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MOLTEN-SALT REACTOR EXPERIMENT

Front cover: Lithium-uranium fluoride salt crystals magnified approximately 160 times. Above, the MSRE building houses the reactor and offices for operating personnel. Back cover, the reactor vessel, fuel pump and heat exchanger in containment cell.

OAK RIDGE
NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

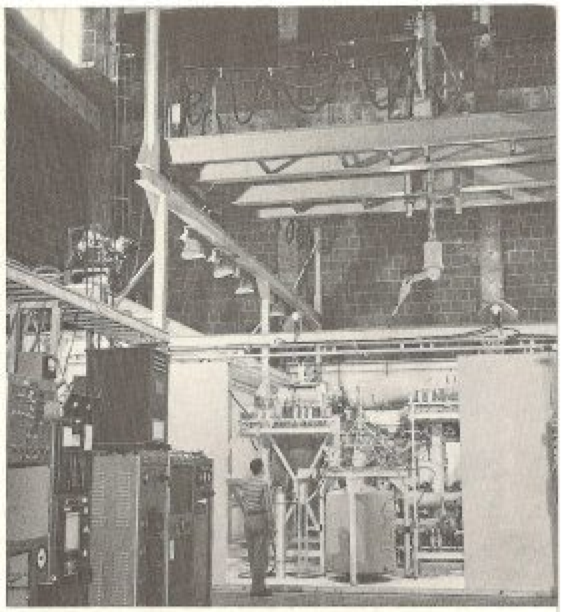
A LIQUID FUEL REACTOR

Molten-salt reactors are liquid fuel reactors that use solutions of uranium and thorium fluorides in lithium and beryllium fluorides as fuels. They operate at high temperature and low pressure and have excellent nuclear characteristics. They offer promise as breeders of fissionable material and as producers of low cost electricity in large central power stations.

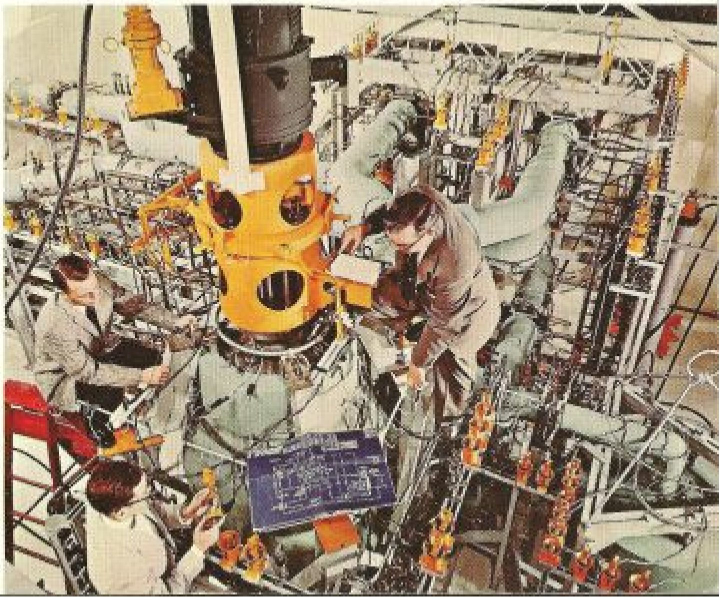
The Molten-Salt Reactor Experiment (MSRE) is being conducted by Oak Ridge National Laboratory to demonstrate that the desirable features of the molten-salt concept could be embodied in a practical reactor which could be constructed, operated and maintained with safety and reliability. Additional objectives are to provide the first large-scale, long-term, high-temperature tests in a reactor environment of the fuel salt, graphite moderator and the high-nickel-base alloy Hastelloy N. Operating data from the MSRE should provide important information regarding the feasibility of large-scale molten-salt reactors.

Molten-salt reactors were first investigated as a means of providing a compact, high-temperature power plant for nuclear powered aircraft. In 1954, an Aircraft Reactor Experiment (ARE) was conducted at ORNL which demonstrated the nuclear feasibility of operating a molten-salt-fueled reactor at high temperature. Fuel entered the ARE core at 1200° F and left at 1500° F when the reactor power level was 2.5 megawatts.

Immediately after the successful operation of the ARE, the Aircraft Reactor Test (ART) was started at ORNL as part of the Aircraft Nuclear Propulsion Program (ANP). This test was discontinued in 1957 when the ANP Program was revised, but the high promise of the molten-salt reactor type for achieving low electric power generating costs in central power stations led ORNL to continue parts of the basic study program. The studies resulted in a proposal to the U. S. Atomic Energy Commission for construction of a molten-salt reactor experiment to investigate remaining areas of uncertainty which could be resolved only by actually building and operating a reactor.



The MSRE is the result of a detailed research and development program in a number of engineering and scientific principles. A reactor mock-up was constructed to demonstrate the feasibility of remote maintenance on highly radioactive systems.



The completed reactor vessel above is shown during inspection and before being installed in its containment cell. On page 3, a simplified flow diagram of the reactor's principal components.

FUEL AND COOLANTS CIRCULATE

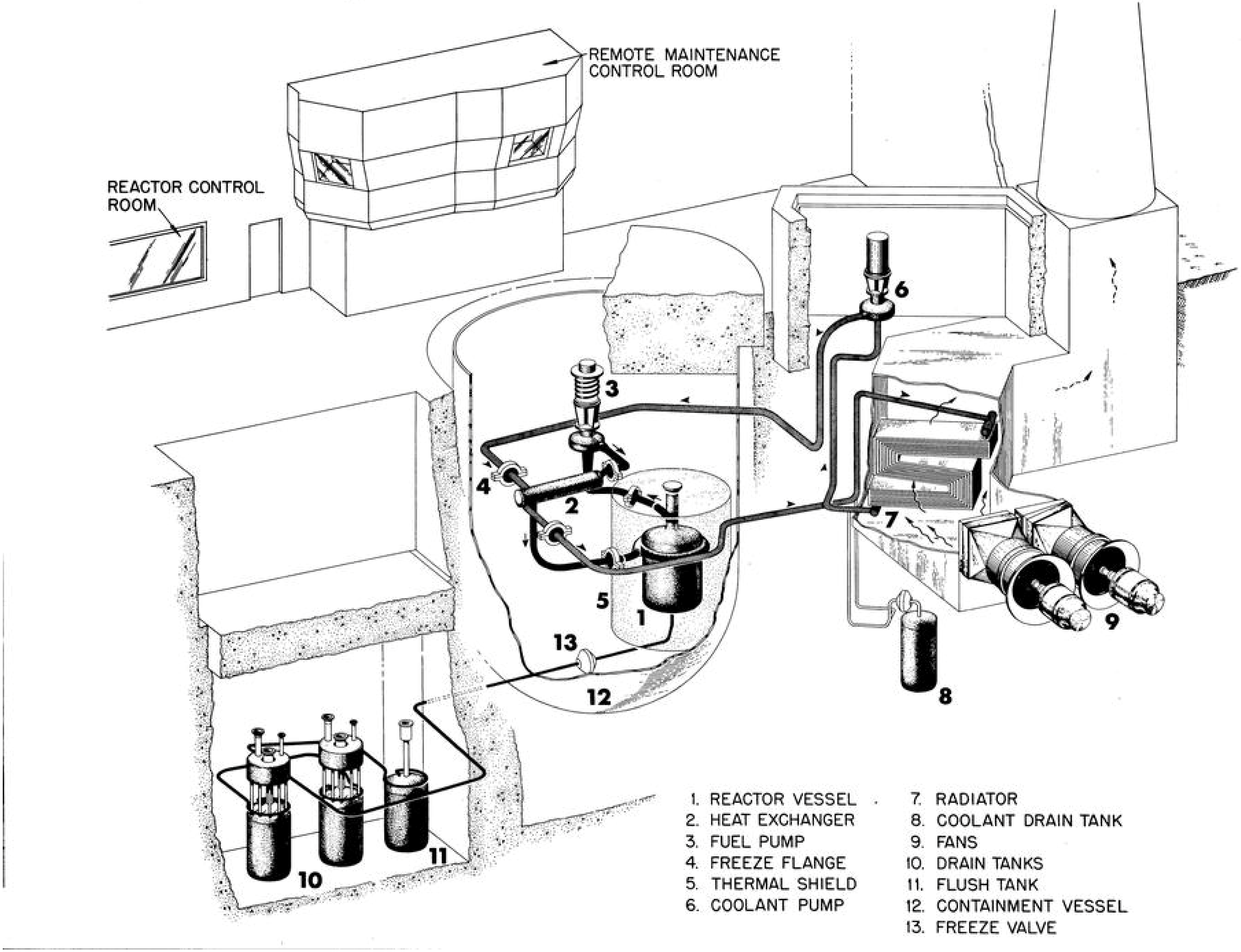
The Molten-Salt Reactor Experiment is a circulating fuel, graphite-moderated, single-region reactor designed for a heat generation rate of 10 megawatts. The fuel employs a molten mixture of lithium, beryllium and zirconium fluoride salts as a solvent for uranium or thorium and uranium fluorides.

The fuel is pumped through 1,140 channels in the graphite core—4-1/2 feet in diameter and 5-1/2 feet high—where fissioning occurs to heat the fuel to 1225° F. The heat is removed from the fuel through an intermediate heat exchanger that uses lithium and beryllium fluorides as the secondary coolant. Since power recovery is not an objective of this experiment, no electric power equipment is utilized. The heat produced by the reactor is released to the atmosphere through an air-cooled radiator.

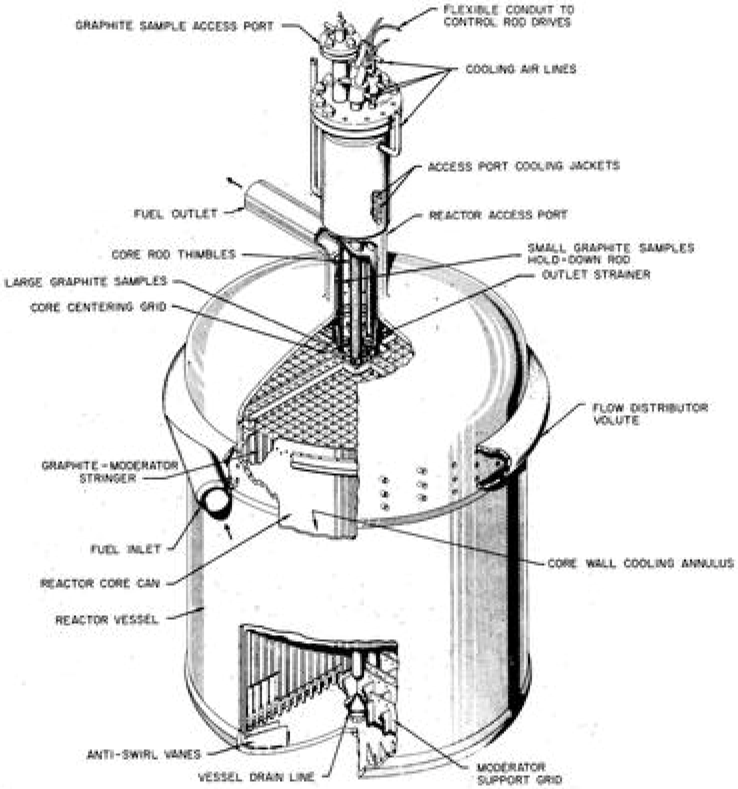
The primary fuel system consists of the reactor vessel which houses the graphite core, a heat exchanger for transfer of heat from fuel salt to coolant salt, a sump-type centrifugal pump for circulating the fuel salt, and connecting piping.

The secondary coolant system consists of a coolant-salt pump, a radiator in which heat is transferred from coolant salt to air, and piping which connects the pump, heat exchanger and radiator.

Both the primary and secondary systems are connected to drain tank systems for storage of the fuel, coolant and flushing salts.



1. REACTOR VESSEL
2. HEAT EXCHANGER
3. FUEL PUMP
4. FREEZE FLANGE
5. THERMAL SHIELD
6. COOLANT PUMP
7. RADIATOR
8. COOLANT DRAIN TANK
9. FANS
10. DRAIN TANKS
11. FLUSH TANK
12. CONTAINMENT VESSEL
13. FREEZE VALVE



This reactor vessel drawing shows the vertical graphite stringers pinned to a base of horizontal graphite bars. The liquid fuel, moderated by the graphite, reaches its critical mass within the vessel to generate 10 megawatts of fission heat.

REACTOR VESSEL

The reactor vessel is 58 inches in diameter and about 94 inches high. It was designed for a pressure of 50 psig at 1300° F. The vessel has two 58-inch inner diameter heads, flanged and dished, one-inch thick. The wall thickness of the cylindrical portion is 9/16-inch, except for the top portion which is one-inch thick. The extra thickness is needed in the upper section to allow for 84 holes, 3/4-inch in diameter, to distribute the incoming salt evenly around the circumference. Salt is delivered to the holes through a flow distributor, half-circular in cross section, with an inside radius of about four inches.

The six-inch diameter inlet to the distributor is arranged tangentially to the vessel. The holes enter the vessel at an angle of 30 degrees to impart a spiralling flow to the salt as it moves downward through a one-inch wide annulus between the reactor vessel wall and the outside of the core. Turbulent flow is promoted in this annulus to improve the cooling of the wall.

The salt then flows into the bottom head which contains 48 swirl-straightening vanes extending radially 11 inches toward the center of the vessel. These vanes are fabricated of 1/8-inch-thick plate. Elimination of the swirl in the bottom head reduces the radial pressure gradient and promotes more even flow distribution through the core.

After passage through the core, the salt flows through the upper head to the 10-inch nozzle opening. It is diverted through a five-inch opening in the nozzle to flow to the fuel circulating pump.

GRAPHITE MODERATOR

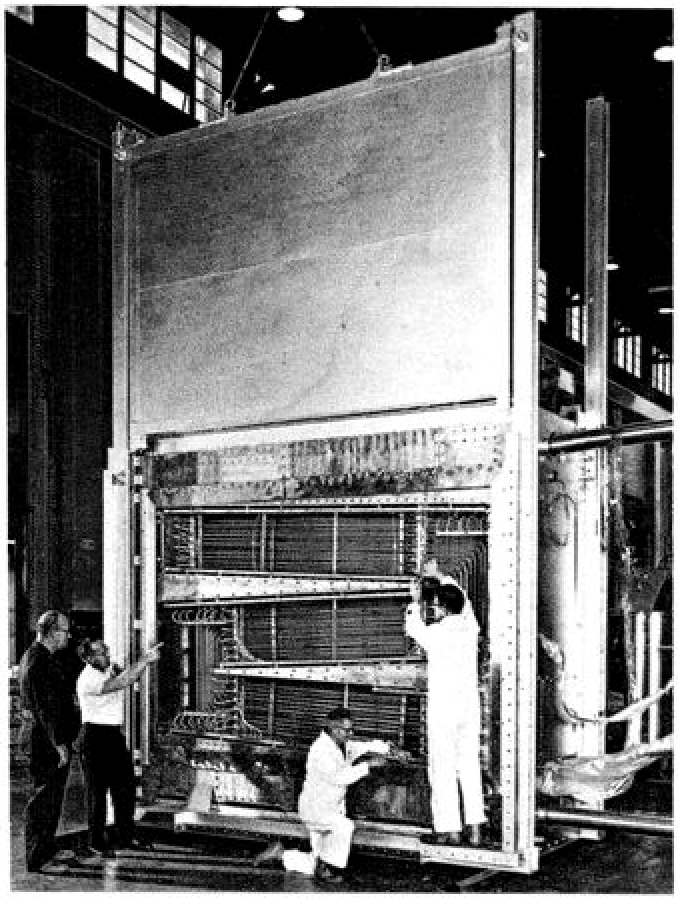
A moderator is desirable in a molten-salt type reactor to achieve good neutron economy and low inventory of fissile material. It is particularly desirable that the moderator be used without cladding to obtain high breeding or conversion ratios. Graphite is compatible with molten salt, thereby making it possible to design the MSRE with a heterogeneous type core, using unclad graphite as the moderator.

The reactor core is formed of 513 graphite core blocks, or stringers, each two inches square and about 67 inches in overall length, mounted in a vertical close-packed array. In addition, there are 104 fractional-sized blocks at the periphery. Half-channels are machined in the four faces of each stringer to form flow passages in the assembly. There are 1,108 full-sized passages. Counting fractional sizes, the equivalent total is 1,140 full-sized passages. The dimensions of these flow channels were chosen to provide a passage which would not be blocked by small pieces of graphite, and to obtain a nearly optimum ratio of fuel to graphite in the core.

The vertical graphite stringers rest on a lattice of graphite blocks laid horizontally in two layers at right angles. The lattice blocks are supported by a grid of 1/2-inch-thick Hastelloy N plates set on edge vertically. This supporting grid is fastened to the bottom of the core can, and moves downward as the can elongates during a temperature rise.

Clearance is provided in the center of the core for inserting three gadolinium oxide control rods and small test samples of graphite or metal. The samples are contained in three baskets which can be withdrawn individually. In addition, full-sized graphite stringers located in the center of the core can be examined in place by periscope. They also can be withdrawn occasionally for hot cell examination by removing the reactor vessel access nozzle plug and control rod thimble assembly.

The reactor core, shown while being assembled, contains 69 cubic feet of graphite. The 1,140 fuel channels contain about 20 cubic feet of molten salt fuel when the reactor is in operation.



The primary heat exchanger (components seen at right) has a heat-transfer area of nearly 259 square feet. Heat is removed from the coolant-salt mixture in the air-blast radiator (above) and is dissipated through a metal stack to the atmosphere.

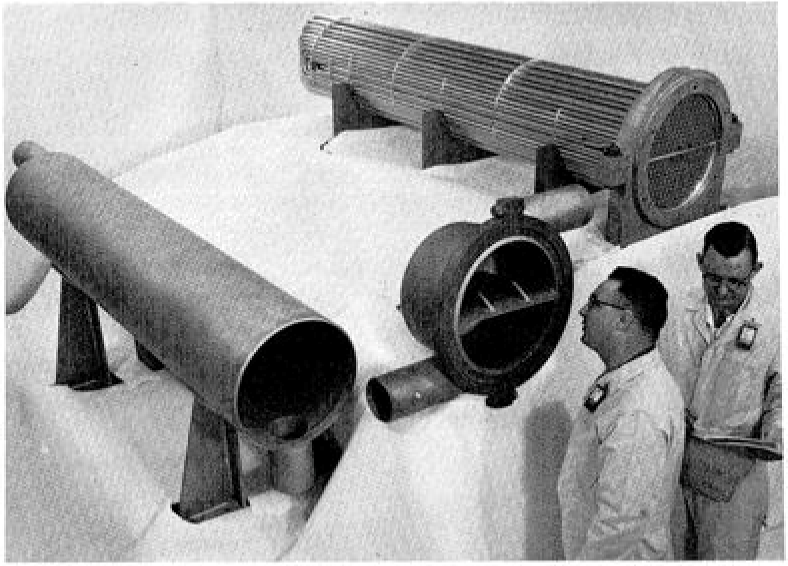
PRIMARY HEAT EXCHANGER

The 10 megawatts of heat generated in the core is transferred from the fuel salt to the coolant salt in the primary heat exchanger. Fuel enters the shell side at 1225° F and leaves at 1175° F. The flow rate is 1,200 gallons a minute. Coolant salt flows through the tube side, entering at 1025° F and leaving at 1100° F. Its flow rate is about 850 gallons a minute.

The primary heat exchanger is about eight feet long and 16 inches in diameter. Its 169 U-tubes—each 14 feet long and a half inch in diameter—form an effective heat transfer area of nearly 259 square feet.

Heat is removed from the coolant salt mixture in an air blast heat exhanger and dissipated through a metal stack to the atmosphere. The coolant flows through tubes 3/4-inch in diameter and 30 feet long. The tubes, formed into an "S," are arranged in 10 banks containing 12 tubes each. Cooling air is supplied by two axial-vane blowers with a combined capacity of 200,000 cubic feet a minute.

Electric heaters inside the radiator provide heat for startup, and keep the salt in a molten state within the tubes when it is not circulating. The temperature of each tube is monitored by thermocuples.

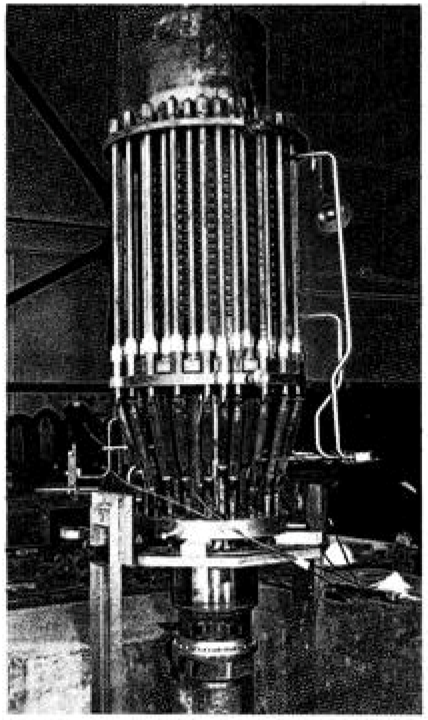


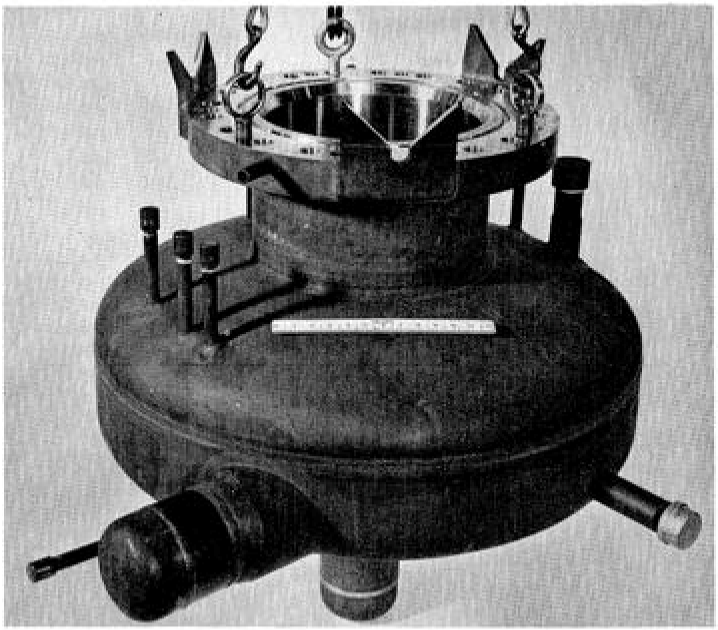
FUEL PUMP

The fuel pump runs at 1,160 revolutions a minute and is driven by a 75 horsepower motor. The pump circulates fuel at a rate of 1,200 gallons a minute, at about a 50-foot head. There is also a bypass flow of 65 gallons a minute inside the pump bowl to facilitate the removal of volatile fission products from the fuel stream. The motor-pump combination is hermetically sealed to prevent the escape of fission gases to the cell. The assembly is 8.6 feet in overall height.

The unit is designed so that the motor and rotary element can be replaced semi-remotely. Procedures and tools have been developed for the remote or semi-remote maintenance or replacement of all reactor components.

The fuel-pump bowl is 36 inches in diameter. It normally holds 5.2 cubic feet of molten salt, and provides for a gas volume of two cubic feet above the salt. The volute is built into the bowl to provide for bypassing a 65-gallon-per-minute spray of fuel to remove the volatile fission products. The gases then are swept to a charcoal trap where fission products are adsorbed. The continuous helium purge flows through a filter to the off-gas stack.





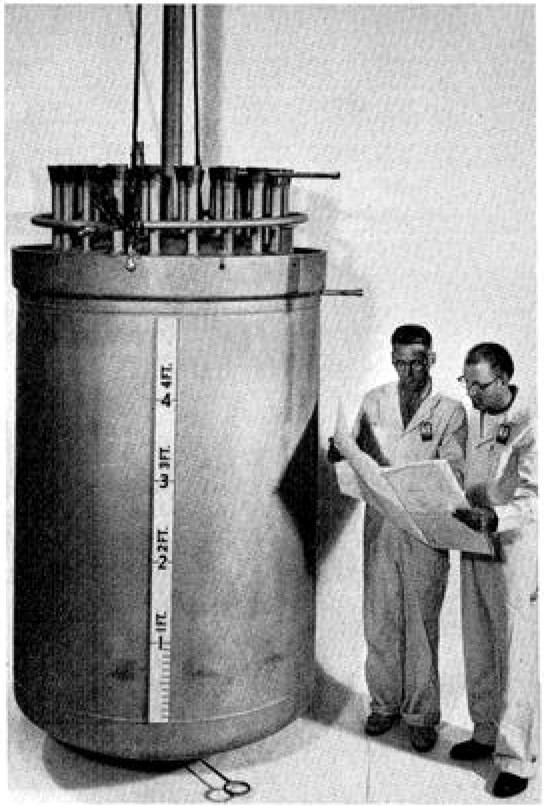
The fuel pump shown above circulates fuel at 1200 gallons per minute. The fuel-pump bowl at left serves both as sump and expansion volume.

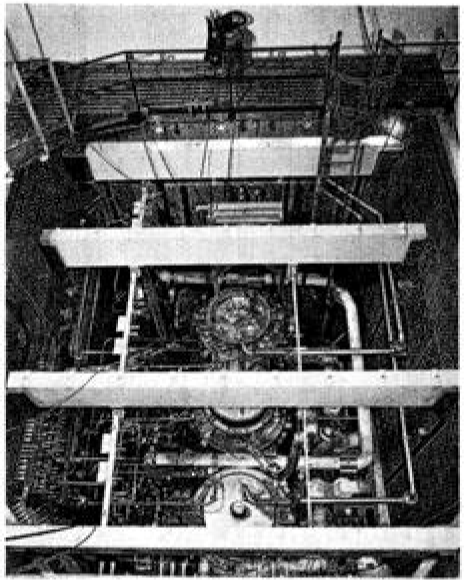
DRAIN TANKS

Four tanks are provided for the safe storage of salt mixtures when they are not in use in the fuel and coolant salt circulating systems. Two fuel-salt drain tanks and a flush-salt tank are connected to the reactor by means of a fill and drain line. One drain tank is provided for the coolant salt.

A fuel drain tank is 50 inches in diameter and 86 inches high. It has a volume of about 80 cubic feet and is sufficient to hold, in a sub-critical geometry, all the salt that can be contained in the fuel circulating system. The tank is provided with a cooling system capable of removing 100 kilowatts of fission product decay heat. The cooling is accomplished by boiling water circulated in 32 bayonet tubes inserted in thimbles in the tank.

The flush-salt tank is similar to the fuel-drain tank, but is 40 inches in diameter, 78 inches high and has a volume of 50 cubic feet.





When the reactor is not operating, the molten-salt fuel is stored in a fuel drain tank (above). Two such tanks are provided, each capable of storing all the fuel in a safe configuration. At left, the drain tanks are shown in their containment cell.

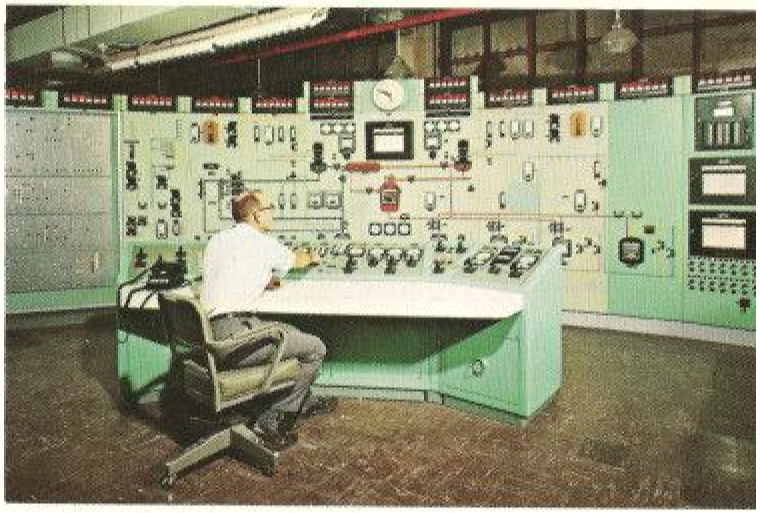
INSTRUMENTS

Maintaining desired temperature ranges is a vital function of the MSRE instrumentation and control system. If the salts drop below 840° F, they will begin to freeze. It is also important that overheating does not occur.

More than a thousand thermocouples are installed throughout the fuel and coolant salt systems. About three-fourths of these serve indication, alarm or control functions. The heating and cooling equipment is controlled to maintain temperatures throughout the system with specified ranges.

Three control rods are used to absorb neutrons produced in the core. Their major function is to eliminate wide temperature variations which otherwise would accompany changes in power and xenon poison level, and to make it possible to hold the reactor sub-critical to a 200–300° F range below the normal operating temperature.

Digital computer and data handling equipment are available to provide rapid compilation and analysis of the process data. This equipment has no control function, but it provides current information about all important variables and warns of abnormal conditions.



Information which is needed immediately by the reactor operator is displayed on the main control panel (above). Auxiliary instruments not requiring constant surveillance are located in other areas. Below, a digital computer and data handling equipment are utilized to provide current information on important variables within the reactor system.

PREPARATION OF FUEL AND COOLANT SALTS

Fully loaded, the MSRE uses 11,260 pounds of a lithium, beryllium, zirconium, uranium fluoride fuel salt mixture. The coolant salt contains 15,300 pounds of lithium and beryllium fluorides.

Fused fluoride mixtures are prepared in two batch processing units from fluoride salts normally purchased from commercial sources. Although the units are operated independently, both are charged with molten raw materials from a single meltdown furnace assembly.

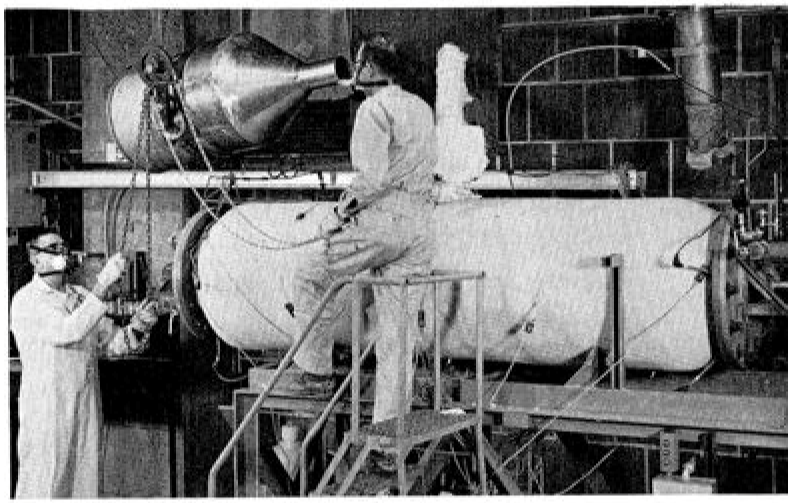
Since the salts are toxic, raw materials are handled by operating personnel in a loading room isolated from other areas of the production plant by shower facilities and air locks. Personnel working in the loading room wear fully-protective, plastic, fresh-air suits to avoid exposure to the chemicals. Raw materials are assembled in this area, weighed into appropriate batch sizes in a well-ventilated hood enclosure, and then transferred to the meltdown furnace by a vibratory conveyer.

A meltdown furnace assembly, joining the raw materials loading room, provides a molten raw-material charge to each of two adjacent batch processing units.

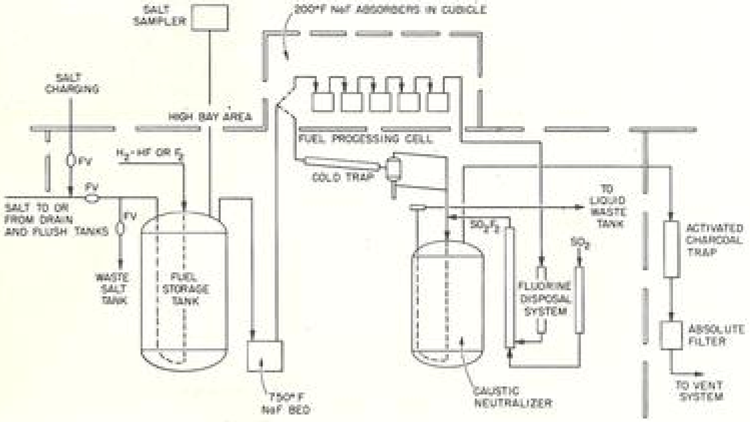
After meltdown, the molten fluoride mixture is sparged with hydrogen and helium at relatively high flow rates to remove insoluble carbon by entrainment. Beryllium metal turnings are added to the molten charge to reduce structural metal impurities to their insoluble metallic states, and to reduce sulfate impurities to sulfides. During subsequent transfer of material to a batch processing unit, some of the insoluble impurities are separated by decantation.

At the completion of the production cycle, the purified fluoride mixture is transferred to the salt storage container and allowed to cool. The containers are shipped to the reactor site, as needed, for re-melting and transfer into the fluoride drain tanks of the MSRE.

Fluoride salts used in the MSRE are displayed (above) in a solid state. From the left are the coolant (lithium-beryllium fluoride), fuel solvent (lithium-beryllium-zirconium fluoride) and fuel concentrate (lithium-uranium fluoride). Below, a horizontal kiln is used in the densification of lithium fluoride.

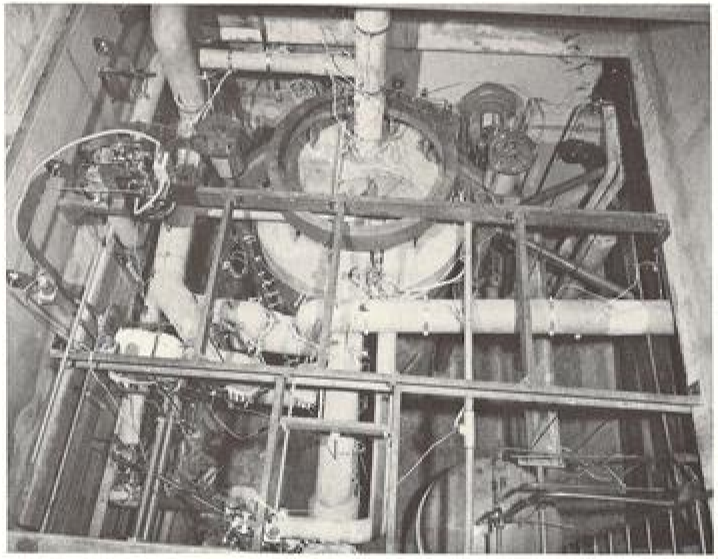


Protective clothing is required in the raw materials handling area of the Fluoride Production Facility (above) to avoid inhalation of the toxic salts. Below, a diagram of the fuel processing system. At right below is the fuel processing containment cell located in the reactor building.



FUEL PROCESSING AT THE REACTOR SITE

MSRE fuel is processed in a facility adjacent to the drain tank cell, and is operated from a separate control board in the high-bay area above the cell. The facility has two functions: the removal of oxide contamination by bubbling hydrogen fluoride gas through the molten-salt, and the recovery of uranium by treating the salt with fluorine gas. It handles 75 cubic foot batches of salt. This is equal to the volume of the blanket salt which would be processed daily in a 1,000 electrical megawatt thermal breeder station operating on an 80-day cycle.



THE POTENTIAL OF THE MOLTEN-SALT CONCEPT

The fuel is fluid at reactor temperatures, thereby eliminating extra costs associated with fabrication, handling and reprocessing of solid fuel elements. Burn-up in the fuel is not limited by radiation damage or reactivity loss. The fuel can be reprocessed continuously in a side stream for removal of fission products, and new fissionable material can be added while the reactor is in operation.

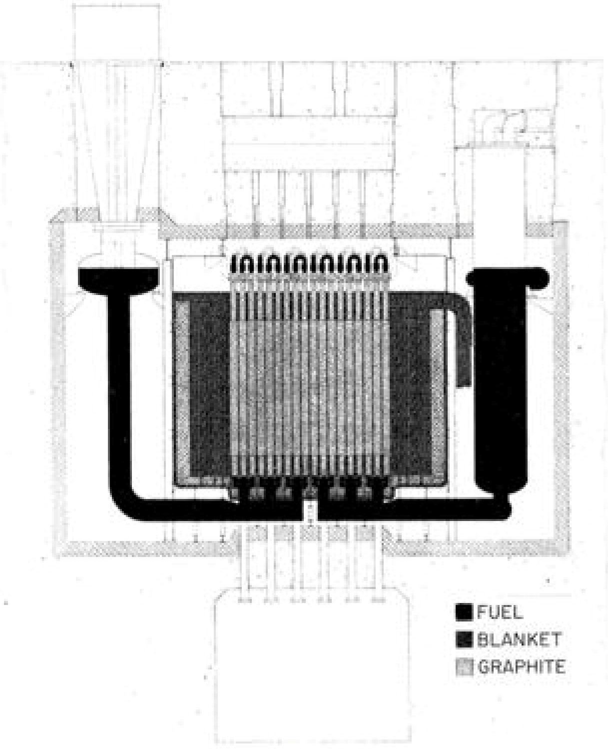
Molten-salt reactors can operate at high temperatures and produce high pressure superheated steam to achieve thermal efficiencies in the heat-power cycle equal to the best fossil fuel plants. The relatively low vapor pressure of the salt permits use of low pressure containers and piping.

The negative temperature coefficient of the reactor and the low excess reactivity are such that nuclear safety is not primarily dependent upon fast acting rods.

The fuel salt has a low cross section for the parasitic absorption of neutrons. When it is used with bare graphite as the moderator, very good neutron economies can be achieved. Molten-salt reactors, thus, are attractive as highly efficient converters and breeders in the thorium-uranium fuel cycle.

The fluoride salts used as the fluid fuel mixture have good thermal and radiation stability and do not undergo violent chemical reactions with water or air. They are compatible with the graphite moderator and can be contained satisfactorily in a specially developed high-nickel alloy. The volumetric heat capacity, viscosity, thermal conductivity and other physical properties also are within desirable ranges.

Use of relatively high circulation rates and temperature differences result in high mean power density, high specific power and low fuel inventory.



A molten-salt breeder reactor of advanced design, capable of producing 2,300 Mw of heat to generate 1,000 Mw of electricity, is shown in this schematic. Such a reactor would have a core about 8 feet tall and 13 feet in diameter, and be surrounded by a 2-foot-thick blanket of thorium salt.

CHARACTERISTICS OF THE MOLTEN-SALT REACTOR EXPERIMENT

First criticality	June, 1965
Power	Electricity, 0; Heat, 10,000 Kw
Fuel	65% Li^7F-29.1% BeF_2-5% ZrF_4-0.9% UF_4
Fuel load	20 ft^3 in core; 70.5 ft^3 system total
Reactor vessel	Hastelloy N, 68 in. high, 56 in. diameter
Moderator	69 ft^3 graphite, 1,140 channels
Coolant	66% LiF-34% BeF_2
Control rods	3, hollow cylinder, Gd_2O_3-Al_2O_3
Fuel temperature	Into reactor, 1,175°F; exit, 1,225°F
Function	Power reactor development