began studying another possible source of gas: methane hydrates. Found where natural gas encounters very cold water, methane hydrates are solid ice crystals that enclose methane gas. They exist in deep undersea deposits along the edges of the North American continent and in shallow sediments on land in the Arctic. Initial speculation in the 1980s posited that these crystals might contain more methane than did all other U.S. natural-gas resources combined. Researchers at METC examined samples of methane hydrates and analyzed the geology of methane-hydrate fields along the Arctic Ocean coast of Alaska to assess how much recoverable natural gas was actually there.

Little known in the mid-1970s, the unconventional underground was a lively scene twenty years later. According to the Energy Information Administration, coalbed methane, tight-sands gas, and gas from Devonian shales together accounted for 18 percent of U.S. natural-gas output in 1990 and 24 percent in 1998. Underground coal gasification was an available technology if the price was right, and work continued on in situ shale oil and methane hydrates. As it helped to expand the range of methods for obtaining fossil energy from the earth, METC had emerged as a national leader in natural-gas research.

Electrical Coal

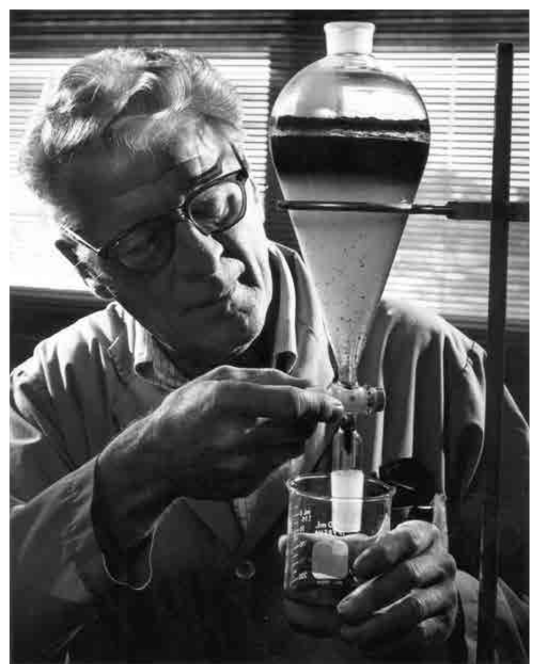
Above ground, promoting the use of coal remained a cornerstone of national energy strategy throughout the 1980s and the early 1990s. Coal production and consumption rose steadily as coal prices stayed low. Driving this expansion was the growth of electrical-power generation, which turned over 80 percent of the coal that was mined in the United States into about 60 percent of the country's electricity. Power-plant operators needed innovations that would allow the upward trend in power output to continue while keeping costs and pollution under control. PETC and METC, the DOE's lead centers for coal research, responded by improving coal preparation and developing advanced coal-based power systems.

"Part mineral separation, part physics and chemistry, and more than just a little engineering, the art and science of coal preparation is not new to PETC," Director Sun W. Chun observed in 1992. The Pittsburgh station had been involved for most of its history in this unglamorous but vital work of tailoring raw coal to specific human uses. It had cooperated with industry on methods of sorting coal by size and by mineral content, controlling dust, removing impurities, and matching coals to the fuel specifications of particular industries.

Beginning in the 1970s, however, coal preparation took on unprecedented significance for the economy and the environment, and PETC greatly expanded its activities in this field. The coal industry had strong economic and political incentives to eliminate impurities that reduced power-plant efficiency and caused pollution. For Eastern bituminous coals, getting rid of sulfur remained the highest priority. For Western low-rank, low-sulfur coals, moisture and alkaline metals (such as potassium and sodium) were the principal contaminants that had to go. The smaller the particles of coal, the easier it was to separate these unwanted minerals through conventional means of physical cleaning. But grinding coal to small sizes not only consumed much more energy, it also increased waste in the form of "fines," tiny pieces of powdered coal that are hard to handle and hard to use. The industry faced a dilemma: Making coal cleaner, as its customers and society as a whole demanded, resulted in costly losses of product.

The Coal Preparation and Solids Transport Division at PETC addressed the intertwined problems of cleaning coal more thoroughly and making coal fines more useful. On the Bruceton campus, a new Coal Preparation Laboratory opened in 1984 and was later expanded with the addition of the Coal Preparation Process Research Facility in 1992. Scientists and engineers used these facilities to study alternative physical-cleaning methods, such as advanced froth flotation and selective agglomeration. The division investigated chemical and biological processes for removing sulfur and metals that bonded with the molecules in coal. A Fuels Evaluation Facility, established in 1989, allowed systematic testing of the effects that different methods of coal preparation had on the actual behavior of coal in a furnace. By finding more effective ways

The Coal Preparation Laboratory at PETC.



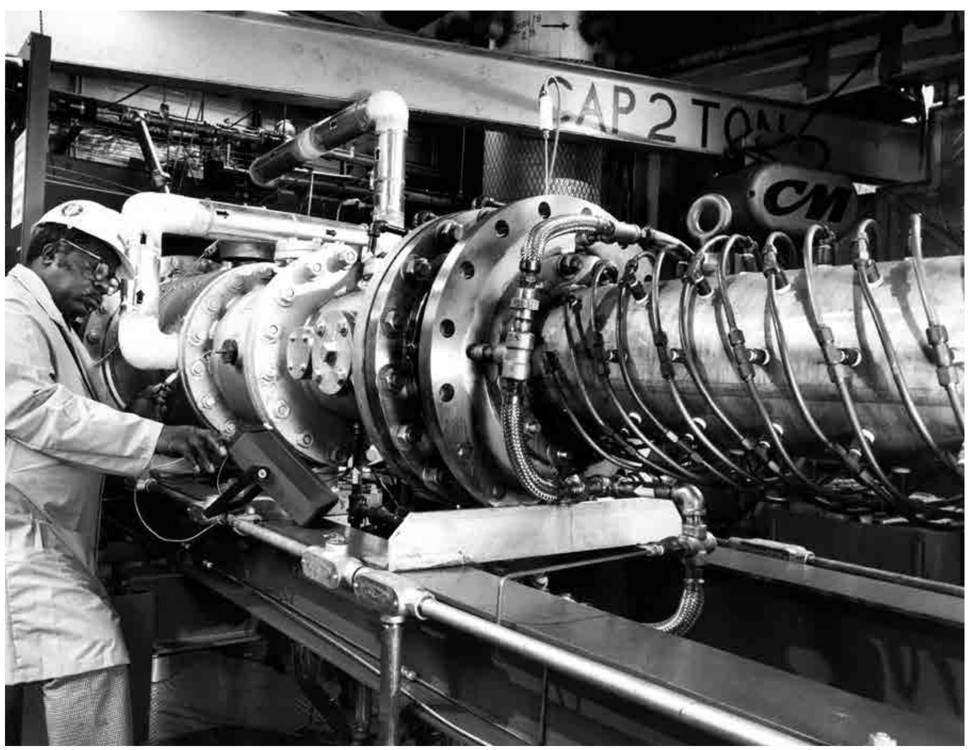
Henry F. Mesta at PETC demonstrates how ash can be removed from coal through a coal-preparation method called selective agglomeration.

to recover coal fines, clean them, and ready them for conversion into higher-value products, PETC engineers transformed waste into economic gain.

"Coal preparation is the *enabling* technology, serving as the foundation for coal use across the full spectrum of current and future applications of coal," the center's official journal, *PETC Review,* asserted in 1992. Cleaner coal was clearly a wellspring of many other benefits. Eliminating contaminants from coal before it was burned saved wear and tear on power-plant boilers and limited the need for expensive scrubbers to strip pollutants from flue gases. Coal that contained little sulfur or ash made a superior feedstock for gasification and synthetic-chemical production, and an excellent base for coal-and-water or coal-and-oil mixtures that PETC and METC were trying to perfect as substitutes for fuel oil.

By finding more effective ways to recover coal fines, engineers transformed waste into economic gain.

Yet the next wave of environmentally responsible coal-fueled power plants would need more than just a supply of highly cleaned coal. They would also require systems for transforming that coal into electricity as efficiently as possible. The combustion of pulverized coal, which had dominated power-plant design since the 1920s, still had room for improvement. PETC began its Combustion 2000 program in 1989 to show how advances in industrial boilers, burners, combustors, and flue-gas cleanup over the past two decades could be combined to form a total Low-Emission Boiler System. Because it would not differ radically from existing practices, this system would offer a model that companies could quickly adapt for new or retrofitted plants.



Leonard Kirkland measuring the temperature of combustion gases in an experimental coal combustor at PETC.

Combustion 2000 also included a parallel initiative to create a High-Performance Power System (HIPPS) that would depart further from traditional boiler designs. In the basic concept of this project, coal would be burned in a special high-temperature furnace to heat air. The hot air, supplemented with natural gas, would drive a gas turbine and also heat water to produce steam. Objectives included increasing thermal efficiency by 12 percent, reducing smog-causing pollutants to as little as 25 percent of the legal limits, and cutting electricity costs by 10 percent.

Replacing conventional boilers with fluidized-bed versions was another option. Fluidized-bed combustion went mainstream during the 1980s, with several commercial boiler manufacturers beginning to offer it. Researchers at METC kept testing and refining the basic concept of fluidized-bed boilers that operated at normal atmospheric pressure, addressing problems such as erosion of surfaces and boiler tubes. In addition, they set out to develop a second generation of pressurized fluidized-bed combustion technology.

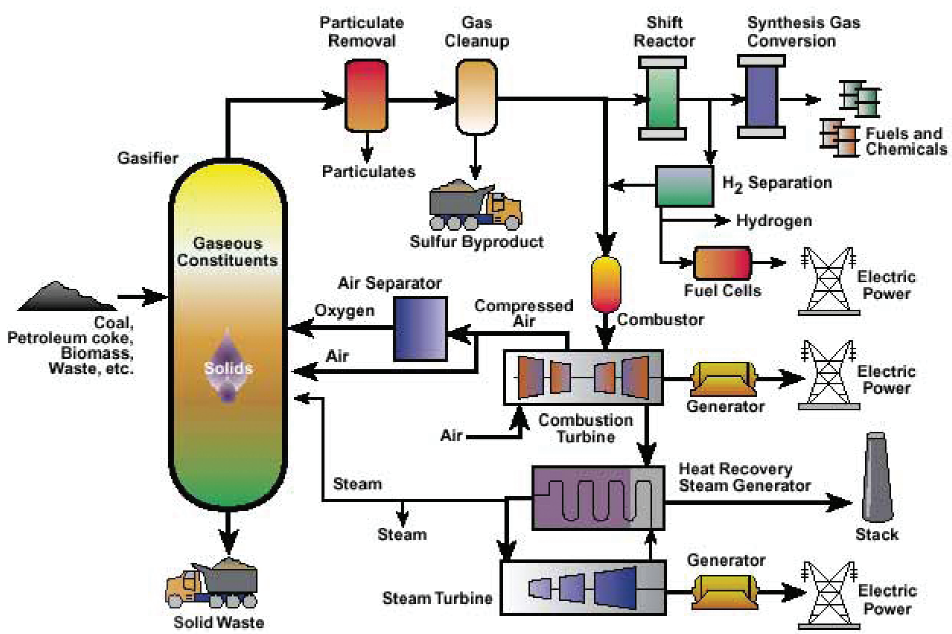
Diesel engines fueled by coal might also serve as power generators. Several projects at METC used liquefied coal or mixtures of coal and water to run diesel stationary engines or diesel locomotives. Working closely with major American engine manufacturers, the Clean Coal Diesel initiative during the mid-1980s worked out specifications for small modular power plants that could meet industrial standards for ruggedness and reliability as well as comply with air-pollution limits.

Alternately, the electric-utility industry might choose to adopt power systems that did not involve burning coal directly. There were several possible candidates for the power-plant technology of the long-term future, with Integrated Gasification Combined Cycle (IGCC) being a strong contender. In the IGCC process, power is generated via two cycles. First, synthesis gas is burned in a gas turbine to produce power. Second, the hot exhaust gases from the gas turbine heat water to make steam that drives a steam turbine, producing more power. Combining these two cycles in one process results in increased efficiency, as electrical power emerges from both the gas turbine and the steam turbine. IGCC took a major step forward through the Cool Water demonstration project at a Southern California Edison station near Barstow, California. Launched in 1979 by a consortium of energy companies, the Cool Water plant received public financial support from the federal Synthetic Fuels Corporation. It operated from 1984 to 1989, using a General Electric turbine and a gasifier devised by Texaco, and was the first IGCC plant in the world to generate electricity for commercial sale.

IGCC remained a focus of research and development on coal-fueled gas turbines at Morgantown throughout the 1980s and the 1990s. A new round of work on ultra-efficient turbines began in 1992 with the Advanced Turbine Systems (ATS) Program, which resulted from a convergence of interests in environmental stewardship and economic competitiveness. Although American turbine-engine manufacturers had long dominated their industry, global competition was challenging their leadership. Congress designated funding specifically to help domestic companies stay at the forefront of turbine engineering. Teaming up with the DOE Office of Conservation and Renewable Energy, METC managed contracts for the design and testing of turbines that would be as much as 60 percent more energy efficient than standard models were. ATS projects were intended primarily to use natural gas, but every contractor had to show how its turbine could be adapted to run on coal-based fuels.

The METC Combustion Research Facility opened in 1993 to support work on ATS, fluidized-bed combustion, and other advanced research on power systems that used coal or natural gas. It contained space for testing and repairing equipment, a sophisticated computerized control system, and services such as high-pressure air and water. The facility was available to researchers from companies and universities that had cooperative agreements with METC.

Fuel cells offered yet another path for indirectly converting coal to electrical power. A fuel cell produces electrical current when a fuel source reacts with a source of oxygen in the presence of an electrically conductive substance (electrolyte). Hydrogen—or hydrocarbons, such as natural gas or synthesis gas made from coal—can serve as the fuel. The METC fuel-cell program evaluated the performance of various types of fuel cell that differed in the electrolytes they used—for example, phosphoric acid, molten carbonate, or solid oxide. It configured coal gasifiers to work together with fuel cells, looking toward the eventual scale-up of this technology to create Integrated Gasification Fuel Cell power plants. Most near-term applications of fuel cells, however, were likely to be small units for use in individual buildings or groups of buildings, industrial processes, or transportation.



Flow diagram of an Integrated Gasification Combined Cycle (IGCC) process for producing electricity from gasified coal.

The DOE's investments in coal chemistry and power-systems initiatives signaled a judgment that in some way, shape, or form, coal would remain the nation's preeminent source of fuel for electrical power well into the twenty-first century. Technical changes and the need for environmental protection would redefine how coal was used, but would not alter the basic fact of its persistence in this crucial economic sector.

Synthetic Fuels

The DOE's investments in coal chemistry and power-systems initiatives signaled a judgment coal would remain the nation's preeminent source of fuel for electrical power well into the twenty-first century.

Among the many uses of coal that PETC and METC studied during the closing decades of the twentieth century, synthetic liquid and gaseous fuels still held a special place. The oil shocks and natural-gas shortages of the 1970s had reinvigorated the view that the United States should have a strategic reserve of capability to produce synthetic fuels from domestic coal. Even after the energy crisis diminished, this conviction remained.

The DOE's Surface Gasification Program inherited a set of coal-gasification projects from the ERDA and its predecessors. Two important experimental gasifiers, the fixed-bed units at Morgantown and Grand Forks, belonged to the DOE itself. METC's modified Lurgi gasifier had the distinction of becoming one of only three completely integrated coal-gasification systems in the country as of 1982. That meant, as a METC document explained, that all its elements—gas production, gas purification, and control mechanisms—worked together to make synthesis gas that was "tailored to a particular end use" and met all environmental standards. The GFETC pilot plant for gasifying lignite conducted environmental studies until the Grand Forks site was transferred to the University of North Dakota in 1983, leaving a METC projects office as the only direct federal presence there.

Half a dozen other private demonstration projects, illustrating a variety of purposes and processes, operated under DOE sponsorship during the early 1980s. One was a substitute natural gas (SNG) plant at Homer City, Pennsylvania. Two low-BTU fuel-gas producers in Pennsylvania and Minnesota reflected a brief revival of interest in industrial uses for manufactured gas. Westinghouse was testing a fluidized-bed gasifier near Pittsburgh, and General Electric operated a fixed-bed gasifier in Schenectady, New York, as part of its cooperative agreement with METC on IGCC research. In Utah, a gasifier owned by a company called Mountain Fuel Resources demonstrated an innovative method of ash removal.

With a few exceptions, these demonstration projects were legacies of concerns about the reliability of the natural-gas supply during the late 1960s and 1970s. PETC's ongoing research on SNG had similar origins. So did the first commercial SNG plant in the United States: the Great Plains Coal Gasification Plant at Beulah, North Dakota. Completed in 1984, this venture traced its roots back to efforts by gas-pipeline operators and Midwestern utilities to find alternative sources of fuel in the early 1970s. It gasified North Dakota lignite to produce up to 1.5 million cubic feet of SNG per day for distribution through the regional pipeline network. GFETC and METC did environmental analysis for the

Great Plains project, while the DOE provided loan guarantees and briefly took ownership of the plant from 1986 to December 1988 after the original financing fell through. To a degree, the Great Plains Gasification Plant vindicated the longstanding determination of North Dakotans and the federal government to put the lignite resources of the Upper Midwest to broader use.

But the circumstances that had given rise to this achievement were memories by the mid-1980s. Natural-gas prices echoed the downward trend of petroleum prices (although not as steeply), and deregulation and unconventional natural-gas sources added new supplies. Political opposition to government subsidies for synthetic fuels crested with the abolition of the Synthetic Fuels Corporation in 1985. After having spent roughly $4 billion on synthetic-fuels programs between 1970 and 1984, the federal government ended most of the remaining demonstration projects and slashed its overall budget for civilian energy research and development. The vision of a massive American synthetic-fuels industry supported by public policy vanished as quickly as it had emerged.

During this retrenchment phase, the idea that government investments in energy research should focus primarily on basic science and rely as much as possible on private industry to commercialize new knowledge reasserted itself. Secretary of Energy James Edwards (1981–1982) had spoken in 1981 of limiting federal intervention to "areas where . . . market forces are not likely to bring about desirable new energy technologies and practices within a reasonable amount of time. . . ." His successors Donald Hodel (1982–1985), John S. Herrington (1985–1989), and James D. Watkins (1989–1993) took the same position, which was reflected in DOE budget priorities. Individual sites felt the sting of budget cuts; for example, METC encountered delays after it started work on the expansion of its main administration building in 1988. Nevertheless, successive administrations and Congresses found reason to keep supporting both

An experimental hot-gas cleanup system at METC in the mid-1980s. Using zinc ferrite as a sorbent, this system could remove up to 99.9 percent of the sulfur from a stream of hot synthesis gas or fuel gas.

The Great Plains Coal Gasification Plant at Beulah, North Dakota. (photo credit: U.S. DOE) basic and applied research, and the Energy Technology Centers found ways to adapt to the new realities.

When the twenty-year-old coal-gasification pilot plant at METC was at last retired from service in 1988, it was replaced with a smaller fluidized-bed pressurized gasifier that had a capacity of one ton of coal per day. This device was designed to be highly flexible, providing low-BTU gas for any purpose that DOE engineers or private contractors might desire. It constituted part of the center's Advanced Gasification and Hot Gas Cleanup Facility, in which the latest methods of gas purification could be tested.

METC was known for its specialized competence in testing and upgrading valves and other components of gasification systems.

A valuable feature of this arrangement was its suitability for Cooperative Research and Development Agreements (CRADAs), which became an important form of public-private collaboration at the Energy Technology Centers in the 1990s. CRADAs differed from earlier forms of cooperative agreement in how they assigned property rights in inventions and discoveries. As a METC report in 1993 explained:

> *CRADAs were authorized by several Congressional actions that encourage federal laboratories to work with industry. The general goal of the CRADAs is to improve U.S. competitiveness. Under a CRADA, data generated in the project can be kept confidential to the parties for up to five years, and the industrial party can be given an exclusive license to inventions made under the CRADA or prior inventions owned by the government. CRADAs are not contracts and do not fall under the government acquisition regulations. [They] must be cost shared between the government and the industrial party. No government money may go to the partner under the CRADA, although money may be received by the government in the form of royalties and direct payments from the partner.*

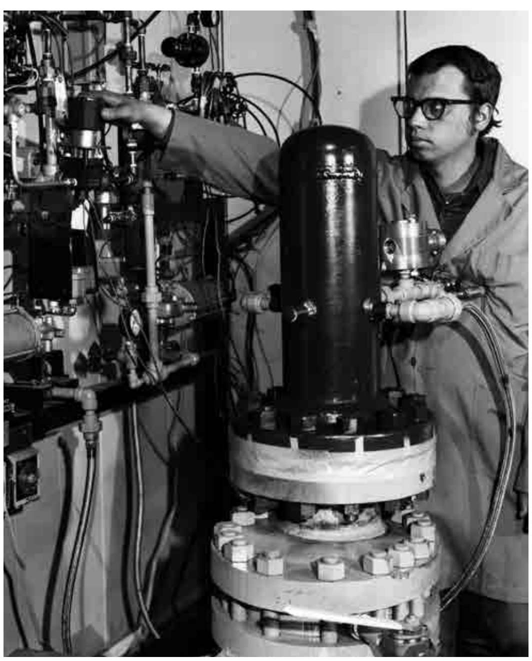
The Advanced Gasification and Hot Gas Cleanup Facility participated in implementing several CRADAs with private companies that wanted to use its equipment or gain the rights to sell inventions that had originated at METC. In 1994, one of these agreements brought METC its first entitlement to royalties—specifically, the right to share in any royalties that flowed from sales of a filter-cleaning device that three staff members at the center had patented.

METC was especially known for its specialized competence in testing and upgrading valves and other components of gasification systems. This need had been a familiar one since the earliest days of the Morgantown station in the 1940s: High pressures, high temperatures, and abrasive and corrosive substances wreaked havoc with equipment. Someone had to solve the unusual engineering problems that resulted. Texaco, among other private-sector beneficiaries, credited the METC staff with making significant improvements in valve design.

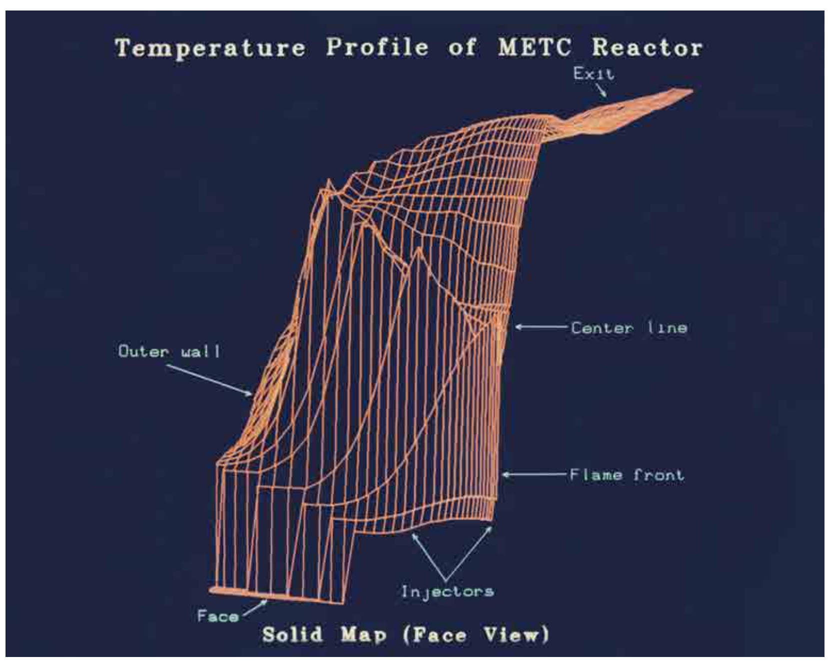
As contracts and CRADAs with private industry became more central to its work, METC limited its in-house research to certain areas that supported key topics such as IGCC and removing sulfur from hot gases, or that pointed to new processes for converting coal to synthesis gas. Computer modeling was essential. The Advanced System for Process Engineering (ASPEN) software, originally designed at the Massachusetts Institute of Technology and adapted at METC for use in fossil-fuels research during the early 1980s, placed the center in the vanguard of modeling technology. Later in the decade, METC developed its own mathematical models of coal gasifiers and power systems.

Transforming synthesis gas into liquids was the province of PETC, the DOE's lead center for synthetic liquid fuels. Since advances in coal gasification had lowered the cost of synthesis gas, the main input in the Fischer-Tropsch process, the economics of Fischer-Tropsch coal-based fuels and chemicals looked better than ever. Researchers at PETC were confident that the latest reactor designs, which used the slurry method of suspending particles of iron catalyst in waxy oil and allowing the gas to bubble upward through this suspension, would solve most of the operating problems that earlier plants had experienced. Besides, there were environmental benefits. Synthetic diesel fuel from this process tended to be low in pollutants such as carbon monoxide and soot. Fischer-Tropsch reactors were good at producing oxygenating chemicals (for example, alcohols) that, when used as gasoline additives, could reduce toxic emissions from motor vehicles. Clearly, a Fischer-Tropsch revival was in order.

The Fischer-Tropsch program at PETC stepped up during the early 1990s with new research on catalysts and slurry-type reactors. In 1993, the center completed a new Bench-Scale Unit (BSU) for testing reactor performance under various conditions. Like other recent additions to the Energy Technology Cen-



Valve testing facility at METC.

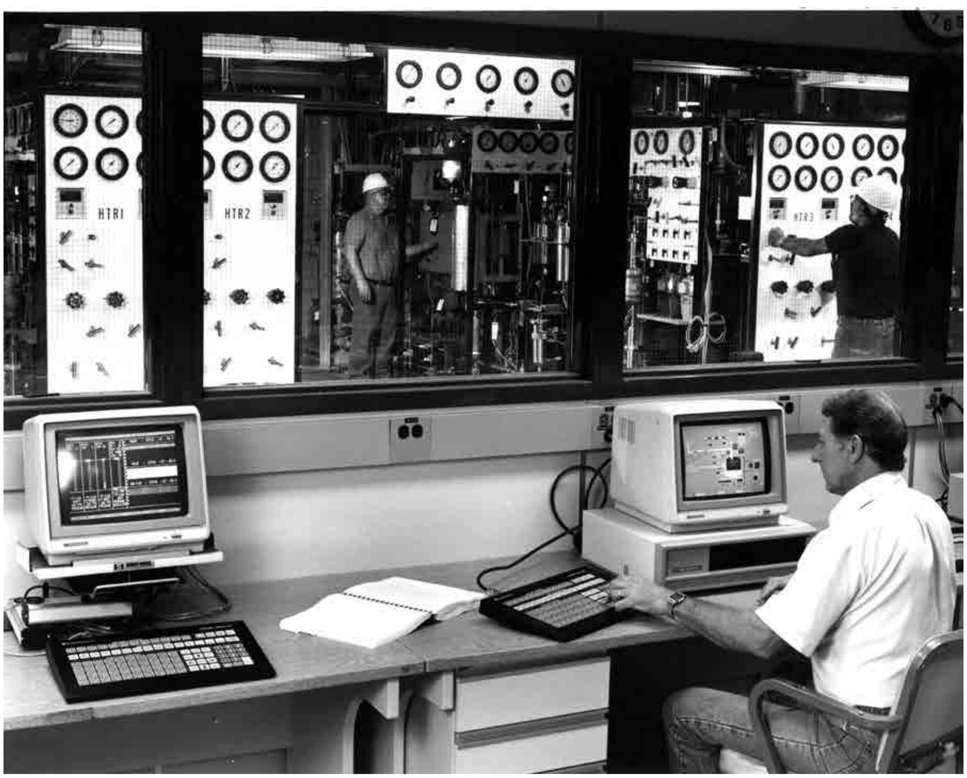


This profile of temperature variations caused by burning a mixture of coal and water inside a combustor was generated on a computer that used the ASPEN software system.

ters, this BSU was open to contractors and other researchers from outside the DOE who could make good use of it in their experiments.

A similar "generic BSU" served PETC's program on direct coal hydrogenation. Over the three-decade span between the late 1950s and the late 1980s, direct hydrogenation had made even greater technical progress than the Fischer-Tropsch synthesis had. Government agencies and energy companies had sponsored several demonstration plants for converting coal into gasoline or fuel oil. Most of these projects ended in disappointment. A case in point was the Synthoil demonstration plant at PETC itself—a plant that never actually operated and was eventually converted into office space for project managers and contractors. But much was learned about *why* coal-to-liquids processes failed and what to do next.

The worst drawback of the original Bergius–I. G. Farben process—the need to run coal-to-liquids converters at exceptionally high pressures—was overcome by the 1970s as better catalysts accelerated the reaction sufficiently at much lower pressures. Among specialists, a consensus then emerged that dividing the first stage of the process (the liquid phase) into two distinct steps would yield further gains in product quality and cost reduction. Two-stage liquefaction (TSL) became the coal-hydrogenation technology of choice and the centerpiece of synthetic liquid fuels research at PETC. It was tested in small reac-



Testing a high-temperature catalytic reaction system at PETC that evaluated the performance of catalysts for turning synthetic crude oil into high-grade fuels and organic chemicals.

tors on the Bruceton campus, in contractors' laboratories, and in a pilot plant that the DOE and the Electric Power Research Institute operated at Wilsonville, Alabama.

In 1990, the National Resources Council estimated that TSL and other process innovations had cut the cost of a barrel of synthetic oil made from coal by half over the preceding decade. The notion that coal liquids and substitute natural gas might replace petroleum and natural gas in everyday life was still a stretch, but less so than it had been before the energy crisis of the 1970s. Synthetic fuels had come a long way.

The Clean Coal Technology Demonstration Program

For many Americans in the late twentieth century, two words summed up the relationship between coal and the environment: acid rain. Scientific evidence and everyday observation indicated that rain, ice, and snow had become contaminated with acidic pollutants. These invisible but pervasive airborne hazards were destroying forests, harming aquatic life in lakes and streams, and damaging historic buildings. Although acid rain had many sources, coal-fueled power plants were significant and highly visible contributors to the problem. The DOE, through PETC and METC, partnered with the coal and electric-utility industries to showcase creative engineering solutions for mitigating the environmental impact of these power plants.

Acid rain emerged as a major issue in American domestic politics and foreign policy during the 1980s. At home, it threatened to pit region against region as states in the Northeast complained about air pollution from states in the Ohio Valley and the Midwest that blew eastward on the prevailing winds. Environmental groups pressed for stricter federal air-quality standards, while associations representing industry and coal-producing states opposed new regulations. Concurrently, the acid-rain situation created diplomatic complications with Canada, whose government and citizens blamed U.S. sources for environmental degradation in eastern Canadian provinces. The need for a national response was evident—but what form should that response take?

The Clean Coal Technology Demonstration Program (CCTDP, or Clean Coal Technology) was Congress's first attempt to define an answer. Enacted in 1984 and first funded in 1985, this program was designed to accelerate the development and dissemination of technologies for using coal efficiently and cleanly in power generation and industrial production. Supporters held that the rapid spread of these clean coal technologies could reduce or eliminate the need for stricter mandatory air-pollution controls. That view ultimately did not prevail; Congress went on to adopt the Clean Air Act Amendments of 1990, one of the most complex and far-reaching environmental laws in American history, which tightened limits on the emissions that cause acid rain and set up a market-like system for trading pollution allowances. The CCTDP then became an instrument for helping industry comply with the new law.

Under the CCTDP, the Department of Energy solicited proposals from the private sector in a competitive review process. There were five rounds of competition for funding, beginning with Round 1 in 1986 and ending with Round 5 in 1992. The department evaluated the proposals according to several criteria, including technical and environmental merit, energy efficiency, cost, and potential for commercial success. Once the finalists in a round were selected, the DOE negotiated cooperative agreements with the sponsors of the winning proposals, specifying that private and state or local sources had to cover at least 50 percent of a project's total cost. METC and PETC were responsible for monitoring and assisting with the implementation of the projects.

The CCTDP became an instrument for helping industry comply with the Clean Air Act Amendments of 1990.

Clean Coal Technology finalists were very diverse, but they fell into several broad categories. One group of projects emphasized coal selection and coal preparation to limit the amount of impurities that entered power-plant boilers. For example, a consortium led by ABB Combustion Engineering and CQ Inc. developed a computer software system called the Coal Quality Expert. This system was designed to advise power plant managers about what types of coal to purchase and how best to use them. Building on existing industrial databases, it evaluated information about the characteristics of different coals, coal-cleaning processes, available pollution-control equipment, and the operating performance of a given power plant. It could help managers choose coals or blends of coals that were economically and environmentally optimal.

Another class of technologies focused on combustion, on making coal burn more evenly and thoroughly in order to limit the release of pollutants. Several Clean Coal Technology partnerships focused on controlling nitrogen oxides (NO_X), which are acidic gases that contribute to acid rain. Specially designed burners limited the formation of $NO_{X,}$ especially if used in combination with a technique called overfire air that injected additional air into the top of a boiler's furnace to encourage complete combustion. So did gas reburning, in which the exhaust (the flue gas) from coal combustion reacted with injections of air and natural gas.

A third category of projects relied primarily on post-combustion technologies—methods of cleaning up pollutants that had already formed during combustion and preventing them from escaping to the atmosphere. Two technologies at Ohio Edison's Edgewater Plant on the Lake Erie shore in Lorain, Ohio, illustrated an approach to removing acidic sulfur dioxide (SO_2). Edgewater was typical of older Midwestern coal-burning power plants that were hard to retrofit with emissions-control equipment. As an alternative to installing a costly and awkward conventional scrubber system, the Babcock & Wilcox Company proposed its Coolside and LIMB sorbent-injection processes. The Coolside process sprayed lime and a humidifying sodium-based mist into the plant's flue-gas stream to absorb and neutralize SO_2. In the LIMB process, a calcium-based sorbent was injected directly into the boiler to start a series of chemical reactions that captured SO_2 as it was on its way out of the boiler.

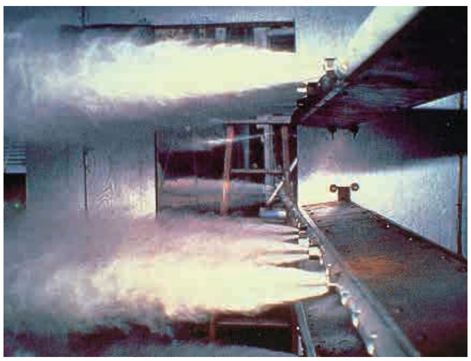
Some Clean Coal Technology initiatives blurred the distinction between combustion improvements and post-combustion cleanup by deploying multiple means to control NO_x *and* SO_2 simultaneously. In Denver, Colorado, a city that was grappling with serious air-pollution problems, the Colorado Public Service Company's Arapahoe Station hosted a combined NO_x-SO_2 reduction scheme that encompassed four distinct methods: low- NO_x boilers, overfire air, sorbent injection, and a process called selective non-catalytic reduction that further decreased NO_x emissions.

Replacing conventional boilers with fluidized-bed boilers was another form of comprehensive emissions control. The CCTDP was notably successful in furthering the development of fluidized-bed combustion. A preexisting atmospheric-pressure fluidized-bed demonstration plant at Nucla, Colorado, operated from 1988 to 1991 as part of the program. In 1990, a subsidiary of American Electric Power inaugurated the first commercial-scale pressurized fluidized-bed boiler in the United States at Brilliant, Ohio, on the Ohio River downstream from Pittsburgh. This Clean Coal Technology demonstration was located in the Tidd Station, a power plant that had been built in 1945 and decommissioned in the late 1970s because it could not economically comply with the Clean Air Act. Over four and a half years of operation from October 1990 to March 1995, the revived Tidd Station established a baseline of data on the performance of this type of advanced power system.

Finally, the program moved coal gasification and Integrated Gasification Combined Cycle technologies closer to being viable alternatives to traditional coal-burning boilers. The crown jewels of the CCTDP were three commercial IGCC plants in three different regions of the country: the Wabash River Generating Station near West Terre Haute, Indiana; the Polk Power Station near Mulberry, Florida, between Tampa and Orlando; and the Piñon Pine project at the Tracy Station near Reno, Nevada. Each had a distinctive story. The Wabash River station, which came on line in 1995, was the first full-size commercial IGCC plant in the country and the first to be permanently integrated into a local electric-utility network. It illustrated the concept of *repowering* an aging plant with new or greatly modified core components while keeping most of the existing infrastructure. By contrast, the Polk station was a *greenfield* plant, designed from scratch as an IGCC facility. Completed in 1996, it was part of an ambitious environmental restoration project at an abandoned phosphate strip mine. Piñon Pine, also finished in 1996, was a new facility co-located alongside existing conventional power plants on a site in the Mojave Desert. It featured a distinctive fluidized-bed gasifier and a first-of-its-kind advanced turbine engine.

Perhaps Piñon Pine attempted too much innovation at once, for it never succeeded in reaching full operation. Problems with the gasifier and the filter system frustrated repeated startup efforts. But both the Wabash River project and the Polk project functioned well and achieved important economic and environmental benefits. They were among the cleanest coal-fueled power plants in the world, generating very low NO_x and SO_2 emissions. By proving that IGCC technology could function well in everyday commercial service, these plants helped to establish it as a viable option for the American electrical-power industry.

All told, the Clean Coal Technology Demonstration Program funded 33 completed projects over its lifetime, at a cost of $2.1 billion to the federal government. This public expenditure leveraged over $3 billion in private investment and assisted in commercializing proven pollution-reducing methods such as advanced flue-gas cleanup, fluidized-bed combustion, and IGCC. Six of the sponsored projects won the coveted Power Plant of the Year award from *Power* magazine. More limited and temperate than earlier federal programs to spur



At Edgewater, an important step in the Coolside and LIMB sulfur-removal processes involved spraying the flue gas with mist to humidify it.

A barge carrying the pressure vessel for the country's first commercial-scale demonstration of a pressurized fluidized-bed combustion boiler approaches the Tidd Station at Brilliant, Ohio, in 1989.

The coal-fired Edgewater Plant at Lorain, Ohio, site of two interrelated Clean Coal Technology Demonstration Program projects for cleaning power-plant flue gases.

View of the Wabash River Generating Station. The new section of the plant, comprising the coal gasifier, gas-purification system, and a gas turbine, is in the foreground; the old section, containing the steam-powered component of the IGCC process, stands at the upper right.

View of the Polk Power Station.

the use of new energy technologies, the program was nevertheless a major commitment of public resources that produced significant and lasting results.

Innovations at Albany

During the energy crisis of the 1970s, the Albany Metallurgical Research Center received an unorthodox assignment: Develop a pilot plant to extract oil from wood waste. This project, begun in 1972, had no obvious connection to metallurgical research and was seemingly more in line with Bartlesville's petroleum studies or Pittsburgh's work on synthetic liquid fuels. Indeed, it derived from a process that was initially developed in Pittsburgh. But the problem was one of location: the extensive lumber industry of the Pacific Northwest put Albany closer to a major source of wood waste.

As described in the July 27, 1972, *Albany Democrat-Herald*, the pilot plant "would use continuous hydrogenation to heat scrap wood from 480 to 750 ° F under high pressure (2,000 to 4,000 psi) to extract oil from wood waste." The resulting oil would be of a low grade suitable for use as a heating-oil substitute. Strong hints that the impetus for the project came directly from Congress were confirmed in August 1973, when the U.S. Senate specifically approved the plans and added $1.5 million to the budget for the initial construction of the facility.

Plant designed to extract oil from wood waste materials from the lumber industry, 1977.

The wood-waste plant began to take shape in 1974, with an expected completion date of 1976. But then the situation began to change as costs spiraled upward and the objective shifted. "Originally the plant was designed to test the economic feasibility of turning wood chips into oil on a commercial basis," U.S. Senator Mark Hatfield explained in December 1975. "But a study by Bechtel Corp. of San Francisco, Calif., recommended that the plant be modified to process trash and garbage." Bechtel had been awarded the contract to build and operate the pilot plant.

The work lagged because of delays in funding, but the pilot plant was finally running in 1977. On July 2 of that year, Bechtel called a press conference to show off the first wood oil, which had been produced the previous day. A reporter from the *Albany Democrat-Herald* who attended wrote, "If there hadn't been an explanation, you wouldn't have called the end product oil at all. The half-pint glass jar was filled with a black tar-like substance looking like a pile of creosote which has oozed out of a utility pole on a hot day." The explanation, officially provided by one of the development engineers on the project, was that less than a third of the oil on display was wood oil at all. Most of it was actually a coal-tar liquid that had been used during the startup of the plant. The wood-oil percentage would increase over time.

Despite initial optimism, Bechtel's contract expired without renewal in 1978, and Wheelabrator Clean Fuel Corp. of Washington, D.C., was named to operate what was now being called the "biomass liquefaction facility" in Albany for two years. In July 1979, a team of DOE representatives toured the plant to inspect progress. They learned that the wood-oil production was a success, that coal tar was no longer being added, and that the researchers had begun investigating the use of other biomass such as straw.

Wheelabrator's contract expired on June 30, 1980, but the Rust Engineering Co. was given the operating contract through March 1981, when the pilot plant was shut down. The very small volume of the plant, which had never exceeded more than three barrels per day, made drawing conclusions about its significance difficult. One thing seemed clear, however: As with other synthetic liquid fuels, the economics did not quite work. Oil from wood was more costly than petroleum was, and becoming more so as petroleum prices headed downward from their all-time high in 1980.

The story of Albany's brief venture into wood oil captured, in miniature, the trajectory of federal energy programs during and after the energy crisis of the 1970s. Albany was not a center of synthetic-fuels research. After 1975, it did not even belong to the ERDA or the DOE; it remained a unit of the Bureau of Mines. Yet the urgency of the situation led people to make unusual decisions and to pursue any option that might lead to new sources of energy. Some of those decisions did not pan out as expected.

A reversion to the center's roots as a metallurgical laboratory began in the mid-1970s as Albany announced in 1975 that it had achieved a breakthrough in developing a new process to recover nickel from low-grade minerals called laterites, which contain approximately one-half of one percent nickel. At the time, the only significant nickel production in the United States occurred at Riddle, Oregon. The laterite minerals of Southern Oregon and Northern California had not been mined because no process existed for extracting the small amounts of nickel they contained at an economical price. Now, after four years of research, Project Coordinator Richard Siemens was ready to test a new method of extraction on laterites.

According to the newspaper *The Oregonian*, which cited Bureau sources, the breakthrough lay "in low-temperature roasting of the ore in the presence of carbon monoxide. Most production of nickel utilizes heat up to 1,600 °C; the Albany process roasts the ore at no more than 600 degrees [Centigrade]. Through a series of ion exchanges, the metallic nickel, copper and cobalt end up in a petroleum-based solvent solution, from which they are electrolytically extracted." This approach promised to lessen U.S. dependence on imported nickel and reduce the amount of energy needed for nickel production at a time when rising energy costs made such savings valuable.

By June 1977, Albany officials were soliciting bids from contractors to build and operate a pilot plant that would process 5,000 tons per day of laterite for nickel extraction. Construction was expected to take two years. In the meantime, the Bureau had built a smaller continuous-flow process development unit to test the process by processing one ton of ore per day. A major setback occurred on November 14, 1978, when the experimental unit was destroyed by an accidental fire. The laterite program continued, but did not have an immediate impact on the development of nickel resources along the Pacific Coast.

In June 1978, Research Director Rollien "Ray" Wells retired after 36 years of service. Howard O. Poppleton was named the acting research director. The center had a staff of 180 people at that time and was conducting 22 research projects in metallurgical chemistry, thermodynamics, pyrometallurgy, and analytical chemistry. Frank Block, who had started his career at Albany in 1948, became the next research director in February 1980. He served in that capacity until January 1983, when Poppleton once again accepted the position as the acting director.

Conservation of scarce, valuable metal and mineral resources became a priority in the 1980s. The 1986 Annual Report from Albany stated, "Research conducted at the Albany Research Center encompasses all aspects of the mineral cycle, with special emphasis on materials classified as strategic and critical. With America's growing dependence on foreign sources for these vital minerals, this phase of our research program had become increasingly urgent."

One of those vital metals was chromium. Chromium was and is a key element of stainless steel; it accounted for about 18 percent of the composition of common stainless steel product at the time. But only 1 percent of the world's chromium came from the Western Hemisphere, so the United States had to import most of its chromium from South Africa—an untenable situation in terms of defense needs. So Bureau researchers in Albany investigated new, low-chromium alloys that could do the job of stainless steel. Their work showed that the chromium content of stainless steel might be reduced by half using silicon and aluminum, or silicon and copper, as substitutes. Replacing chromium with molybdenum, copper, and vanadium was also being investigated. Another group tried to develop methods to extract chromium from low-grade ore available in the United States using oxidation or reduction roasting.

Researchers in Albany investigated new, low-chromium alloys that could do the job of stainless steel.

Another aspect of conservation that is generally overlooked is reducing the wear of machines and tools that contain critical, scarce elements. "Equipment wear costs U.S. over $100 billion annually. Wear involves loss of critical elements like chromium, cobalt, manganese and tungsten, which are used to impart wear resistance to heavy processing equipment in the mines and minerals industries," the 1986 Albany Annual Report stated. For example, when a mining drill bit becomes dull in the process of cutting into a wall of coal, chromium and other elements in the steel bit are lost. Albany researchers studied "cast-on surface coatings" to protect against this type of loss. They developed a method to bond an abrasion-resistant surface to cast parts while the molten metal was poured.

Recycling has long been a common method of conservation. In 1986, Albany metallurgists responded to the question posed by some foundrymen: Is the quality of recycled iron changing? These workers believed that the quality of scrap iron was deteriorating because increased alloying had changed the composition of the iron and steel used in industry. Albany engineers worked with the American Foundrymen's Society to analyze scrap iron and steel over a four-year period, and discovered increasing levels of boron and tin in the scrap.

Methods were also being investigated to recycle superalloys—high-temperature, high-strength alloys—to recover chromium, cobalt, and nickel. Much superalloy scrap was too contaminated or too complex to be used in alloys again, so it was typically downgraded and used in scrap iron, thus wasting the scarce, costly alloying elements. In 1986, Albany had a project to recover critical metals from superalloy scrap by converting the superalloys to a sulfide form and then separating the metals by grinding, flotation, and magnetic separation. A Strategic Materials Recycling Survey was initiated in 1988 to follow critical metals from production through disposal in order to develop a model to discover where most of the metal was being lost. By 1995, the Materials Recycling & Scrap Reduction division was one of four major divisions at the Albany site.

Another priority was the study of electric-arc furnaces. Used in metals production for many years, furnaces of this type experienced fluctuations that made them difficult to control. "[Electric] Arc [furnaces] use AC [alternating current], and the arc must be re-established at each half-cycle," the 1986 Albany Annual Report noted. "During startup with a cold charge, the arc has difficulty stabilizing its path. As with natural lightning, there is a loud noise associated with each stroke, and it occurs many times a second. In addition, there is feedback into the electric power grid, which causes flicker and undesirable power surges each time the path is re-established. Within the furnace itself, there is a decrease in heat transfer to the molten bath and an increase in refractory erosion." Research was underway at Albany to understand the instabilities in the arc. By 1988, this work had shown that "[a]rcs can be stabilized by maintaining an active cathode spot and promoting a stable ion path," and that "physical modifications to the electrodes themselves can provide a quieter arc."

By 1990 the problem with electric arc furnaces had been attributed to non-linear dynamics. "I cannot convey my excitement for the concept of non-linear dynamics," the mechanical engineer Tom Ochs was quoted as saying in the 1990 Annual Report. "The real world is, after all, non-linear. If we can learn how to control non-linear systems, it will surely open a whole new world to us." Ochs and his colleagues at Albany had found through analysis that the fluctuations of the arc were not random, but deterministic and therefore predictable, though still chaotic. They were therefore "concentrating on the concept of short-term predictability with the intent of being able to control the electric arc furnace," the Annual Report noted. "Using ultra-high-speed photography and high-speed electric waveform analysis, the electric arc phenomenon is slowed down temporarily to the point where distinct events can be individually analyzed, then controlled through the course of a full cycle." This major victory in taming the noise and fluctuations of the electric arc furnace had the potential to save metals companies many millions of dollars over the following decades.

Work continued on titanium, Albany's signature metal. Kroll's process for producing pure ductile titanium, which he had developed in the 1930s, was still being used—with some modifications—in the 1980s. But researchers had long been searching for an alternative method. The basic problem was that the Kroll process was a batch process, which limited the amount of titanium that could be made at one time. A continuous process would be faster and cheaper. Moreover, the Kroll process had many steps, and it required high-quality titanium minerals that had to be imported into the United States.

Research that began in 1986 used imported titanium minerals processed in an induction slag furnace. This method yielded acceptable results, but slag tended to contaminate the final product. By 1988, Albany researchers had improved the process so that domestic ilmentite could be used to produce ductile titanium in a continuous process. The modifications involved the synthesis of alkaline earth fluorotitanates from ilmentite, which were then reduced in the furnace. This approach eliminated the slag inclusions. "We're producing titanium from domestic ore, using Bureau-patented equipment and a Bureau-developed process," said Dave Traut, a supervisory chemical engineer, in the 1988 Albany Annual Report. "I think that speaks well of our capabilities."

Albany even had its own angle on the problem of sulfur contamination that the DOE Energy Technology Centers struggled with in their fossil-fuels research. Sulfur, the major impurity in coal, petroleum, and other natural resources, resulted in millions of tons of waste every year from industrial processes.

Starting in 1972, the Bureau had been searching for a way to put this excess sulfur to some good use. In 1986, researchers at Albany, working under Research Leader W.C. "Bill" McBee, developed "sulfur concrete" as a replacement for Portland cement. Tests of this material at industrial sites worked so well that the product received an R&D 100 Award as one of the 100 "most significant" technical developments in the United States for 1986, as selected by the publishers of *Research and Development* magazine. It was the nineteenth R&D 100 Award presented to the Bureau of Mines in nine years.

Albany's "sulfur concrete" received an R&D 100 Award as one of the 100 "most significant" technical developments in the U.S.

In addition to these major initiatives, researchers at Albany in the late 1980s and the early 1990s pursued a host of projects in diverse areas of metallurgy. Its four principal areas of inquiry were Pollution Prevention and Control, Materials Performance, Materials Conservation, and Materials Recycling and Scrap Reduction. From thermodynamic analysis of metals to studies of how acid rain corroded building materials to criteria for evaluating the safety of wire rope used in mine shafts, the center carried on the Bureau of Mines tradition of what Research Director George Dooley III termed "stewardship for the Nation's mineral resources."

Tragedy Strikes

The Third Annual Clean Coal Technology Conference, held in Chicago September 6-8, 1994, attracted many of the best researchers and project managers in the field of clean coal from national laboratories, universities, and the private sector. A contingent from METC and PETC attended, presenting technical papers, exchanging ideas with colleagues, and forging relationships that might lead to future collaborations. By all accounts, the conference was a success.

After the final presentation on Thursday, September 8, attendees said their goodbyes and scrambled to catch their flights home. But those who boarded USAir Flight 427 that evening never made it. About 6,000 feet in the air and six miles short of landing at Pittsburgh International Airport, the aircraft experienced a mechanical malfunction and began a steep nosedive that ended in a nearly vertical crash in Hopewell Township, Pennsylvania. All 127 passengers and five crew members were killed.

Word of the disaster spread quickly, and family, friends, and colleagues frantically tried to determine who had been on Flight 427. When passenger information was officially confirmed by the airline, PETC had lost five dear colleagues, METC four. Many other Pittsburgh companies and academic institutions lost friends and colleagues as well. A pall of sadness engulfed the community at this terrible loss of lives.

On September 20, 1994, PETC employees gathered for a memorial service to their fallen colleagues. A marble memorial stone was unveiled in front of Building 922 in Bruceton. On it were chiseled these words:

We Will Never Forget

Our friends who perished in the crash of USAir Flight 427 on September 8, 1994

Thomas W. Arrigoni	Steven J. Heintz
Robert J. Evans	Timothy S. McIlvried

William C. Peters

And our colleagues from METC

Randall J. Dellefield	Manville J. Mayfield
William T. Langan	Holmes (Sandy) Webb, Jr.

And our other friends returning on the same flight.

METC colleagues held a memorial service for their fallen friends on April 19, 1995, at which they revealed a monument that read:

In Memory of
the Members of the
METC Family Who
Died Aboard Flight 427
September 8, 1994
—
Randall J. Dellefield
William T. Langan
Charlotte L. (Shirley) Langan
Manville J. Mayfield
Holmes A. (Sandy) Webb

Among the many prominent Americans who sent condolences to METC and PETC in the aftermath of the Flight 427 crash was President Bill Clinton. "The men and women who died in this tragic accident will long be remembered for their dedicated service," the President asserted. At a commemoration in Morgantown on September 15, 1994, METC employee Lou Salvador offered a heartfelt local variation on the same theme. Those who had perished "were good...they were very good...at what they did," Salvador affirmed to his assembled colleagues. "Like all of you, I came to rely on them...I trusted them...I respected them. Like all of you, I loved them...they can never be replaced...they will never be forgotten."

A Century of Innovation

From the U.S. Bureau of Mines to the
National Energy Technology Laboratory

Chapter Twelve: Diversification and
Innovation, 1996–2010

Chapter Twelve:

Diversification and Innovation, 1996–2010

All the world's citizens need equitable access to affordable, reliable, environmentally sustainable energy to feed our families, provide clean water, and operate hospitals, schools, and businesses. Fortunately, we have the scientific and technical ability to develop advanced energy technologies that could provide every nation with affordable energy supplies while leaving behind a smaller environmental footprint.

--Anthony Cugini, Director, NETL, GlobalPittsburgh International Bridge Awards Celebration, April 2010

At the turn of the twenty-first century, the distinctive and eventful histories of energy research at the Pittsburgh, Bartlesville, and Morgantown centers and of metallurgical research at Albany reached another confluence. A series of mergers between 1996 and 2005 combined these four sites—along with the Arctic Energy Office, which was established at Fairbanks, Alaska, in 2001—to create the National Energy Technology Laboratory (NETL). With its nationwide reach and its deep pool of scientific and engineering talent, this latest addition to the DOE's prestigious National Laboratory System immediately made its influence felt in the development of fossil-energy technologies and in broader public debates over American energy policy.

Artist's rendition of the Morgantown Technology Support Facility in 2008.

NETL came into being at a time when concern about the nation's energy situation was on the rise. Once again, demand for fuel and power seemed to be exceeding supply. Sharply increasing fuel prices during the first decade of the new century constrained economic prosperity. The terrorist attacks of September 11, 2001, and the subsequent wars in Afghanistan and Iraq highlighted the perils of continuing American reliance on imported petroleum. Scientific consensus held that global climate change, driven in part by soaring emissions of carbon dioxide and other "greenhouse gases" from human activities, threatened the planet's fundamental ecosystems. To flourish in the years ahead, the United States would need to diversify its energy sources and change how it used its abundant fossil-fuel reserves.

The employees and contractors of NETL plunged enthusiastically into meeting these challenges. They used a repertory of tools that would have dazzled their ancestors, including supercomputers, lasers, and the ubiquitous communications capability provided by the Internet. But the core purposes of the new National Laboratory were consistent with the original goals of its forerunner, the Bureau of Mines. NETL remained committed to promoting safety and conservation in the processes of extracting fossil fuels and putting them to human use. It still pursued basic scientific knowledge about fuels and materials, and it still worked closely with private industry to commercialize energy innovations. Accomplishments in advanced power systems, unconventional petroleum and natural-gas recovery, metal alloys, and control of greenhouse gases reflected recognizable continuities across a century of federally sponsored energy research.

Rita Bajura, first Director of NETL.

Beginnings and Endings

In the mid-1990s, the DOE, under the leadership of Secretary of Energy Hazel O'Leary (1993–1997), charted a new future for its program of fossil-energy research. The Pittsburgh Energy Technology Center (PETC) and the Morgantown Energy Technology Center (METC) merged on December 2, 1996, to form the Federal Energy Technology Center (FETC). Heading the unified organization was Rita Bajura, who had been with METC since joining the staff there in 1980 as a mechanical engineer. Bajura knew her way around all major aspects of fossil-energy research. She had held a series of increasingly responsible positions at the Morgantown center, including Chief, Process Technology and Engineering Branch; Director, Systems and Technology Support Division; Director of the Coal Projects Management Division; Director of the Product and Strategic Management Division; Deputy Director of METC; and finally Acting Director of METC after Thomas Bechtel departed in October 1996.

The impetus for the merger came from several sources. Because the Pittsburgh and Morgantown centers were only 65 miles apart and had agendas that were sometimes complementary and sometimes overlapping, the idea of combining them had been under discussion at DOE headquarters for some time. Integration promised substantial cost savings and could better leverage the centers' research efforts by sharing resources and jointly coordinating projects.

Advances in telecommunications technology and information systems made it practical to administer the two sites as a single entity. The 1990s witnessed the next phase of the computer revolution as the Internet and other innovations transformed both the exchange of scientific knowledge and everyday working conditions. "METC will soon be on-line with the Internet," the *METC News* had reported excitedly in January 1994. "For many first-time users, the Internet will be a bewildering experience, but the benefits that will come from this improved communications resource should outweigh the challenges of mastering its use." Employees at both METC and PETC quickly took advantage of rapid online interaction, which dovetailed with a suite of electronic tools that was already becoming familiar: voice mail, teleconferencing, Local Area Networks, and document scanners. With these technologies, physical proximity—although still important in scientific work—was less essential than it had been before. A wired world also opened the door to leaner organizations with fewer layers of management and greater autonomy and responsibility for individual staff members.

Moreover, the DOE and the federal government as a whole were under intense pressure in the mid-1990s to streamline their operations. Amid public concern about the rising federal budget deficit, the Clinton administration and Congress pursued a set of "reinventing government" initiatives designed to pare costs and increase efficiency and accountability at federal agencies. The Government Performance and Results Act of 1993 mandated that agencies set clear priorities through strategic and annual planning and document the public benefits that resulted from the projects they managed. Other laws overhauled federal procurement and contracting. These measures created incentives to coordinate or combine programs. For the DOE Office of Fossil Energy to have a single organization in charge of implementing its research program was an advantage in complying with the new legal requirements and making the most of limited budgets.

FETC logo with mission statement.

The creation of FETC proceeded smoothly. Although METC and PETC had different organizational cultures and traditions that were not lightly relinquished, a spirit of accommodation prevailed. Site equity was the guiding principle; all involved strove to avoid favoring one location over the other. Anyone from either site could apply for positions on the unified 550-member FETC staff. The routine of regular commuting between Morgantown and Pittsburgh became firmly established as people forged new working relationships. In October 1997, Associate Director Joseph Strakey observed that the transition had turned out well. "I have staffs that work with me both at Morgantown and at Pittsburgh as do all the other managers," he reported. "We travel back and forth, and it is going pretty seamlessly at this point. I think the other good thing that has happened with the merger is that we are working better with Headquarters, and Headquarters people also participate on our product teams." Strategic planning and budgeting had consequently improved.

As FETC got underway and looked toward the future, an important piece of its past was being shuttered permanently. Congress and the Clinton administration had decided during the fall of 1995 to eliminate all funding for the Bureau of Mines, a choice that became final on March 30, 1996, when the Bureau closed its doors. The abrupt closure was another outcome of the contemporary political climate, which stressed cost effectiveness and the downsizing of government. It also reflected longer-term shifts in public perceptions of the Bureau's value.

Having already lost several key aspects of its original mission—including energy research—during the previous two decades, the Bureau was left with a limited focus on minerals and mining safety that lacked a broad audience. Mining constituted a smaller proportion of the overall U.S. economy in the mid-1990s than it had a century or even a half-century before. Although the mining industries remained very dangerous for workers and communities, spectacular mine disasters had become sufficiently uncommon that most Americans paid little heed to mining-safety concerns. Military planners no longer insisted that the country had to maintain large stockpiles of strategic minerals other than petroleum. There was a widespread consensus that private enterprise could handle most minerals issues, and that remaining Bureau functions that still had merit could be parceled out to other federal agencies.

"We leave knowing that the proud accomplishments of this agency did make a difference in the quality of life we now enjoy, and [that] they will continue to do so well into the twenty-first century."
--Rhea Lydia Graham, 1996

Thus an organization that had begun dramatically and auspiciously in 1910 with a pledge to stop catastrophic mine explosions, and that had served the people and the government of the United States honorably for almost 86 years, came to an end with little notice. The Bureau's final director, Rhea Lydia Graham (1994–1996), captured the sentiment of the occasion: "We leave knowing that the proud accomplishments of this agency did make a difference in the quality of life we now enjoy, and [that] they will continue to do so well into the twenty-first century." That legacy included innumerable lives saved and injuries prevented, profitable industries established and expanded, knowledge of fossil fuels and other minerals gained, and a tradition of constructive cooperation between government and industry bequeathed to successors such as the DOE.

Some elements of the Bureau lived on after the March 1996 closing date. The U.S. Geological Survey regained responsibility for collecting and publishing statistics on mineral supplies and use. Although most of the Bureau's experiment stations and field offices were abolished, a few were transferred elsewhere. Mining-safety work at the Pittsburgh Research Center on the Bruceton campus and at Spokane, Washington, was assigned first to the DOE and then given over to the National Institute of Occupational Safety and Health (NIOSH) in the Department of Health and Human Services by the end of 1996. And the Albany Metallurgy Research Center—now renamed the Albany Research Center—joined the DOE, reporting directly to the Office of Fossil Energy.

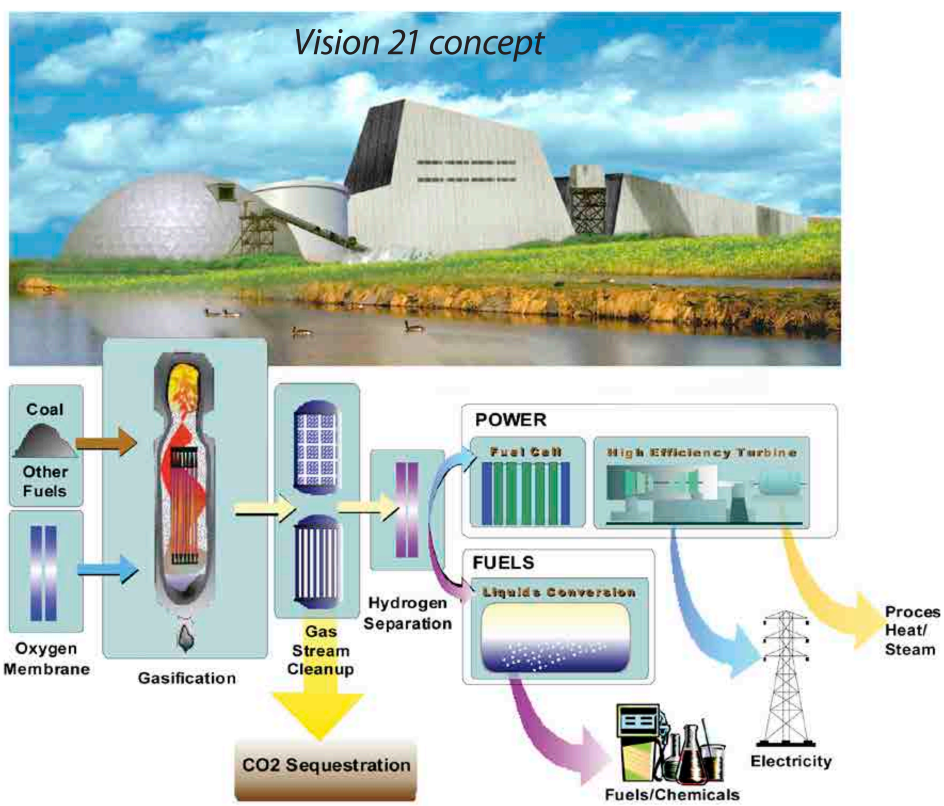
The Albany center carried on essentially the same types of metals and materials research under DOE control that it had conducted while it belonged to the Bureau of Mines. Although not all aspects of its research agenda were related to the energy industries, many of its projects had definite implications for energy production and use.

For example, innovative thin-wall steel castings developed at Albany made possible the production of lighter-weight motor vehicles that got better fuel economy. Researchers studied the chronic problem of erosion in the linings of high-temperature furnaces and gasifiers and came up with longer-lasting refractory materials that meant fewer shutdowns for maintenance and repairs. Over time, the connections between energy and materials science strengthened as the Albany Research Center became more deeply engaged with the Office of Fossil Energy's policies and programs.

FETC at the Turn of the Millennium

At the close of the twentieth century, the study of coal and uses for coal remained central to the identities and missions of both FETC locations at Pittsburgh and Morgantown. Coal preparation, now known as the Solid Fuels and Feedstocks Program, continued to be a major focus. An important accomplishment of this program during the 1990s was the center's patented GranuFlow process for recovering "fines," the very small waste particles that resulted from grinding and washing coal. By simultaneously removing water from these particles and reconstituting them, the process transformed the sticky, messy fines into a dry, granular product that was much easier to transport and store. Basic and applied research on coal combustion was another area of concentration. FETC's Coal Combustion By-Products Utilization Program encouraged the reuse of power-plant wastes in products such as building materials and soil enhancers, and helped industry and government evaluate environmental concerns about this kind of recycling.

Familiar endeavors in the areas of synthetic fuels and advanced power systems went forward under a new banner: the Vision 21 initiative, an overarching rubric that the DOE adopted in 1997 for the future of power generation. Vision 21 looked toward the development of "powerplexes": modular systems that would allow the simultaneous production of power, heat, fuels, and industrial chemicals from any organic material. Although coal was still anticipated to be the primary feedstock over the long term, powerplexes would be able to



use natural gas, petroleum coke (the solid residue of petroleum processing), biomass, or waste products. The ambitious goal, as the DOE's newsletter *Clean Coal Today* explained in 1998, was to create power plants "with near-zero pollutant emissions at efficiencies greater than 60 percent." (Conventional plants operated in the 33-to-45 percent efficiency range.)

Vision 21 integrated several core research topics at FETC. The center contributed its knowledge of coal gasification and combustion to the further refinement of Integrated Gasification Combined Cycle (IGCC) power systems and fluidized-bed boilers Chemical engineers from FETC and its contractors improved catalysts and reactor designs for the Fischer-Tropsch process of producing liquids from synthesis gas or natural gas. Research on solid-oxide fuel cells paid off in 1998 with the startup of a pilot plant at Westervoort, The Netherlands, that used this type of fuel cell to produce electricity and hot water. This project was one of several collaborations among the DOE, industry, and other government agencies domestically and abroad to advance fuel-cell technology.

LP Methanol Plant at Kingsport, Tennessee.

A particularly important aspect of applied coal research was gas purification. FETC studied how pollutants form when coal is burned, with the aim of creating models that could inform engineers and government regulators about what types and amounts of pollution coal-fired boilers could be expected to emit. Flue-gas cleanup, which had originally focused on removing the sulfur dioxide (SO_2) and nitrogen oxides (NO_X) that caused smog and acid rain, widened its scope to encompass the removal of mercury and other pollutants as well. Work at FETC emphasized the use of membranes, which separated the constituent parts of flowing gases by imposing selective physical barriers that blocked some substances while allowing others to pass through. For example, the Hot Gas Particulate Filtration Program helped to develop *candle filters*: long, thin, hollow devices made of ceramic materials that eliminated fine particles from hot gas.

Also during the late 1990s, the Clean Coal Technology Demonstration Program (CCTDP) entered into its final stage. This program had not accepted new applications since 1993, but several projects that had received funding were still coming to fruition. FETC continued to manage cooperative agreements with the project sponsors and evaluate the results. Several technologies that had been under development at Pittsburgh and Morgantown and in private industrial laboratories for decades received their first real-world trials in the demonstrations, which brought important engineering concepts vividly to life.

One such tangible result was the Liquid Phase Methanol Process Demonstration, located at Kingsport, Tennessee. This venture was part of an Eastman Kodak Co. chemical-manufacturing plant that illustrated the continuing vitality and economic significance of coal chemistry in the age of petroleum. At the Kingsport works, Eastman turned high-sulfur bituminous coal from nearby mines in southwestern Virginia into a variety of industrial chemicals. The company had opened its first coal-gasification plant there in 1983 so that it could use coal-derived synthesis gas instead of petroleum for manufacturing organic chemicals called acetyls, which are key ingredients in film, plastics, and pharmaceuticals. This gasification plant offered a logical feedstock supply for testing a new synthetic-methanol process that Air Products and Chemicals, Inc. had developed with DOE assistance during the 1980s.

Obtaining synthetic methanol from coal had been a major engineering triumph in the early twentieth century, but most methanol production had subsequently shifted to reliance on natural gas. Toward the end of the century, however, interest in coal-based approaches revived. Coal offered a dependable and inexpensive base for producing this important chemical, which, in addition to its value as an intermediate for making other chemicals, could serve as a clean-burning alternative fuel for motor vehicles and stationary engines. Methanol also had a potential role to play in improving the cost effectiveness of coal-fueled IGCC power plants. Adding a synthetic-methanol reactor to an IGCC plant could ensure that the plant's coal gasifier was always fully utilized even when demand for electricity was low. Any synthesis gas that was not immediately needed to drive a turbine generator could become an input for producing methanol, and revenue from sale of the methanol could help offset operating costs.

With its innovative slurry-bubble reactor design, Air Products and Chemicals had created a compact, reliable, and easily controllable means of converting synthesis gas to methanol. The process was tested extensively at a small pilot plant, the Alternative Fuels Development Unit, which the DOE maintained at LaPorte, Texas. A partnership between Air Products and Eastman won a Clean Coal Technology grant in 1989 to build a commercial-size version at Kingsport, but construction was delayed until 1995 and the methanol plant did not begin to function until April 1997.

The demonstration project, which lasted through 2002, outperformed its designers' expectations. It yielded 104 million gallons of high-quality, sulfur-free methanol, with few operating difficulties and low pollutant emissions. Eastman used most of the methanol for chemical manufacturing, but samples of the plant's output were tested in automobiles, public buses, gas-turbine engines, and even fuel cells. This experience showed that the high-sulfur coals of the eastern United States could still find markets in chemical industries, and that methanol from coal was a feasible synthetic liquid fuel for many purposes. So impressive were the results that Eastman kept the methanol facility in service after the DOE funding expired and made a commitment to include gasification facilities—which would use either coal or petroleum coke—in chemical plants that it planned to build in Texas, Louisiana, and Tennessee.

Another Clean Coal Technology success story unfolded at Jacksonville, Florida, a fast-growing city with an urgent need for more electrical power. JEA, the local publicly owned utility, wanted to expand its coal-burning Northside Generating Station to help meet rising demand. But this plant stood amid environmentally sensitive marshlands along the St. Johns River, near an ecological preserve and historic landmarks. Vigilant city residents laid out their position: No enlargement of the station unless JEA agreed to abide by tough environ-

The combination of the CFB boilers, advanced NO_x controls, and a state-of-the-art flue-gas scrubber made the Jacksonville facility one of the cleanest coal-burning power plants ever built.

mental standards that went beyond what state and federal laws required. JEA did agree, and entered into a Clean Coal Technology agreement with the DOE in 1997 for assistance in repowering the Northside Generating Station. The engineering solution to Jacksonville's predicament was to construct what were then the largest atmospheric-pressure circulating fluidized-bed (CFB) boilers in the world. Designed by the Foster Wheeler Energy Corporation, these boilers used a type of fluidized-bed technology in which air flowed through pulverized coal at such high velocity that some of the coal particles were lifted out of the boiler and had to be captured and returned for reuse—hence the name, "circulating fluidized bed," to distinguish it from more-sedate "bubbling bed" versions. Advantages of the CFB approach included improved combustion efficiency and better performance with coals that had high ash content. JEA replaced one of the Northside plant's three existing oil-fired boilers with a coal-fired CFB boiler as part of the Clean Coal Technology agreement and replaced a second boiler with another, identical CFB unit at its own expense. By operating at relatively low temperatures and using limestone to absorb sulfur, the new boilers allowed the plant to burn cheap fuels—Eastern high-sulfur coal or petroleum coke—while decreasing its emissions of polluting SO_2 and NO_x.

Construction began in 1999, and by the spring of 2002 the renovated Northside Generating Station was fully operating. Although the repowering project more than doubled the plant's output of electricity, air pollution declined. The combination of the CFB boilers, advanced NO_x controls, and a state-of-the-art flue-gas scrubber made the Jacksonville facility one of the cleanest coal-burning power plants ever built. This achievement showed that the CFB method, previously used only in much smaller boilers, could be scaled up for very large electric-utility applications.

JEA clean coal plant in Jacksonville, Florida.

Such practical knowledge was the main benefit of the program. Clean Coal Technology projects gave engineers, executives, and government officials the information they needed to verify that innovative coal-utilization methods were trustworthy alternatives to traditional power-plant designs. Private industry and state and local governments covered over two-thirds of the $4.8 billion total cost, making the CCTDP a relative bargain for American taxpayers. The pollution-reducing technologies that the program helped to popularize contributed to progress in the fight against acid rain. Although the tonnage of coal burned for electricity generation doubled between 1980 and 2008, the combined efforts of industry and government nevertheless cut the average concentration of SO_2 in the air by 71 percent and the average concentration of nitrogen dioxide by 46 percent.

Although the tonnage of coal burned for electricity generation almost doubled between 1980 and 2008, the combined efforts of industry and government nevertheless cut the average concentration of SO_2 in the air by 71 percent and the average concentration of nitrogen dioxide by 46 percent.

FETC also inherited the Morgantown station's role as a hub for the study and development of natural-gas resources. Natural gas, whose prospects had seemed doubtful after the shortages and price spikes of the 1970s, was poised for a larger role in the nation's energy future by the mid-1990s. In particular, interest in using it as fuel for electric-power generation rebounded. With increased exploration and production, including the mainstreaming of unconventional gas sources such as coalbed methane and Western tight-sands formations, industrial purchasers were more confident in the stability of gas supplies. Lower prices and the cleanliness of natural gas appealed to power-plant operators who had to meet the standards set by the Clean Air Act Amendments of 1990. It appeared that natural gas could serve as a "bridge" fuel while clean-coal technologies and renewable energy sources became more firmly established.

Nevertheless, many questions lingered whether the natural-gas supply would hold up over the long term. FETC was the lead center in implementing the DOE's multifaceted strategy to ensure that it would. Efforts to increase American natural-gas reserves included more intensive development of known gas fields through advances in location and drilling technologies and secondary-recovery methods. The GASIS (Gas Information System) project, which had

In 2002, the JEA Northside Generating Station received Power magazine's Powerplant Award for outstanding technological achievement. Pictured at the award ceremony, from left to right, are Chairman Mike Hightower of JEA; Project Manager Joey Duncan of JEA; the Honorable Corrine Brown, U.S. House of Representatives; Director Rita Bajura of NETL; and Bob Schweiger, a consulting editor at the magazine.

originated at Morgantown and was completed in 1999, constituted the first publicly available comprehensive database on natural-gas reservoirs in the continental United States. It gave natural-gas producers—especially small firms that had limited research capabilities—unprecedented access to information that they could use to guide their exploration and drilling decisions. It also provided a basis for constructing sophisticated computer models of gas-reservoir dynamics. Via the National Gas and Oil Technology Partnership, an alliance between the DOE and the energy industries, FETC helped to fund projects such as a compact "microdrilling" system that could reduce the cost of sinking exploratory gas wells.

The Methane Hydrate Research and Development Act of 2000 officially made the DOE the lead agency in this field.

Supply expansion included fuller use of natural gas that was either too low in quality or too distant from markets to be recovered profitably with traditional methods. Many natural-gas fields in the Untied States contained so-called subquality gas that was high in impurities such as nitrogen, carbon dioxide, and hydrogen sulfide, making it unsuitable for commercial use without additional treatment. The DOE natural-gas program funded studies of membrane-based technologies that could separate out the unwanted contaminants more effectively and cheaply than current processing methods allowed. Economically extracting and transporting gas from isolated small fields, or from remote areas such as the North Slope of Alaska, was another problem. One possibility that FETC explored was liquefying this "stranded gas," either by compressing it or by converting it to oil via the Fischer-Tropsch synthesis, so that it became easier to ship.

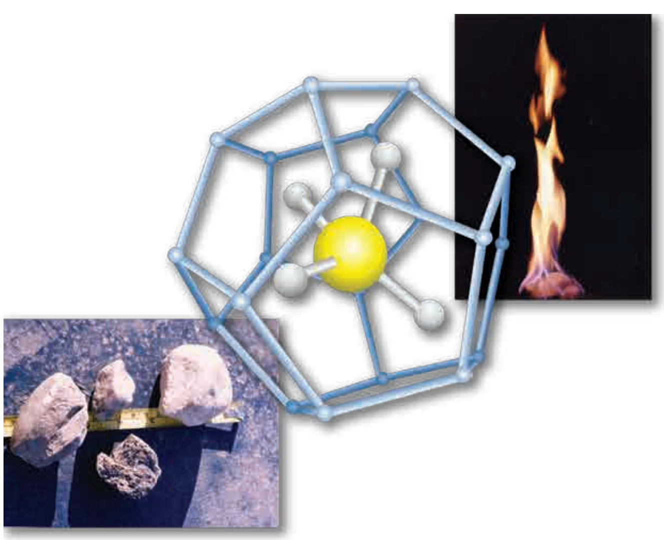
The impact of unconventional gas sources continued to grow. By 1999, coal-bed methane was in such widespread use that it was no longer considered unconventional, but extracting gas from deep, impermeable rock remained a challenge. Residents of the Central Appalachians began hearing about the potential importance of the Marcellus Shale, one of the largest, most promising gas-bearing Devonian shale formations in the East. After startling new U.S. Geological Survey estimates in the mid-1990s suggested that methane hydrates contained more methane than all the country's other forms of natural gas combined, hydrate deposits deep undersea and in the Arctic attracted great attention. Responding to a recommendation from the President's Committee of Advisors on Science and Technology, the DOE released a National Methane Hydrate Multi-Year R&D Program Plan in 1999 to survey U.S. methane-hydrate resources and to find out whether recovering gas from them was feasible and safe. The Methane Hydrate Research and Development Act of 2000 officially made the DOE the lead agency in this field.

Improving the capacity and reliability of the natural-gas storage and distribution system was another priority. Underground storage reservoirs, which pooled gas in abandoned wells and other formations so that it would be available even at times of high demand, were crucial to making natural gas a dependable fuel for households and industry. But many older storage reservoirs were deteriorating and becoming more difficult to operate smoothly. FETC investigated methods of reinvigorating these existing facilities and constructing new ones.

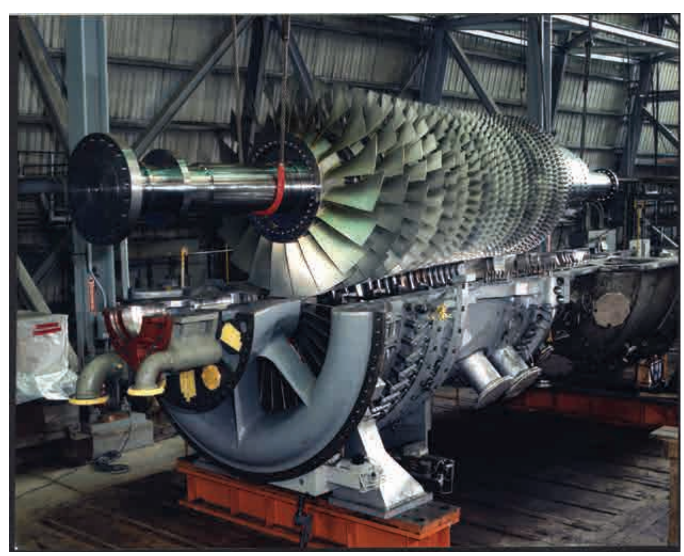
FETC also encouraged new and expanded uses for natural gas. Obvious candidates were advanced stationary power systems such as those envisioned in the Advanced Turbine Systems (ATS) program. Power plants that burned natural gas to run high-efficiency turbines seemed to offer the best chance for quickly reducing air pollution while keeping up with the nation's demand for electricity. DOE estimates forecast that 70 to 80 percent of new U.S. power-generating capacity in the early twenty-first century would take this form.

By the late 1990s, ATS public-private partnerships had met the goal of creating turbine engines that could reach 60 percent efficiency while simultaneously slashing emissions of NO_x and reducing the cost of electricity generation. FETC and the Oak Ridge National Laboratory, in cooperation with participating turbine manufacturers, natural-gas companies, and a network of research universities called the Advanced Gas Turbine Systems Research Consortium, sponsored investigations that led to the crucial breakthrough of enabling turbines to operate reliably at temperatures above 2300° F. Getting there required innovation in almost every aspect of turbine design and manufacturing, including air compressors, combustors, heat-resistant materials, cooling systems, and methods of fabricating and inspecting components. The realization of the benefits began in February 2000, when General Electric announced that its H System turbines, developed through the ATS program, were ready for commercial sale.

Another possibility was to turn natural gas into a source of energy for motor vehicles, either by deriving clean-burning synthetic liquid fuels from it or using it in small fuel cells that could power transportation equipment. FETC's natural-gas program included consideration of producing synthetic oil from



Collage showing the molecular structure of methane hydrates, samples of methane hydrates, and the burning of a methane hydrate sample.



A power plant turbine. (Westinghouse design) natural gas, or using the gas as a source of hydrogen for fuel cells that could substitute for internal combustion engines in the next generation of automobiles. Broader use of fuel cells, or even of hydrogen as a fuel for conventional automotive engines, would constitute an important step toward an eventual "hydrogen economy" that could lessen U.S. dependence on petroleum.

The designation as a national lab affirmed the importance of fossil energy to the past, present, and future of the American economy and the environment.

In 1999, natural-gas initiatives within FETC and elsewhere in the DOE were consolidated into a new Strategic Center for Natural Gas. "We need one place that looks out for the future of natural gas—from borehole to burnertip," Secretary of Energy Bill Richardson (1998–2001) declared at the official announcement of this decision. The formation of the center was one component of the most far-reaching reorganization of federal energy research since the mid-1970s. FETC was about to become a full-fledged National Laboratory.

Assembling NETL

Secretary Richardson made history in several ways when he visited FETC's Morgantown location on December 10, 1999. He was the first Secretary of Energy to visit the Morgantown campus. He was also the bearer of good news: Little more than three years after the successful merger of the Morgantown and Pittsburgh sites, the DOE was elevating FETC to the rank of a National Laboratory. The center would henceforth be known as the National Energy Technology Laboratory (NETL). No longer would there be a distinction in organization or status between the National Laboratories and the research and development program of the Office of Fossil Energy. NETL, with its unique concentration of expertise in fossil fuels, would at last be the institutional equal of other celebrated DOE laboratories such as Argonne, Oak Ridge, Los Alamos, and Lawrence Livermore.

The designation affirmed the importance of fossil energy to the past, present, and future of the American economy and the environment. "For much of this century, U.S. government research facilities here [in Morgantown] and in Pittsburgh have been at the forefront of advancements in fossil fuel and environmental technologies," Richardson noted. These subjects remained vital to prosperity and the quality of life as concerns about global economic integration and global climate change mounted. NETL would "elevate the potential for high-tech fossil fuels" and help to guarantee a "balanced mix of traditional and nontraditional fuels" in the nation's energy portfolio. It would complement the National Renewable Energy Laboratory that the DOE had established at Golden, Colorado, in 1991 to focus on wind energy, solar power, and biomass.

In keeping with his longtime strong support for fossil-energy research, Senator Robert C. Byrd of West Virginia accompanied Secretary Richardson at the signing ceremony that created NETL. Senator Byrd predicted that the newest National Laboratory would soon be at "the center of the universe" in its fields of scientific endeavor. He reiterated the theme that there was no fundamental opposition between using fossil fuels and caring for the environment—or between environmental protection and economic growth. "We can both grow and protect the planet," Byrd asserted, calling for a redoubled drive to deploy clean-coal technologies more widely at home and abroad.

The change in status did not immediately have drastic impacts on the daily lives of the organization's staff and contractors. NETL retained FETC's distinctive position as a government-owned, government-operated facility. Unlike other National Laboratories that were wholly managed by private contractors, it was under the direct control of federal employees, with contractors playing supporting roles in its administration. Its Office of Research and Development oversaw the onsite program of research at Pittsburgh and Morgantown. Support for offsite, "outside the fence" research projects was provided through competitive solicitations, with NETL providing ongoing project management through cooperative agreements with the sponsors of the winning proposals. This arrangement had proven to be highly productive in cultivating research and development partnerships with universities and private companies. "It works, and I don't want to change it," Secretary Richardson explained.

Senator Byrd predicted that the newest National Laboratory would soon be at "the center of the universe" in its fields of scientific endeavor.

Continuity also dominated at first in NETL's management and mission. Rita Bajura stayed on as the laboratory's director until 2005, thereby becoming the first woman ever to lead a National Laboratory. Many other key staff members remained in place. NETL focused its initial research efforts on six areas that extended the earlier priorities of FETC and its predecessors: Vision 21 advanced power systems; the use of natural and synthetic gas for power generation; ultra-clean transportation fuels; environmental research; carbon capture and sequestration; and computational energy science. Thanks to the ongoing use of cooperative agreements and CRADAs with other organizations, the laboratory had 1,100 distinct research activities underway in all 50 states and 16 foreign countries during 2000, its first full year of operation.

Soon, however, NETL began to expand and diversify. In 2000, the National Petroleum Technology Office (NPTO) in Tulsa, Oklahoma, became part of NETL. NPTO was the last government-controlled remnant of the original Bartlesville station. It had originated in 1996, when plans for the privatization of the NIPER site in Bartlesville became final. BDM-Federal, the parent company of BDM-Oklahoma, had acquired full responsibility for NIPER and had decided to move that laboratory's activities into leased space at the Bartlesville research and development facilities of the Phillips Petroleum Company. A BDM-Oklahoma subsidiary called BDM Petroleum Technology henceforth operated the former NIPER organization in its new quarters at Phillips, although DOE financial support continued until a preexisting contract expired in November 1998.

As NIPER made the transition to private ownership, the DOE concluded that the Bartlesville Project Office—which still had 23 federal employees and oversaw over 200 petroleum research, development, and demonstration projects—should move to Tulsa. "By relocating to one of the nation's major centers of activity for the oil industry, the staff of our petroleum field office will be able to strengthen day-to-day interactions with a key segment of the industry," Energy Secretary O'Leary explained. "Our employees will be more accessible to their customers. The benefits we expect to achieve with this move—improved service along with cost savings—reflect two important goals of the Clinton administration's reinventing government program." Space for staff members who relocated from Bartlesville was leased from the Southwestern Power Administration, another division of the DOE, on the fourteenth floor of the Williams Tower One in downtown Tulsa.

NETL had developed great competence in managing complex projects, and shared this know-how with other DOE divisions and other federal agencies through the Office of Project Management.

In September 1997, the remaining elements of the Bartlesville Project Office became the NPTO. Tom Wesson retired as the director of the NPTO in December 1987. William F. Lawson, who had previously headed the Fuels Resources Division at the DOE's Morgantown site, succeeded Wesson as director on April 12, 1998.

Significant areas of mutual concern and overlap existed between the NPTO and the Strategic Center for Natural Gas at NETL. For example, both were involved in developing underground fracture-stimulation methods and advanced drilling technologies. Both had taken an interest in methane hydrates. The similarities indicated another opportunity for cost-saving consolidation, an opportunity that the DOE seized by folding the small Tulsa office into the NETL organization. Reflecting the addition of this petroleum research capability, the name of the Strategic Center for Natural Gas was changed to the Strategic Center for Natural Gas and Oil. On April 6, 2001, the story of the Bartlesville station quietly came to an end when DOE officials signed an official land transfer that gave the 17-acre site of the former research facility back to the City of Bartlesville, which had donated the property to the federal government in 1917. The Tulsa branch of NETL remained active until March 31, 2009, when it was shut down; a few remaining employees were transferred to Houston, Texas.

The next addition to NETL was the Arctic Energy Office, which opened in 2001. Located in Fairbanks, Alaska, this newest (and coldest) branch of the laboratory addressed the distinctive energy resources and needs of the Arctic region. Its research focused on developing this mineral wealth through petroleum and natural-gas recovery, gas-to-liquids conversion, and pipeline transportation. A second area of interest was electric-power generation in Arctic climates, with a particular eye toward supplying the region's many small, remote communities. The office considered not only fossil fuels but also wind, geothermal energy, and small hydroelectric plants as potential solutions.

On November 27, 2005, the final piece was added when the Albany Research Center became part of NETL. As one of the leading materials-science laboratories in the United States and the world, Albany was well positioned to help the fossil-energy research programs address an increasingly urgent problem: the need for materials that could endure the extraordinary temperatures and pressures found in modern power plants and industrial operations. It was already engaged in several projects related to this need. For instance, Albany was devising refractories and metal alloys suitable for coal gasifiers and advanced turbine engines in IGCC plants. The center participated in an international effort to develop corrosion-detecting sensors that could be installed in key components of a boiler or reactor to give early warning of deterioration in metals that were under severe stress. Bringing Albany into NETL allowed materials scientists there to cooperate more intensively and effectively with designers of advanced power systems.

Carl O. Bauer, Director of NETL 2005-2009.

NETL was thus a unified and balanced organization by the middle of the decade. It had seven principal divisions, including the Strategic Center for Natural Gas and Oil and a corresponding Strategic Center for Coal (founded in 2004). The Office of Research and Development remained in charge of onsite research programs on fossil energy and related environmental issues. The Office of Systems, Analyses, and Planning studied the institutional and social context of energy production and use, employing a systems-analysis perspective to keep researchers, policymakers, and the public informed about trends that affected the energy industries. Administrative duties were the province of the Office of Institutional and Business Operations and the Office of Crosscutting Functions. And because NETL and its predecessors had developed great competence in managing complex projects, the laboratory was often able to share its know-how with other DOE divisions and other federal agencies through the Office of Project Management. This capability extended NETL's reach beyond fossil-energy issues.

Rita Bajura had retired in February 2005, and her deputy, Carl Bauer, had been the acting director until September 29 of that year, when he was officially appointed as Bajura's successor. Bauer had served as the deputy director since October 2003. With an engineering background that included a degree in nuclear power engineering from the U.S. Naval Academy, he had worked at

The Alaska Energy Office, a partnership between NETL and the University of Alaska-Fairbanks (UAF), is located on the UAF campus.

the Department of Defense, several private corporations, and the DOE headquarters in Washington, D.C. His previous responsibilities at NETL had included directing the Office of Coal and Environmental Systems and organizing the development and demonstration of technologies for cleaning up hazardous and radioactive wastes.

A Unified Organization Faces the Future

Advances in supercomputers and software programs allowed simulation of the complex processes that occurred inside a coal gasifier or across an entire power plant.

As it approached its centennial in 2010, NETL was conducting, sponsoring, or participating in an expansive array of programs. It maintained a vigorous onsite research program and also oversaw a portfolio of some 1,800 research projects conducted by its partners and contractors. The basic mission of the laboratory was consistent: to provide the federal government and private industry with the technological tools to ensure that the United States had an adequate energy supply while also promoting economic growth and safeguarding environmental quality. Several broad categories—including computing, advanced power systems, materials science, and geological and environmental systems—brought conceptual order to its proliferating activities.

One of NETL's core research areas was Computational and Basic Sciences (CBS). Thanks to advances in supercomputers and software programs, incredible tools had become available for simulating the complex physical and chemical processes that occurred inside a specific device such as a coal gasifier or across an entire power plant. The purpose of CBS was to make these tools available at NETL so that scientists and engineers could better understand the fundamental steps of a process and optimize the design of the equipment needed to run it.

An example was MFIX, the Multiphase Flow with Interphase Exchanges software. In 2007, NETL won a prestigious R&D 100 Award for this technology, which gained an international reputation as the preeminent software for modeling gas-solids (multiphase) flow. MFIX could simulate chaotic processes. For instance, coal gasification involves an immense number of different interactions as heated particles of coal rise through the reactor, bump into one another, hit the reactor's sidewalls, and react with gas molecules to form synthesis gas and other products. Modifying variables such as temperature, the diameter of the reactor, or the ratio of coal to air or oxygen alters the mix of products that results. How can engineers track and optimize these behaviors? Experimentally, they could alter one variable at a time, run the reactor for a day or two, and observe what happens. Investigators at Pittsburgh and Morgantown had done just that in the early days of synthetic-fuels research. But MFIX made life easier. It was a computational fluid dynamics model (CFD) that calculated changes in things that flow. It allowed researchers to conduct simulated experiments by letting the supercomputer and the CFD software module figure out the effects of the altered variable.

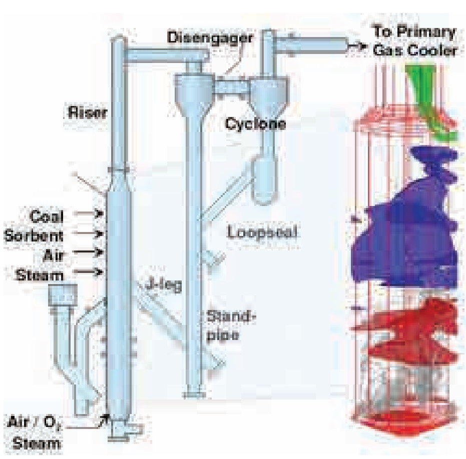
MFIX was so powerful that it could tell the position, velocity, temperature, pressure, and chemical composition of each tiny volume (called a *computational cell*) inside a gasifier every few seconds. In one simulation, NETL researchers divided a small region of a gasifier into 12 million computational cells to gain a high-resolution picture of that region. By collecting multiple "snapshots" of the state of the gasifier at different times and looking at them sequentially using visualization software, they could watch a movie of the simulated experiment and see how the gasification process changed with time. The main goal was to model high-efficiency, low-pollution processes to evaluate proposed system designs and performance.

MFIX was so powerful that it could tell the position, velocity, temperature, pressure, and chemical composition of each tiny volume inside a gasifier every few seconds.

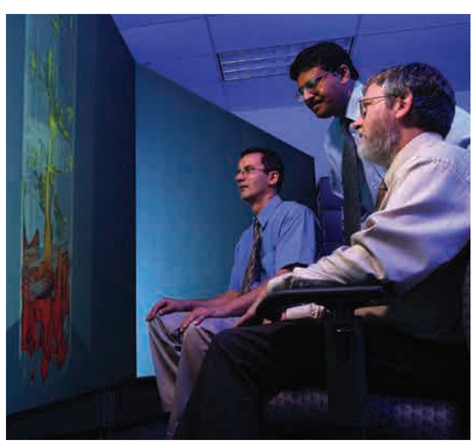
Another important type of software, Carbonaceous Chemistry for Continuum Modeling (C3M), worked together with MFIX to simulate the chemical reactions that occur between coal particles and flowing gases during gasification. MFIX calculated basic properties of the system such as temperature, pressure, and the composition of gases, while C3M used these data to probe deeper into the rates and heats of reactions and mass-transfer effects. This approach provided unprecedented insight into the chemical kinetics and thermodynamics of coal gasifiers. It enabled engineers to observe how different chemicals formed and evolved over time in a reactor—knowledge that could shorten the time needed to design a new gasifier and avoid the expense of building and testing multiple prototypes.

APECS, the Advanced Process Engineering Co-Simulator, could link with MFIX to develop a broader view of operations in an entire power station or chemical plant. It was the first software to combine the disciplines of process simulation and CFD. This unique blend made it possible for engineers to create "virtual plants" and to follow complex flows of heat and fluids from unit to unit through a production process. Advanced visualization software aided in analyzing and optimizing an entire facility's performance, thereby lowering the cost of plant design. APECS won an R&D 100 Award in 2004. A government-industry-university collaboration made it commercially available.

MFIX, C3M, and APECS were just some of the noteworthy software modules that NETL developed, in collaboration with others in industry and the academic world, to make computational models that could substitute for physical



Transport gasifier and MFIX showing particle trajectories and oxygen concentration



MFIX scientists view the results of their development work.

systems. In the areas of energy systems dynamics and clean power generation, researchers at NETL and its industrial and academic partners took advantage of these simulation capabilities to help increase the efficiency and cleanliness of the U.S. "fleet" of power plants. Engineering effort focused on two goals: substantially improving new or existing plants that burned pulverized coal, and bringing the near-zero-emissions plants called for in Vision 21 closer to reality.

After tests at dozens of sites around the U.S., activated carbon injection was ready for commercial use.

Since national policy and low coal prices continued to favor using coal for power generation, and since advanced power systems were unlikely to make deep inroads into the electric-utility market for at least another decade, there was still a great need for technologies to upgrade the performance of conventional pulverized-coal systems. NETL made important contributions to pollution abatement, ultra-supercritical boilers, and reusing the byproducts of coal combustion. Successors to the Clean Coal Technology Demonstration Program tested some of these innovations in commercial settings.

During the 2000s, the campaign against air pollution stressed additional reductions in NO_x emissions and the problem of mercury control. Anti-NO_x measures included further cost-reducing improvements in low-NO_x burners, catalytic reduction methods, and the development of oxygen-enhanced combustion. Mercury was a tougher proposition. No satisfactory commercial methods were available for dealing with this highly toxic pollutant. Even measuring and tracking mercury emissions was difficult, because mercury takes several different chemical forms and occurs in low concentrations within power-plant flue gas. NETL helped to develop better techniques for detecting mercury. It also evaluated processes for introducing mercury-collecting sorbent materials, the most common of which was activated carbon, into the flue-gas stream. By

The Advanced Process Engineering Co-simulator (APECS) research team views some promising results of their work.

2008, when the laboratory's primary mercury program concluded after tests at dozens of sites around the United States, activated carbon injection was ready for commercial use.

Three important advances in mercury control were patented at NETL and licensed to private firms. In the Thief Process, a small amount of incompletely burned coal was extracted from a boiler furnace and used as an effective sorbent to capture mercury from the flue gas. PG Trace Metal Sorbents were capable of removing both mercury and arsenic at temperatures higher than activated carbon could tolerate. The Photochemical Oxidation Process used ultraviolet light radiation to turn pure mercury into compounds that were easier to remove.

Through the Power Plant Improvement Initiative and the Clean Coal Power Initiative, NETL managed commercial demonstrations of innovative retrofits to existing plants.

The trend in power-plant design was to maximize efficiency by using boilers that operated at ultra-supercritical conditions, which entailed pressures greater than 3,210 pounds per square inch and temperatures of at least 1,100 °F. Such harsh environments demanded a new generation of extremely sturdy materials. NETL was on the case, managing a consortium of U.S. boilermakers that cooperated with the DOE and the Electric Power Research Institute to define procedures for identifying, selecting, testing, and fabricating advanced heat-tolerant, corrosion-resistant metal alloys. The laboratory's onsite materials research program and offsite contractors made advances in treatments and coatings that protected the components of ultra-critical boilers.

Another way that coal-burning power plants could improve the cost effectiveness of electricity generation was to sell more of their byproducts—ash, boiler slag, and residues from pollution-control equipment—for conversion into goods that had market value. For example, a significant synthetic-gypsum industry had developed in the United States since the 1980s, using the byproducts of flue-gas desulfurization to produce wallboard, fertilizers, and other materials. Several NETL-managed partnerships explored opportunities for similar economic success by reusing coal utilization byproducts (CUBs, for short) in items such as foam glass and paving bricks. The volume of CUBs was increasing as coal use grew and as byproducts that had once been dumped as wastes were recovered, so new outlets for these substances were welcome.

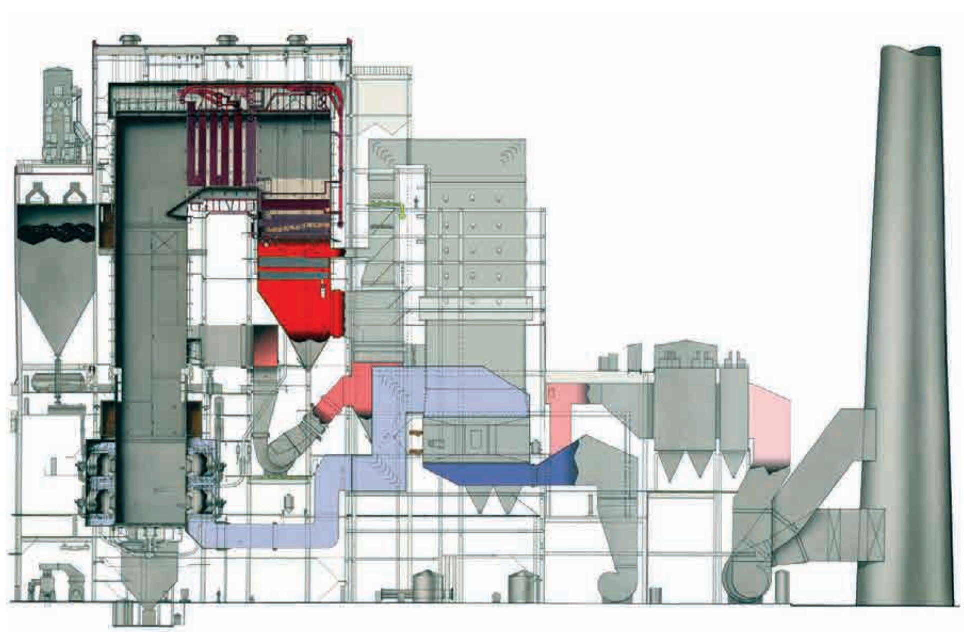
Close-up picture of the "Thief" apparatus used to extract partially-combusted coal from NETL's pilot-scale combustor

Through the Power Plant Improvement Initiative (PPII), begun in 2000, and the Clean Coal Power Initiative (CCPI), launched in 2001, NETL co-sponsored and managed commercial demonstrations of innovative retrofits to existing plants. Congress had specifically authorized these programs as follow-ups to the original Clean Coal Technology initiative. In the words of the legislation, both were meant to "reduce the barriers to continued and expanded coal use" and "strengthen electricity reliability." Twelve demonstration projects were complete or underway by the end of the decade, with the DOE's private and local partners covering at least half of the costs.

Several PPII and CCPI projects rejuvenated old power plants with high-tech electronic wizardry. At the Baldwin Energy Complex, a facility owned by Dynegy Midwest Generation in Baldwin, Illinois, work started in 2004 on an integrated computer software network to manage the various components of the plant. Based on cutting-edge concepts of artificial intelligence, five distinct computer systems developed by the Boston technology firm NeuCo collected data from sensors that continuously monitored the plant's operations and made adjustments to optimize its performance. This optimization process mimicked human capabilities of pattern recognition and learning, but it could outdo even a highly skilled human operator in making judgments about the relationships and tradeoffs among multiple goals and variables that affected power-plant performance. The demonstration project, conducted during 2007 and 2008, slashed Baldwin's NO_x output by an average of 12 to 14 percent. It also significantly reduced emissions of other pollutants, including mercury, and increased reliability.

Similar artificial-intelligence systems performed well at the Limestone Power Plant in Jewitt, Texas, where the CCPI Mercury Specie and Multi-Pollutant Control Demonstration took place between 2006 and 2010; at the We Energies Presque Isle Power Plant in Marquette, Michigan, which hosted the CCPI TOX-ECON Retrofit project from 2006 to 2009; and at a PPII site, the Big Bend Power Station at Apollo Beach, Florida, where the Big Bend Power Station Neural Network Sootblower-Optimization Project received testing from 2002 to 2004. The success of optimization software and integrated pollution-control systems in several different regions with different types of coal proved that much could still be done to improve conventional power plants. With the right updates, even old plants that had not been designed with modern environmental concerns in mind could do better than expected.

However, incremental progress in pulverized-coal combustion could only go



Cutaway of the Baldwin Energy Complex.

so far. This century-old technology was approaching the limits of its efficiency. New plants would increasingly rely on advanced power systems that worked according to different principles. If they still used coal combustion, they would likely feature approaches such as fluidized-bed combustion—which was already gaining acceptance in the U.S. electric-power industry—or NETL's High Performance Power System, with its indirect method of running a turbine generator with compressed air heated by a coal-burning furnace. But the prevailing view at NETL was that coal should be gasified rather than burned directly. Integrated Gasification Combined Cycle (IGCC) power systems were cornerstones of the Vision 21 concept for the future of electricity generation.

By the first decade of the twentieth century, coal gasification had come a very long way but still faced some of the same basic problems that the founders of the Morgantown station had wrestled with in the 1940s. It was still more expensive and more temperamental than it needed be for widespread mass-production purposes. So NETL kept up the relentless search that its predecessors had begun for ways to drive down costs and drive up the quality and reliability of synthesis-gas production.

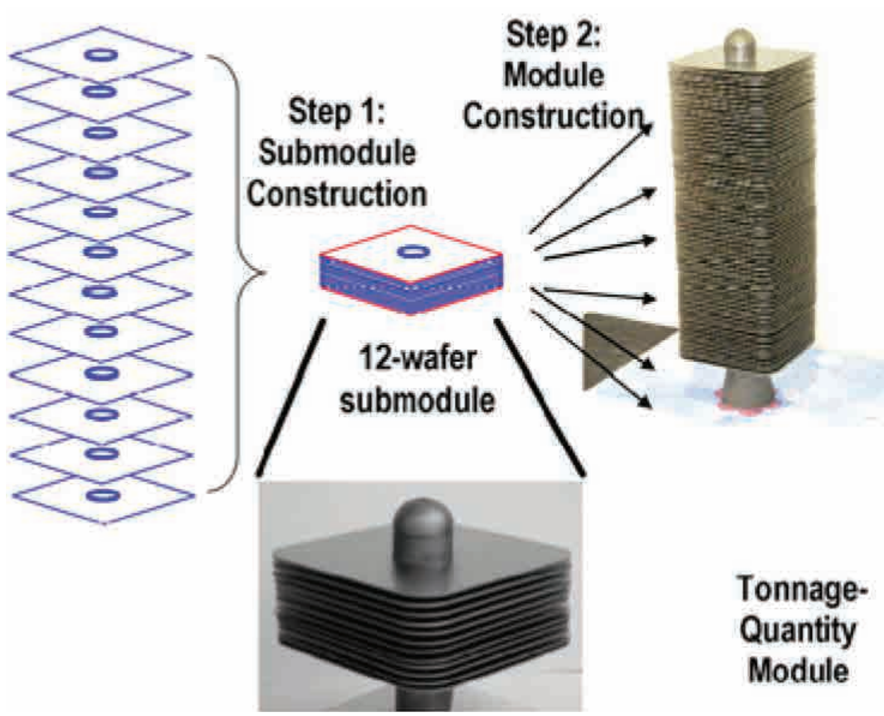
One area that called out for improvement was the development of cheaper methods for supplying gasifiers with oxygen. Gasifying coal with oxygen rather than air had many advantages. It converted the coal to gas more completely and yielded high-grade synthesis gas with minimal dilution by nitrogen and other substance. It was a prerequisite for many industrial uses and for doing flue-gas cleanup and carbon capture at IGCC power plants. But in the 2000s as in the 1940s, oxygen was an expensive input.

Presque Isle Power Plant in Marquette, Michigan, where the TOXECON mercury-removal technology was tested.

The membrane revolution in gas-separation technology offered an exciting new angle on this old concern. NETL partnered with companies such as Air Products and Chemicals Inc. to develop ceramic-oxide Ion Transport Membranes (ITMs) that could pure oxygen from air. "The electrochemical properties of these membranes," *Clean Coal Today* explained in 2006, "make it possible to selectively separate oxygen ions from a stream of air at high temperature and pressure. Those ions are transported across the ITM" and recombined to form pure oxygen, leaving the oxygen-depleted air on the other side of the ITM boundary where it could be put to work in driving a turbine. Since an ITM plant could thus generate both oxygen and electricity, it could be a very efficient component of a Vision 21 powerplex.

Other projects in the NETL Gasification Technologies Program contributed to the development of advanced high-pressure gasifiers that could make synthesis gas not only from coal but also from mixtures of coal with other fuels, especially blends of coal and biomass materials such as agricultural wastes or sewage sludge. New technologies continued to improve feed systems, pumps, coolants, and methods of protecting gasifier linings against damage from heat, slag, and abrasion.

Synthesis-gas purification, another staple of gasification research for decades, became even more important as NETL pursued the goal of near-zero-emissions power plants. The difficulty and expense of removing contaminants from the gas remained among the practical obstacles to wider use of gasifiers. Researchers at NETL developed better methods of capturing impurities with sorbent materials, such as the RVS-1 sorbent for capturing sulfur. In coopera-



Commercial-scale Ion Transport Membrane oxygen modules.

tion with private industry, they focused particularly on purification techniques that worked at moderate or high temperatures. Traditional approaches required synthesis gas to be cooled after leaving the gasifier and then reheated before entering a turbine or a chemical-processing plant. If these steps could be eliminated, much time and energy would be saved.

Many innovations that benefited coal gasification and synthetic liquid fuels production, especially the use of membranes, were also applicable to a closely related issue: obtaining pure hydrogen from other gases such as methane (natural gas) or synthesis gas. Beginning in 2003, the NETL Hydrogen from Coal Program was in the vanguard of efforts to develop hydrogen gas-separation membranes. Made from various types of ceramic materials or metal alloys, these membranes were permeable to hydrogen but blocked out carbon compounds and destructive impurities such as sulfur. They constituted a great advance over existing multi-step processes for hydrogen production and purification. The main point of streamlining hydrogen manufacturing was to secure large quantities of hydrogen for use as a fuel in power generation and in future ultra-clean transportation systems.

Pellets of RVS-1 sulfur sorbent material.

During the 2000s, the development of fuel cells made great strides with the assistance of NETL's funding and technical expertise. Small fuel cells began to dot the American landscape. They provided power to isolated areas that had little access to the electric grid. They appealed to institutions with strong interests in an efficient, minimally polluting, relatively self-contained energy supply that could go on if the grid went off: hospitals, schools, military bases. Many of these early commercial fuel cells were of the phosphoric-acid type, but molten-carbonate fuel cells also made progress. A decade-long cooperative agreement between NETL and Connecticut-based FuelCell Energy, Inc. ended in 2005 after spurring commercialization of the company's molten-carbonate technology. By then, the largest coal-based fuel-cell power plant in the country, using a FuelCell Energy molten-carbonate design, was transforming synthesis gas into electricity at the Wabash River coal-gasification facility in Indiana.

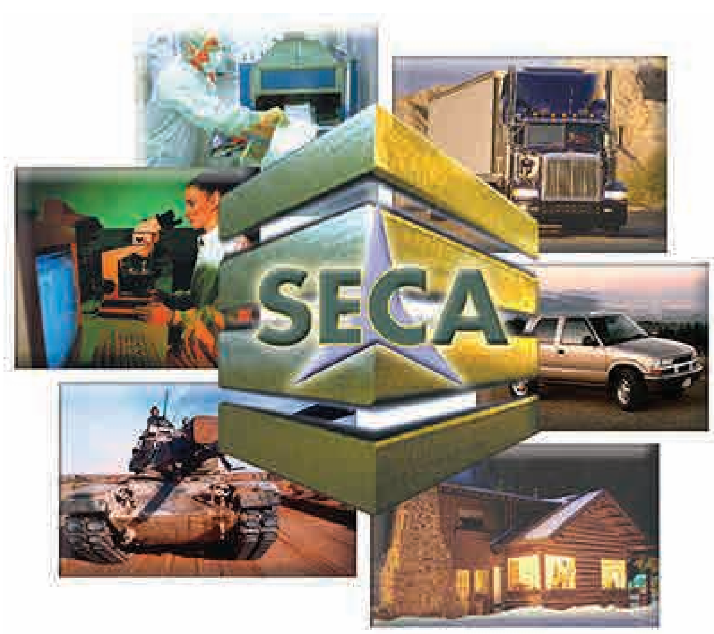
Development of fuel cells made great strides with the assistance of NETL's funding and technical expertise.

The NETL fuel-cell program looked toward scaling up fuel cells so that they could become alternative power sources for large Integrated Gasification Fuel Cell electrical generating stations. Solid-oxide fuel cells held great promise for this purpose. SECA, the Solid-State Energy Conversion Alliance, was the laboratory's principal means of advancing solid-oxide fuel cell technology. Initiated in 1999 by NETL and the Pacific Northwest National Laboratory, SECA supported competitively selected "industry teams" of researchers from private organizations who vied to create reliable, inexpensive fuel-cell power systems that could be of any desired size. NETL independently tested and verified the concepts and products that the teams devised.

SECA was so effective that in 2006, the federal Office of Management and Budget (OMB) called it a model of how public-private partnerships should work. Government funding to the industry teams, the OMB observed, continued only "as long as the teams continue to exceed a series of stringent technical performance hurdles. This novel incentive structure has generated a high level of competition between the teams and an impressive array of technical approaches. The SECA program also develops certain core technologies that can be used by all the industry teams to avoid duplication of effort." The alliance had exceeded its goals and was "on track" to have commercially viable solid-oxide fuel cell technology ready by 2010. Soon after this glowing appraisal, fuel cells based on SECA's work began to appear in public places where Americans could see the early results of the program. The Phipps Conservatory in Pittsburgh, for example, unveiled a 5-kilowatt solid-oxide fuel cell in 2007 that used natural gas to supply electricity and hot water for the conservatory's Tropical Forest exhibit.

SECA was so effective that it was called a model of how public-private partnerships should work.

Whether centered on coal combustion, coal gasification, natural gas, or the indirect use of fossil energy via fuel cells, advanced power systems still needed high-efficiency gas turbines to achieve the maximum possible electrical output. The NETL Turbine Program built on the previous successes of the Advanced Turbine Systems initiative by working on the next generation of turbines that could burn natural gas, synthesis gas, or hydrogen. Using oxygen instead of air to fire turbine combustors was a major focus. Applied research continually improved blades, combustors, and cooling systems. With the help of Combustion Control and Diagnostic Sensor (CCADS), a patented NETL invention, investigators could analyze the behavior of flames inside a gas turbine and detect trouble such as flame flashback or blowout. This close observation of flame dynamics and combustion was just the latest chapter in NETL's century-long heritage of carefully studying how fuels burned, exploded, and changed form.



Some of the application areas for Solid State Energy Conversion Alliance (SECA) projects.

Solid-oxide fuel cell at Phipps Conservatory in Pittsburgh.

FutureGen brought it all together. Launched in 2003 and continued throughout the decade, this project was the first attempt to design and build a commercial-scale plant to demonstrate the Vision 21 idea of a multipurpose coal-fueled powerplex that approached the near-zero-emissions goal. The plant would feature an IGCC core that gasified coal, converted the resulting synthesis gas to hydrogen and carbon dioxide, and burned the hydrogen to power ultra-efficient gas and steam turbines. State-of-the art pollution control technologies would recover ash and sulfur for recycling into valuable coal-utilization byproducts. Carbon dioxide would be captured and stored to keep it out of the atmosphere. The hydrogen made onsite could also be used to produce fuel and industrial chemicals. With an international alliance of coal producers and coal users joining the DOE in providing financial and technical support, FutureGen was one of the first truly global public-private energy ventures of the new century.

NETL cared about the distribution of electricity as well. On August 14, 2003, a massive power blackout in the northeastern United States and Canada had called attention to the fragility of the old, outmoded power grid that served the most highly populated areas of the country. Congress responded with the Energy Policy Act of 2005, which, among many other things, authorized the DOE to research, develop, and demonstrate "smart grid" technologies that could better resist damage and disruption. The new DOE Office of Electricity Delivery and Energy Reliability, established to oversee this program, enlisted help from NETL due to the laboratory's long experience with complex energy systems.

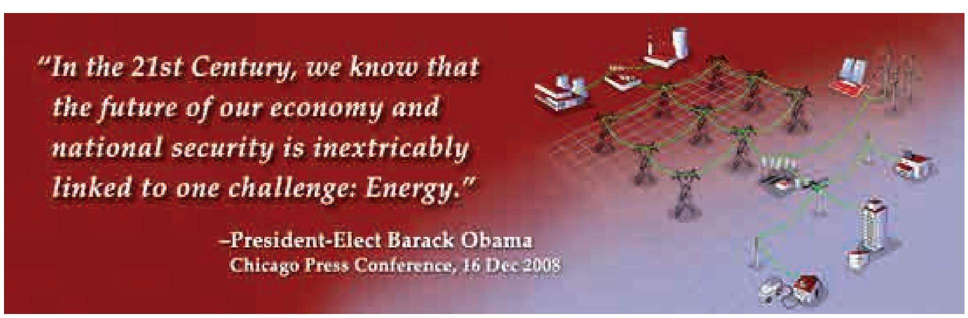
Smart grids were to be examples of distributed, resilient technology. By dispersing key components around the system instead of centralizing them, and by using the principles of modularity and built-in redundancy, engineers could prevent the loss of one section from bringing the whole grid down. Intelligent diagnostic capabilities would make the repair of the grid and restoration of power easier.

An artist's conception of FutureGen.

By 2008, enough progress had been made that a DOE publication entitled "The Smart Grid: An Introduction" could describe some intermediate accomplishments on the way to a smart grid. The University of Hawaii was working on a Distribution Management System that empowered consumers to manage energy consumption in their homes via devices that could communicate with and control the operation of household appliances in order to optimize efficiency. The Illinois Institute of Technology was investigating power distribution networks that were based on microgrids, small units that could respond to changing conditions in the larger system. San Diego Gas & Electric implemented a Beach Cities Microgrid Project that demonstrated how a faulty microgrid could be isolated from the main grid, repaired, and seamlessly restored when the problem had been solved.

Working with industry and with state and local agencies, NETL had defined a concept for a "modern grid strategy" by the end of the decade. This strategy was driven by values such as reliability, safety, security, economy, and active consumer participation. It envisioned a distribution network that would constantly monitor itself and quickly reconfigure itself in case of an emergency so that power supply would not be lost. The system would accommodate all types of power generators and storage methods, and would allow customers to sell any excess electricity back into the market. Much remained to be done in order to make the smart grid a reality, but NETL was leading the development effort in the United States.

Another core research area was advanced materials, a topic that cut across many different investigations at NETL. New processes for extracting or using fossil energy often demanded the simultaneous development of new materials. If a process required a metallic component to withstand higher temperature or pressure, or subjected it to a more corrosive atmosphere than it had previously encountered, then a new alloy might have to be developed. Or, as in the case of some turbine technologies, researchers might decide that no form of metal was suitable and that a ceramic material would be more appropriate. NETL, as its website proudly proclaimed, was a one-stop shop for applied materials science—"one of the few places in the world where alloy development, melting, casting, fabrication, physical and chemical analyses and performance testing (wear, erosion, and various forms of corrosion) can be performed in one place."



An illustration of one version of the Modern Grid.

Resolving questions about materials required the latest in laboratory instrumentation and capabilities. Albany remained NETL's specialized location for this purpose. The Albany site housed part of the Severe Environment Corrosion and Erosion Research Facility, which assessed the performance of materials under a variety of simulated high-temperature conditions. The Liquid Metal Processing Laboratory was equipped to melt, alloy, cast, forge, roll, and heat-treat materials in amounts ranging from a few grams to hundreds of kilograms. Among the outstanding features of Albany's analytical laboratory were electron microscopes, X-ray devices, and a full range of spectrometers for examining the internal structure and composition of materials.

NETL was a one-stop shop for applied materials science, where "alloy development, melting, casting, fabrication, physical and chemical analyses and performance testing can be performed in one place."

Much materials research was carried out through cooperative agreements or CRADAs with scientists and engineers outside NETL. One notable achievement, completed in 2006, was a multi-year joint project in which NETL and ANH Refractories developed a new chrome-oxide refractory material capable of standing up the intensely hot and corrosive conditions in slagging gasifiers. In this collaboration, the researchers determined that one of the main reasons why existing chrome-oxide refractories failed was the chipping or flaking of the material from exposed surfaces. They used this information to formulate a version that resisted this kind of disintegration.

Metallurgists at NETL, along with their partners in industry and at universities, developed a range of nickel-based superalloys for use at high temperatures. They also established corrosion-resistant surface treatments for alloys, etching techniques for stainless steels, and methods of welding dissimilar metals together. New materials often found surprising uses outside the energy industries. A CRADA that NETL arranged with a major supplier of medical devices led to the commercial production of metallic stents, which are used to hold open blocked blood vessels. The hallmark of the stents was a special stainless steel alloy, developed at Albany, that made them more radiopaque—more visible under X-ray illumination. This property helped medical personnel insert the stents in exactly the right locations. In another accomplishment, a type of heat treatment that NETL researchers developed for cast-steel armor plate boosted the armor's resistance to penetration by explosive devices. The U.S. Army Tank and Automotive Command decided in 2007 to order ten million pounds of this enhanced armor for retrofitting military vehicles. NETL then helped American foundries learn how to produce the necessary material.

Comparison of chromia refractory bricks, with NETL's formulation (right) showing much less wear than the standard commercial brick (left).

Finally, NETL's research on geological and environmental systems dealt with relationships between human industries and the natural environment. It explored the enduring questions of where fossil-fuel deposits occurred, why they occurred where they did, and how these resources could best be extracted and used while limiting damage to the land, air, and water. Meeting the challenge of global climate change increasingly became a unifying theme that linked previously separate endeavors in a common cause.

The NETL Natural Gas and Oils Exploration and Production Program continued to work on detecting and mapping conventional sources of petroleum and natural gas. Tools such as the use of seismic waves and electromagnetic data to portray conditions underground aided in this quest. As petroleum and natural-gas drilling activities shifted to more geographically remote areas and to deep reservoirs that lay miles beneath the surface, controlling the rising costs of well location, drilling, and completion became an important objective. NETL joined forces with industry to develop "smart drills" that could send information about their whereabouts and surroundings back to operators on the surface. Field tests demonstrated that microhole drilling rigs, which could quickly drive tiny boreholes of less than 4.5 inches diameter, not only aided exploration but also could recover small concentrations of natural gas that would otherwise be uneconomical to retrieve. By making drilling more precise, these technologies reduced the risk of "dry holes" and the environmental hazards of unnecessary wells.

Meeting the challenge of global climate change increasingly became a unifying theme that linked previously separate endeavors in a common cause.

Enhanced petroleum recovery was also still a high priority. Techniques that the former Bartlesville center and its successors had helped to pioneer—waterflooding, fireflooding (now classified as a form of "thermal recovery"), injections of polymer chemicals, and the use of microbes to thin heavy oil—remained in active use and underwent further refinement. During the 2000s, the newest and fastest-growing method of enhanced recovery was the injection of carbon-dioxide gas (CO_2) into petroleum wells to stimulate their flow. NETL was one of the few organizations in the United States doing comprehensive research and development on CO_2 flooding. It cooperated with other National Laboratories, universities, and petroleum companies on demonstrations of this method in the oil fields of Texas, California, and the Mid-Continent.

Unconventional natural gas from deep shale formations was an energy success story of the decade. Drilling into the Marcellus Shale beneath the Central Ap-

The cast steel armor program at Albany produced this three-piece bustle to protect the rear of the turret and the commander's hatch on the Army's Bradley Fighting Vehicle. The angled slots in the armor are designed to fracture incoming projectiles into numerous pieces, none of which has enough energy to penetrate the vehicle.

palachians soared after 2005, when a company called Range Resources demonstrated that the methods that had worked in the Barnett Shale of Texas were effective in the Marcellus Shale as well. Bill Zagorski, who directed geological investigations for Range Resources, expressly credited the data that NETL and its predecessor agencies had compiled on Devonian shales since the mid-1970s with aiding his company's breakthrough. By 2010, the shale-gas boom in the United States was inspiring governments and energy companies in Europe and Asia to investigate similar deep gas-bearing rocks in their countries.

During the 2000s, NETL was one of the few organizations doing comprehensive research and development on CO_2 flooding.

Methane hydrates remained far away from the commercial-development stage, but much was being learned about them. Scientists from NETL participated in surveys of methane-hydrate resources in the United States and abroad. In 2003, NETL, Anadarko Petroleum, and Mauer Technology had drilled Hot Ice #1, the first test well in the United States developed specifically for studying methane hydrates on the North Slope of Alaska. Numerous other test wells followed, allowing researchers to take core samples and chart the extent of hydrate deposits on the North Slope. Laboratory studies and computer models revealed information about the properties and behavior of methane hydrates. The findings were encouraging: Methane gas from hydrates located in U.S. territory could potentially more than double the country's natural-gas reserves. However, optimism about hydrates was tempered by concerns that sudden large releases of the methane trapped inside them could endanger people at sea or on land and might even accelerate global climate change.

Carbon Capture and Sequestration

Like carbon dioxide, nitrous oxide, and several other chemicals, methane was known to be a "greenhouse gas"—a category of gases whose increasing concentration in the Earth's atmosphere was raising global temperatures and altering the global climate. Climate change was a subject of intense scientific and political interest in the early twentieth century as a scientific consensus emerged that human production and use of fossil fuels was contributing significantly to the buildup of greenhouse gases. From modest beginnings that traced back to initial research projects at FETC in the late 1990s, NETL's involvement in efforts to reduce greenhouse-gas emissions grew rapidly between 2000 and 2010. The DOE Climate Change Technology Program, launched in 2005, gave NETL a leadership role in broadening the range of feasible technological options for controlling these emissions and limiting their impact on the environment.

Hot Ice #1 was the first test well developed specifically for studying methane hydrates on the North Slope of Alaska.

Carbon dioxide (CO_2)—a normal byproduct of heating, burning, or gasifying fossil fuels—constituted the largest part of the greenhouse-gas problem and so received the most attention. Many NETL programs had some bearing on carbon-dioxide control. By promoting more efficient power plants and transportation systems, and by encouraging Americans to use natural gas and to adopt new technologies such as fuel cells that released less CO_2, the laboratory sought to reduce the country's CO_2 output over the long term. But the principal focus of the NETL climate-change initiative was the Carbon Capture and Sequestration Program (CSS). This approach, begun in 1997 and greatly expanded during the 2000s, presumed that large amounts of CO_2 would still be produced in the near-to-mid-term future. It concentrated on diverting those emissions before they reached the atmosphere and redirecting them to do beneficial work or to be stored safely where they could do no environmental harm.

One goal of CCS was to improve technology for capturing CO_2 from power plants and industrial boilers. The program had a goal of developing systems that could achieve 90 percent carbon capture by 2012. It dovetailed with NETL's focus on promoting clean-coal technologies, especially advanced power systems. Coal gasification made separating CO_2 from other coal-utilization byproducts easier, so IGCC plants were inherently better suited to carbon capture than conventional coal-fired plants were. For existing boilers that used coal, fuel oil, or natural gas, NETL worked on new flue-gas cleanup techniques that would be superior to known chemical-scrubbing methods for removing CO_2.

Once in captivity, CO_2 had to be transported to places where it could be put to use or into *sequestration* (long-term storage). This component of CCS relied heavily on knowledge that had been built up over many decades in the petroleum and natural gas industries. Petroleum companies had strong demand for CO_2 to inject underground in enhanced-recovery operations; thus many early CCS projects were linked to efforts to boost output from declining petroleum fields. For example, the Weyburn Project, which the DOE supported in cooperation with the governments of Canada, Japan, and the European Union, piped CO_2 from the

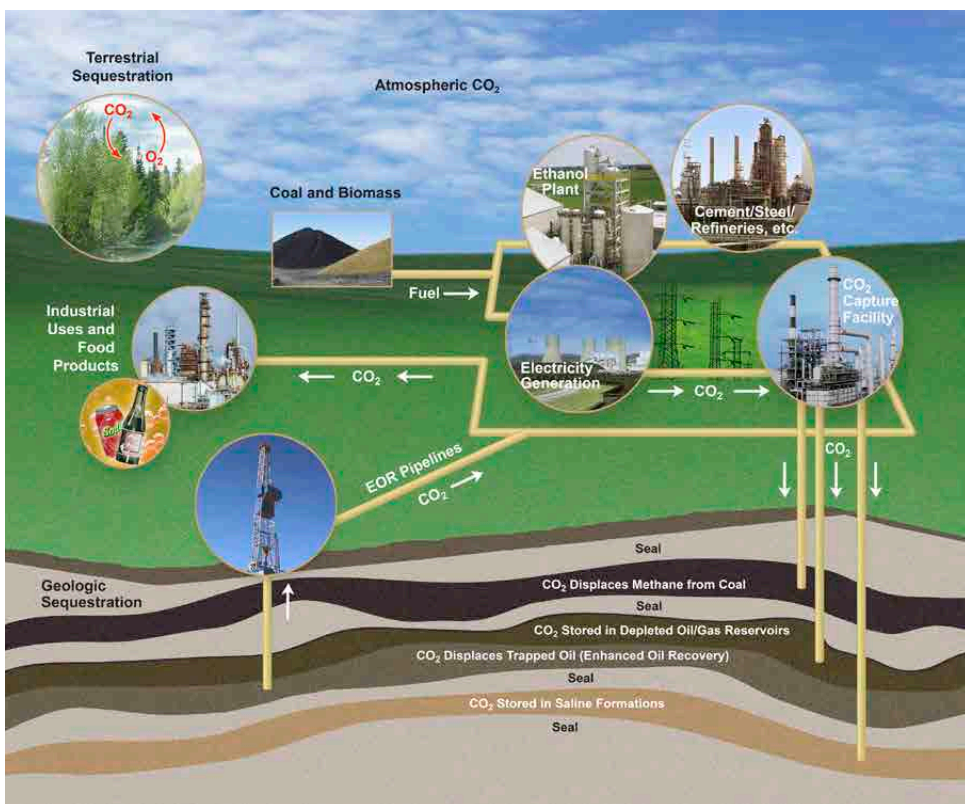


Illustration of various carbon sequestration processes.

Great Plains Gasification Plant at Beulah, North Dakota, for over 200 miles across the Williston Basin to a petroleum field near Weyburn, Saskatchewan. There, the gas increased the underground pressure in the field, forcing petroleum to the surface and extending the field's useful life by an estimated 20 years.

Similar possibilities for combining carbon sequestration with energy recovery existed in coal seams that were not suitable for mining. Injections of CO_2 into a coal seam could drive out usable coalbed methane. Since the CO_2 tended to bond with the surface of the coal even more strongly than the displaced methane had, the seam could then become a permanent CO_2 storage reservoir. NETL cosponsored the first coalbed sequestration field test in 2009 at a site in northern West Virginia.

NETL cosponsored the first coalbed sequestration field test in 2009 at a site in northern West Virginia.

Researchers at NETL studied other types of geological settings to determine if they were appropriate for CO_2 sequestration. Underground brine formations, in which salty water lay trapped in sandstone beneath harder rock, were good prospects. NETL managed the first U.S. field test of this concept: the Frio Brine Project near Dayton, Texas, which had begun in 2004 and was expanded in 2006. In this collaboration among several federal agencies and the University of Texas at Austin, CO_2 was pumped into a mile-deep test well that extended into the brine. Scientists collected abundant data on the effects of these injections, particularly on how the CO_2 moved through the Frio Formation. Other experiments assessed shale formations, basalt formations, and even the depths of the ocean as potential repositories for CO_2.

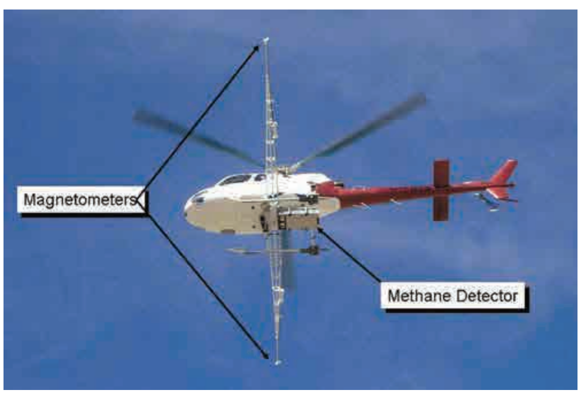
But was carbon sequestration safe? There was plenty of concern that sequestered CO_2 might not stay locked below ground, but rather would percolate back out into the atmosphere eventually, perhaps contaminating groundwater along the way. Much of NETL's research related to this key issue. Using computational science, investigators constructed computer models to simulate the long-term behavior of CO_2 in storage reservoirs. The SEQURE Well Finding Technology, developed at NETL in cooperation with private firms, used airborne sensors to detect leaking wells that could make a proposed CO_2-sequestration site unfit for development or compromise a site that was in use. Monitoring, Verifying, and Accounting projects led to procedures for continuous monitoring of CO_2 storage reservoirs, with the goal of ensuring that 99 percent of the CO_2 that went into underground sequestration remained there.

Terrestrial sequestration, otherwise known as living plants and microbes that naturally absorbed CO_2, was another alternative. Planting trees, restoring wetlands, and keeping grasslands free from cultivation proved to be effective means of CO_2 control as well as for conserving ecological diversity and enriching human communities. NETL managed projects that quantified the benefits of actions such as speeding up the reclamation of formerly strip-mined lands so that the soils and plants there could take up more CO_2.

To demonstrate that the multiple components of CCS could fit together and work in real life, the DOE, acting through NETL, created seven Regional Carbon Sequestration Partnerships. Established in 2003 through a competitive solicitation, these partnerships revived an insight that had guided generations of energy researchers: Understanding of particular local and regional conditions was essential in developing the nation's energy resources. Each partnership covered several states in whole or in part, with some Native American tribes and Canadian provinces also participating. Each comprised an alliance of businesses, universities, state and local government agencies, and nongovernmental organizations. The task of the partnerships was to assess the need for, and potential sites for, CCS within their particular geographical areas and develop plans for cost-effective CCS solutions that could win and sustain local public support.

To demonstrate that the multiple components of CCS could fit together and work in real life, the DOE created seven Regional Carbon Sequestration Partnerships.

The partnerships followed a three-step process. During their first two years, they identified major sources of CO_2 emissions in their regions and pinpointed locations for possible CO_2 sequestration. In Phase II, lasting from 2005 to 2008, they began small-scale field tests to determine whether the suggested sites were feasible. Phase III, scheduled to last from 2008 to 2017, featured large-scale demonstrations of carbon sequestration. This schedule was adhered to assiduously. By 2005, the partnerships had developed the *Carbon Sequestration Atlas of the United States and Canada* and supplied information to a national database called NATCARB. By the end of the decade, they were hard at work on imaginative field tests and demonstration projects.



SEQURE helicopter with magnetometers.

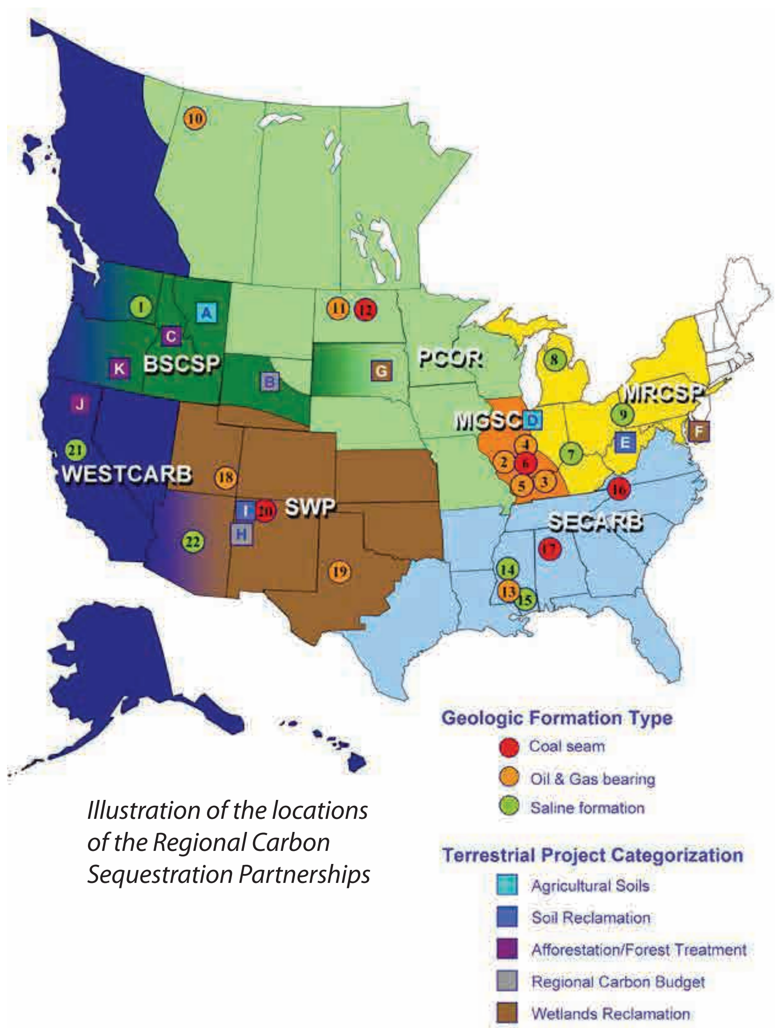


Illustration of the locations of the Regional Carbon Sequestration Partnerships

Stretching from the Mid-Atlantic coast to the Ohio Valley and the Great Lakes, the seven-state Midwest Regional Carbon Sequestration Partnership encompassed the rich Central Appalachian natural resources that had propelled the growth of cities such as Pittsburgh and Morgantown. Its challenge was to find adequate storage for the large amounts of CO_2 generated in the region's many highly urbanized and industrialized areas. Midwest Regional found terrestrial-sequestration opportunities in reclaimed mine sites and in restored wetlands around the Chesapeake Bay, as well as geological-sequestration opportunities in deep brine formations. The largest test site was a deep brine formation that sat amid an aging petroleum and natural gas field near Gaylord in northern Michigan. Due to enhanced petroleum recovery activities, the physical infrastructure for doing CO_2 injections was already in place there, and a nearby natural gas processing plant supplied the CO_2. Tests conducted at the Michigan site during 2008 and 2009 were the largest deep-brine injection experiments yet performed in the U.S.

The Big Sky Carbon Sequestration Partnership covered all or part of six states from the Northern Rockies to eastern Washington and Oregon. Here the principal feature of interest was the region's distinctive deep basalt formations, rocks that were legacies of an active volcanic past. Near Wallula in southeastern Washington, the Basalt Pilot Project began site preparation in 2009 for the first experimental injections of liquefied CO_2 into this type of rock. Scientists believed that the CO_2 would react with the basalt underground to produce harmless calcium carbonate, the main component of limestone. If the tests worked and the calcium-carbonate theory proved to be correct, Big Sky planned to expand the project so that it could sequester up to one million tons of CO_2. The partnership was also working on a large-scale Phase III demonstration that would inject one to three million tons of CO_2 into the Nugget Sandstone Formation on state-owned land in western Wyoming.

Energy-rich areas such as the Green River Formation and the Mid-Continent petroleum and natural gas fields around Bartlesville and Tulsa fell under the Southwest Regional Partnership on Carbon Sequestration. Members of this partnership included nine states and the Navajo Nation. Because the petroleum and natural gas industries were pervasive throughout this region, Southwest Regional focused on using CO_2 injection for enhanced petroleum recovery and storing CO_2 in abandoned petroleum and natural gas reservoirs. A combination of geological and terrestrial sequestration projects took place in the San Juan Basin of New Mexico, where coalbed methane was collected and replaced with CO_2 and the wastewater generated in this process was treated and used for irrigation to promote the growth of vegetation. Looking ahead, Southwest Regional proposed a large-scale sequestration of CO_2 in the Farnham Dome, a deep brine formation in Central Utah.

The biggest carbon sequestration project in the country began in 2009 at Decatur, Illinois, where the Midwest Geological Sequestration Consortium drilled a well into the thick, deep Mount Simon Sandstone. By 2013, the three-state partnership planned to have stored up to one million tons of CO_2 obtained from a local ethanol-manufacturing plant at this site. Other tests had already confirmed that the geology of the Illinois Basin was favorable for sequestering the CO_2 produced by the region's numerous industries and coal-burning power plants.

The biggest carbon sequestration project in the country began in 2009 at Decatur, Illinois.

Knowledge obtained from the Carbon Sequestration Program had value not only to Americans but also to citizens of other countries. Because climate change was a global problem for which political leaders were increasingly seeking global solutions, NETL was active in the Carbon Sequestration Leadership Forum (CSLF). Composed of 23 member countries and the European Commission, the CSLF was a vehicle for sharing technological advances and organizing collaborative research ventures across political boundaries. CCS innovations that had begun at NETL-sponsored projects in the U.S. found their way to far-flung sites such as the Otway Project for storing CO_2 in Australian natural gas fields and the Geologic CO_2 Storage Assurance Project to monitor the safety of CO_2 sequestration at In Salah, Algeria. The CSLF exemplified the international nature of energy research in the twenty-first century.

On August 14, 2008, NETL dedicated its newest building: the Technology Support Facility at its Morgantown site. This structure exemplified the environmentally conscious "green building" revolution in architecture and provided an outward expression of NETL's mission and vision. Every step of its construction, from excavation to physical infrastructure to interior paints and furnishings, was carefully planned to limit waste and minimize energy use. Whenever possible, structural components were made from recycled materials—including cement that incorporated coal-utilization byproducts. A rooftop garden, a heat-recovery system, and a network of sensors to monitor and control the building's energy-efficient lights reduced the need for artificial heating and cooling. The green building attested NETL's commitment to conservation and energy innovation. The dedication of the Technology Support Facility celebrated not only the next-generation structure, but also, in the words of the *2008 NETL Accomplishments* annual report, "the Laboratory's enduring commitment to our Nation's energy future."

The beginning of the new decade brought a change in leadership for NETL. Carl Bauer announced his retirement in December 2009, and Anthony Cugini, who had served as acting director since January 2010, officially took the helm in April of that year. Dr. Cugini brought a wealth of expertise to this post: B.S., M.S., and Ph.D. degrees in chemical engineering from the University of Pittsburgh and a 23-year career at NETL. During his tenure at the lab, Dr. Cugini had overseen the Office of Research and Development, created and directed the lab's Computational and Basic Sciences focus area, and served as division director for the Fuels and Process Chemistry Division. Prior to joining the federal government, he worked in the private sector at Gulf Oil Corporation and Procter and Gamble. Dr. Cugini entered the NETL directorship with a demonstrated breadth of energy and research expertise and a sound understanding of the laboratory's mission and its research and program management capabilities. Dr. Cugini was well prepared to lead NETL into the future.

Conclusion

The path that led from the founding of the Bureau of Mines in 1910 to NETL's 100-year anniversary on May 16, 2010, was a purposeful, industrious, and rewarding one. From its initial focus on improving mine safety, the organization evolved into a comprehensive laboratory dedicated to developing the resources and capabilities necessary to ensure the energy security and environmental sustainability of the United States. Along this journey, energy scientists pioneered breakthroughs that built the foundation for ambitious research and energy solutions. Discoveries along the way—from the mine blast to the dedication of the "green building"—all served to guide research pathways and technology successes. NETL and its predecessors garnered expertise in a broad range of energy research: coal, petroleum, natural gas, electricity, and the materials needed to enable these technologies, all fell under its purview.

In the early twenty-first century, NETL applied its technical skills and project management knowledge to support advanced research, development, and demonstration projects for the next wave: renewable energy sources such as solar, wind, and biomass. NETL set its sights to achieve, in the foreseeable future, sustainable energy that left no environmental footprint. To power the interim, researchers pursued dynamic pathways of fossil and other traditional fuel sources that could seamlessly deliver energy users into tomorrow's renewable supply. NETL's research was compelled by the compound challenges

Officials at the dedication of the Morgantown Technology Support Facility in 2008. L-R: Congressman Alan Mollohan, Senator Robert Byrd, NETL Director Carl Bauer, and Acting Assistant Secretary for Fossil Energy, James Slutz of propelling economic recovery, reducing greenhouse gas emissions, and enhancing the use of domestic energy resources.

Just as the Bureau of Mines' research goals had expanded beyond mine safety, NETL's research had latitude beyond the U.S. borders and encompassed international efforts as well. Concerns about carbon emissions were prevalent and emphasized the need for global cooperation. NETL's expertise—backed by 100 years of innovation and discovery—was an important player in developing and planning energy systems that would provide abundant, affordable, environmentally sustainable energy to ensure not only America's continued prosperity but those of developing nations as well.

These challenges were formidable, as were the challenges faced by the founders of the Bureau of Mines a century before. The love of invention, persistence in the face of adversity, and determination to engage difficult problems that have always driven scientists and engineers continued to motivate the staff of the National Energy Technology Laboratory in 2010. Under skilled and vigorous leadership, NETL entered its second century with the same high spirits and expectations that the founders of the Bureau of Mines had demonstrated at its humble beginnings in July 1910, only 100 short years ago. Then, the Bureau of Mines had the modest motto of "Safety First." After a century of dedicated research, field work, and invention, NETL was known at its centennial as "the ENERGY Lab—Where Energy Challenges Converge and Energy Solutions Emerge."

The Morgantown Technology Support Facility in 2010.

Illustration Credits

Chapter One

Page	Description of Illustration	Credit
2	Men in front of Bruceton mine entrance	National Institute of Occupational Safety and Health
4	View of mine fire gallery at Arsenal	National Archives and Records Administration, Still Pictures, 70-G-3H-11.096-3933
4	Entrance to mine fire gallery at Arsenal	National Archives and Records Administration, Still Pictures, 70-G-3H-11.096-3781
9	Opening of Arsenal Station	National Archives and Records Administration, Still Pictures, 70-G-M-00.102-297
10	First National Mine Safety Demonstration	National Institute of Occupational Safety and Health
10	Mine rescue train car	National Energy Technology Laboratory
10	Mine rescue workers	National Energy Technology Laboratory
16	Pittsburgh station under construction	National Archives and Records Administration, Still Pictures, 70-G-D-00.0132-8430
16	Layout of buildings at Pittsburgh station, 1917	National Energy Technology Laboratory
17	Entrance to main building at Pittsburgh station	National Energy Technology Laboratory
17	Dedication ceremony at Pittsburgh, 1919	National Archives and Records Administration, Still Pictures, 70-G-I-00.055-13029
18	Portrait of Joseph Austin Holmes	National Energy Technology Laboratory
18	Signature of Joseph Austin Holmes	National Energy Technology Laboratory
21	Holmes Safety Association logo	Joseph A. Holmes Safety Association

Chapter Two

Page	Description of Illustration	Credit
24	Bartlesville in 1906	National Energy Technology Laboratory
28	Fire in Oklahoma City oil field	National Energy Technology Laboratory
30	Superintendent J. O. Lewis	National Energy Technology Laboratory
32	Original Bureau of Mines building at Bartlesville	National Energy Technology Laboratory
32	Experimental refinery at Bartlesville, 1919	National Energy Technology Laboratory
33	Peg model of oil field	National Energy Technology Laboratory
34	Superintendent N. A. C. Smith	National Energy Technology Laboratory
38	L. G. Marsh in physical laboratory	National Energy Technology Laboratory
38	Model A Ford lowering bottom-hole sampler into well	National Energy Technology Laboratory
41	Dedication of new building at Bartlesville, 1937	National Energy Technology Laboratory

41	New building at Bartlesville, 1937	National Energy Technology Laboratory
41	Display of waterflooding process	National Energy Technology Laboratory
Chapter Three		
Page	**Description of Illustration**	**Credit**
46	Wall Street after the September 1920 bombing	© Bettman/Corbis Images
48	Directors Manning and Cottrell	National Archives and Records Administration, Still Pictures, 70-G-I-00.055-13096
51	Commerce Department Committee	Library of Congress, Prints and Photographs Division, LC-DIG-npcc-14079
51	Director Turner with George S. Rice	National Archives and Records Administration, Still Pictures, 70-G-M-00.102-41500
54	Testing flammability limits of gases	National Archives and Records Administration, Still Pictures, 70-G-52-11.0921-30130
54	High-speed photography of an explosion	Bureau of Mines document, publication information unknown
54	Rock-dusted coal mine	National Archives and Records Administration, Still Pictures, 70-G-3C-11.09112-4841
57	Natural-gas pipeline under construction	National Archives and Records Administration, Still Pictures, 70-G-76-23.011-19885
58	Diagram of the odorimeter	Bureau of Mines, Warning Agents for Fuel Gases (1931), Figure 2
58	Volunteers using the odorimeter	National Archives and Records Administration, Still Pictures, 70-G-LL-00.052-32258
62	Brockway test truck for carbon-monoxide experiments	National Archives and Records Administration, Still Pictures, 70-G-NN-00.096-14092
62	Toxicity tests at Yale University	National Archives and Records Administration, Still Pictures, 70-G-NN-00.096-15213
64	Diagram of Bruceton test tunnel	Bureau of Mines, Ventilation of Vehicular Tunnels (1927), Figure 36
64	Cars underground at Bruceton	National Archives and Records Administration, Still Pictures, 70-G-NN-00.009611-18379
67	Smoke at railroad tunnel	National Archives and Records Administration, Still Pictures, 70-G-S-00.1161-12784
Chapter Four		
Page	**Description of Illustration**	**Credit**
70	Distillation unit for synthetic gasoline at Pittsburgh	National Archives and Records Administration, Still Pictures, 70-G-59-12.08-52744
75	Prospecting for oil shale in Colorado	National Archives and Records Administration, Still Pictures, 70-G-64-21.024-20701

150	Senator Joseph C. O'Mahoney at Laramie	National Archives and Records Administration, Still Pictures, 70-G-73-22.0613-61571
150	Representative Jennings Randolph	Library of Congress, Prints and Photographs Division, LC-DIG-hec-27120
151	Diagram of Fischer-Tropsch process	National Energy Technology Laboratory
154	WVU Mineral Industries Building	National Energy Technology Laboratory
155	George Strimbeck and Colt Pears at Morgantown	National Energy Technology Laboratory
157	Exterior view of Beechurst Avenue pilot plant	National Energy Technology Laboratory
157	Gas purification plant under construction	National Energy Technology Laboratory
157	Interior view of Beechurst Avenue plant with gasifier	National Energy Technology Laboratory
161	Blackboard diagram of underground coal gasification	National Energy Technology Laboratory
161	Dropping incendiary in shaft at Gorgas	National Archives and Records Administration, Still Pictures, 70-G-58-12.024-65688
161	Smoke and gas emerging from shaft at Gorgas	National Archives and Records Administration, Still Pictures, 70-G-58-12.024-66003
161	Gas flare by night	National Energy Technology Laboratory
165	Representative Harley Staggers at Morgantown	National Archives and Records Administration, Still Pictures, 70-G-08-00.102-H77998P
166	Panorama of Collins Ferry Road site	National Energy Technology Laboratory
167	Pressure gasifier at Collins Ferry Road	National Energy Technology Laboratory
167	Portrait of Sam Taylor	National Energy Technology Laboratory
168	Dedication of Morgantown station, 1955	National Energy Technology Laboratory
Chapter Eight		
Page	**Description of Illustration**	**Credit**
170	Fischer-Tropsch pilot plant at Bruceton, 1953	National Energy Technology Laboratory
173	Aerial view of Bruceton	National Energy Technology Laboratory
173	Cafeteria at Bruceton	National Energy Technology Laboratory
174	Bruceton dedication ceremony, 1948	National Energy Technology Laboratory
175	Liquid-phase hydrogenation equipment at Bruceton	National Energy Technology Laboratory
175	First internally cooled Fischer-Tropsch reactor at Pittsburgh	National Archives and Records Administration, Still Pictures, 70-G-59-12.0812-64881
177	Group award at Bruceton	National Archives and Records Administration, Still Pictures, 70-G-08-00.102-H85729P
178	Catalyst testing unit at Bruceton	National Energy Technology Laboratory

178	Steel lathe turnings used as catalyst	National Archives and Records Administration, Still Pictures, 70-G-74-22.0621-H87631P
179	Countercurrent distribution apparatus	National Energy Technology Laboratory
180	Laramie station	Bureau of Mines Report of Investigations 5506 (1959), Figure 4
182	Shale-oil processing equipment at Laramie	National Archives and Records Administration, Still Pictures, 70-G-75-22.0633-H79625P
184	Underground Quarry at Anvil Points	National Archives and Records Administration, Still Pictures, 70-G-75-22.0632-73588
187	Anvil Points gas combustion retort	National Archives and Records Administration, Still Pictures, 70-G-73-22.0612-H82682P
187	Loading shale gasoline	National Archives and Records Administration, Still Pictures, 70-G-73-22.0612-H78856P
188	Aerial view of Missouri Ordnance Works	National Archives and Records Administration, Still Pictures, 70-G-73-22.0614-H79182P
190	Converter stalls at Missouri coal hydrogenation plant	National Archives and Records Administration, Still Pictures, 70-G-73-22.0614-70813
191	First carload of synthetic diesel oil	National Archives and Records Administration, Still Pictures, 70-G-75-22.0634-71971
192	Fischer-Tropsch demonstration plant at Missouri	National Archives and Records Administration, Still Pictures, 70-G-75-22.0614-77227
197	Overview of oil shale plant at Anvil Points	National Archives and Records Administration, Still Pictures, 70-G-73-22.0612-H82228P
198	Henry H. Storch	National Archives and Records Administration, Still Pictures, 70-G-07-00.101-77194
199	Friedel receiving Storch Award	National Archives and Records Administration, Still Pictures, 70-G-07-00.101-H93424P
Chapter Nine		
Page	**Description of Illustration**	**Credit**
202	Radiation Instrument Laboratory at Bartlesville	National Archives and Records Administration, Still Pictures, 70-G-69-21.0911-H90637P
204	Marling J. Ankeny	National Archives and Records Administration, Still Pictures, 70-G-07-00.101-H84340P
205	Bureau of Mines mainframe computer	Bureau of Mines Annual Progress Report (1969)
207	Mule at Experimental Mine	National Archives and Records Administration, Still Pictures, 70-G-49-11.091-H80020P
209	Diesel engine exiting Experimental Mine	National Archives and Records Administration, Still Pictures, 70-G-52-11.0913-H82412P
209	Photographing ignition and flame	National Archives and Records Administration, Still Pictures, 70-G-09-00.113-H90563P
209	High-vacuum testing of explosives	Bureau of Mines Annual Progress Report (1969)

210	Instructional materials on mine safety	Bureau of Mines Annual Progress Report (1971)
211	Measuring gas flow for methane drainage	Bureau of Mines Annual Progress Report (1971)
211	Roof bolting at coal mine entry	National Energy Technology Laboratory
213	Reclaiming surface mine with power-plant fly ash	Bureau of Mines Annual Progress Report (1972)
213	Washing pyrite from coal	National Archives and Records Administration, Still Pictures, 70-G-58-12.032-H95797P
214	Alkalized alumina pilot plant	National Archives and Records Administration, Still Pictures, 70-G-73-22.0611-H93896P
214	Process Evaluation Group at Morgantown	National Energy Technology Laboratory
217	John S. Berber with low-temperature tar products	National Energy Technology Laboratory
217	James Paul McGee	National Energy Technology Laboratory
217	Modified Lurgi gasifier at Morgantown	Bureau of Mines Annual Progress Report (1971)
219	Closeup of coal-burning gas turbine	National Energy Technology Laboratory
219	Overview of turbine installation at Morgantown	National Energy Technology Laboratory
221	Fluidized-bed Fischer-Tropsch plant at Bruceton	National Energy Technology Laboratory
222	Field study with low-level radioactive tracers	National Energy Technology Laboratory
224	Derrick for Project Gasbuggy	National Energy Technology Laboratory
225	Bartlesville 50th anniversary seal	National Energy Technology Laboratory
226	In situ oil shale retorting at Rock Springs	Bureau of Mines Annual Progress Report (1969)
226	Large block of spent oil shale	Bureau of Mines Annual Progress Report (1967)
229	Smog chamber at Bartlesville	National Energy Technology Laboratory
229	Engine being tested for pollutants	National Energy Technology Laboratory
231	Engineering and Physical Sciences Building at Bartlesville	National Energy Technology Laboratory
233	Metal bomb reduction reactor	National Energy Technology Laboratory
233	Molybdenum mass by metal bomb reduction	National Energy Technology Laboratory
234	First molybdenum casting	National Energy Technology Laboratory
235	Hands holding yttrium sponge and buttons	National Energy Technology Laboratory
235	Samples of ductile chromium	National Energy Technology Laboratory
236	Manipulating rods in Albany hot cell	National Energy Technology Laboratory
236	Cask with Cobalt 60 rods at Albany	National Energy Technology Laboratory
240	Women sniffing diesel fumes	National Energy Technology Laboratory
242	Patricia Estep and lunar materials team	National Energy Technology Laboratory

Chapter Ten		
Page	**Description of Illustration**	**Credit**
246	ERDA sign at Morgantown	National Energy Technology Laboratory
248	Farmington mine disaster, 1968	Mine Safety and Health Administration, United States Department of Labor
252	Closed gasoline station	©Bettman/Corbis Images
253	President Ford signing Energy Reorganization Act	United States Department of Energy
255	ERDA seal	National Energy Technology Laboratory
257	Schematic of micellar-polymer flooding	National Energy Technology Laboratory
258	Schematic of fireflooding	National Energy Technology Laboratory
259	Schematic of alkaline chemical flooding	National Energy Technology Laboratory
263	Diagram of vertical borehole	Bureau of Mines Bulletin 687 (1988), Figure 7-1
263	Diagram of directional drilling	Bureau of Mines Bulletin 687 (1988), Figure 10-2
265	Underground coal gasification at Hanna, Wyoming	United States Department of Energy
266	Underground coal gasification in West Virginia	National Energy Technology Laboratory
269	Exterior view of Rivesville Power Station	National Energy Technology Laboratory
271	Fluidized-bed boiler at Rivesville	National Energy Technology Laboratory
271	Morgantown coal gasifier by night	National Energy Technology Laboratory
271	Installing experimental GE combustors	National Energy Technology Laboratory
273	Synthane plant under construction at Bruceton	National Energy Technology Laboratory
Chapter Eleven		
Page	**Description of Illustration**	**Credit**
278	PETC Bruceton overview	United States Department of Energy
280	President Carter signing DOE organization act	United States Department of Energy
281	Changing the name at Morgantown	National Energy Technology Laboratory
283	Line at gasoline station, 1979	United States Department of Energy
285	Bill Steele with rotating bomb calorimeter	National Energy Technology Laboratory
285	NIPER sign at Bartlesville station	National Energy Technology Laboratory
287	NIPER Core Analysis Lab	National Energy Technology Laboratory
287	Daryl Doughty in nuclear magnetic resonance lab	National Energy Technology Laboratory
287	NIPER Reservoir Characterization Group	National Energy Technology Laboratory
287	NIPER petrographic analyzer	National Energy Technology Laboratory
288	Diagram of microbial flooding	National Energy Technology Laboratory

289	Ron Grigsby in mass spectrometry lab	National Energy Technology Laboratory
289	Rebecca Bryant studying microbes	National Energy Technology Laboratory
291	Cutaway of Rocky Mountain 1 site	United States Department of Energy
294	Devonian shales map	United States Department of Energy, Energy Information Administration
294	Diagram of horizontal drilling	United States Department of Energy, Energy Information Administration
295	Computer model of natural gas	National Energy Technology Laboratory
295	Multi-Well Experiment site	United States Department of Energy
297	PETC Coal Preparation Laboratory	National Energy Technology Laboratory
297	Coal cleaning at PETC	National Energy Technology Laboratory
298	Coal combustor at PETC	National Energy Technology Laboratory
300	IGCC diagram	National Energy Technology Laboratory
302	Hot gas cleanup at Morgantown	National Energy Technology Laboratory
302	Great Plains Gasification Plant	United States Department of Energy
304	Valve testing facility at Morgantown	National Energy Technology Laboratory
304	ASPEN diagram of METC reactor	National Energy Technology Laboratory
305	System for evaluating catalysts at PETC	National Energy Technology Laboratory
309	Edgewater Plant	National Energy Technology Laboratory
309	Coolside process	National Energy Technology Laboratory
309	Tidd fluidized-bed combustion project	National Energy Technology Laboratory
309	Wabash River Generating Station	National Energy Technology Laboratory
309	Polk Power Station	National Energy Technology Laboratory
310	Oil from wood waste plant	National Energy Technology Laboratory
Chapter Twelve		
Page	**Description of Illustration**	**Credit**
320	Portrait of Rita Bajura	National Energy Technology Laboratory
321	FETC logo	National Energy Technology Laboratory
323	Vision 21 concept	National Energy Technology Laboratory
324	Liquid-phase methanol plant at Kingsport, Tennessee	National Energy Technology Laboratory
326	Panorama of JEA Northside Generating Station	National Energy Technology Laboratory
327	2002 Powerplant Award	National Energy Technology Laboratory
329	Methane hydrates	National Energy Technology Laboratory
329	Westinghouse advanced gas turbine	National Energy Technology Laboratory
333	Alaska Energy Office of NETL	National Energy Technology Laboratory
333	Portrait of Carl Bauer	National Energy Technology Laboratory
335	MFIX schematic	National Energy Technology Laboratory

335	MFIX scientists	National Energy Technology Laboratory
336	APECS software	National Energy Technology Laboratory
337	Thief Process for mercury control	National Energy Technology Laboratory
338	Illustration of Baldwin Energy Complex	National Energy Technology Laboratory
339	TOXECON at Presque Isle Power Plant	National Energy Technology Laboratory
340	Ion transport membrane	National Energy Technology Laboratory
341	RVS-1 sulfur sorbent	National Energy Technology Laboratory
342	SECA collage	National Energy Technology Laboratory
342	Phipps Conservatory fuel cell	National Energy Technology Laboratory
343	Artist's conception of FutureGen	National Energy Technology Laboratory
344	Illustration of modern grid	National Energy Technology Laboratory
345	Two refractory bricks from Albany	National Energy Technology Laboratory
346	Armor plating for tanks	National Energy Technology Laboratory
348	Schematic of carbon sequestration	National Energy Technology Laboratory
350	SEQURE helicopter with magnetometers	National Energy Technology Laboratory
350	Regional carbon sequestration partner-ships	National Energy Technology Laboratory
353	Dedication of Technology Facility, 2008	National Energy Technology Laboratory
354	Technology Support Facility at Morgan-town	National Energy Technology Laboratory
345	NETL logo	National Energy Technology Laboratory

National Energy Technology Laboratory

1450 Queen Avenue SW
Albany, OR 97321-2198
541-967-5892

2175 Unversity Avenue South
Suite 201
Fairbanks, AK 99709
907-452-2559

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
304-285-4764

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940
412-386-4687

13131 Dairy Ashford, Suite 225
Sugar Land, TX 77478
281-494-2516

Visit the NETL website at:
www.netl.doe.gov

Customer Service:
1-800-553-7681

Printed in the United States on recycled paper
October 2010