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EFFICIENT USE OF COAL WATER FUELS

TECHNOLOGY ASSESSMENT REPORT 74

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NOMENCLATURE

AIDG	advanced integrated drying gasification cycle by DUT
AFT	ash fusion temperature
ASC	advanced supercritical
Aspirated	drawn into the engine along with the combustion air to form an essentially homogeneous charge (vs direct injection into the cylinder just prior to the time required for ignition of more heterogeneous charge)
AUD	Australian dollars
API gravity	an arbitrary scale expressing the gravity or density of liquid petroleum products. The measuring scale is calibrated in terms of degrees API where: Degrees API = 141.5/(sp.gr.60°F/60°F) - 131.5
Biogas	methane containing fuel gas produced from the anaerobic digestion of biomass and biomass residues and animal wastes.
Bingham fluid	a viscoelastic material (mud-like) that behaves solid when stagnant, but flows as a viscous fluid when pumped
Cavitation	voids or bubbles produced in a liquid which collapse rapidly and cause metal erosion from the local shock waves
CC	combined cycle
CHAT	cascaded humidified air turbine (multi-staged HAT cycles)
CCS	CO_2 capture and storage
CHP	combined heat and power plant.
Crosshead	sliding bearing located below the piston and used in large reciprocating engines (internal combustion engines and steam engines) which transfers the vertical forces between the piston and connecting rod, and carries all of the side thrust from the connecting rod
CWF	coal water fuel, typically containing ground coal in 20-55% water.
CWM	coal water mixture, term used interchangeably with CWF
COE	cost of electricity as delivered to the customer
COG	cost of generation
DACE	direct aspirated coal engine
DCFC	direct carbon (or coal) fuel cell which burns carbon with oxygen ions transferred across an electrolyte to produce electricity at very high thermal efficiency (>80% HHV)
deNO_x	removal of oxides of nitrogen
deSO_x	removal of oxides of sulphur
DACE	dry aspirated coal engine (a dust engine)

DFGT	direct fired coal turbine combined cycle
DICE	direct injection coal engine, where coal is injected pneumatically as dust or as a coal-water fuel
Dispatchable	able to operate at a particular power output over a period nominated in advance - or risk being fined for breaching the rules
DOE	United States Department of Energy
DUOS	distribution use of system: a service provided to a distribution network user for use of the distribution network for the conveyance of electricity that can be reasonably allocated on a locational and/or voltage basis (leading to a DUOS or distribution charge which includes various retail costs)
Entropy	A measure of the disorder or randomness in a system, and for a closed thermodynamic system, a quantitative measure of the amount of thermal energy not available to do work
EPRI	Electric Power Research Institute, Palo Alto, California
FGD	flue gas desulfurisation
Flash drying	extremely rapid evaporation of water due to a sudden reduction in pressure
GE	General Electric Corporation
GGE	greenhouse gas emissions
GHG	greenhouse gas
Gob	waste coal, usually fines containing high moisture and ash
GTCC	gas turbine combined cycle
HAT	Humidified air turbine (equivalent to a humidified gas turbine)
HHV	higher heating value
HTD	hydrothermal dewatering; involves heating coal to near supercritical pressures to cause densification and release of bound water which is removed by centrifuges; suitable for low rank coals/lignites
HRSG	heat recovery steam generator
Hydrodynamic	a film of lubricant (usually 5-20µm microns thick) developed due to relative movement of the 2 mating surfaces, and which separates the surfaces to avoid wear
IDGCC	integrated (coal) drying gasification combined cycle
IDGHAT	integrated (coal) drying gasification humidified air gas turbine
IGHAT	integrated gasification humidified air gas turbine
IFD	integrated flash (coal) drying
kW	kilowatt = 1,000 watts (unit of power)
kWe	kilowatt electrical
kWh	kilowatt hour = energy from 1 kW for 1 hour (unit of energy)

LCA	life-cycle analysis
LHV	lower heating value
LNG	liquefied natural gas
LNGCC	LNG gas turbine combined cycle
MHI	Mitsubishi Heavy Industries
Mtpa	million tonnes per annum (equivalent to 2,740 tpd, or 114 tph)
MW	megawatt = 1,000,000 watts (unit of power)
MWe	megawatt electrical
MWh	megawatt hour = energy from 1 MW for 1 hour (unit of energy)
MWt	megawatt thermal
mPa.s	milli- Pascal.seconds; unit of dynamic viscosity
NA, N/A	not applicable
NGCC	natural gas-fired combined cycle
NOx	nitrogen oxides
O&M	operating and repairs & maintenance
Orimulsion	a 70:30 bitumen water emulsion (produced in Venezuela from 1982-2006, bitumen now being upgraded to oil products)
OTE	overall thermal efficiency (sent out or delivered)
PCC	post combustion capture
pf	pulverised fuel – namely coal
Piston land	the upper circumference of a piston above the top ring
ppmv	parts per million by volume
ppmw	parts per million by weight
R&D	research and development
RD&D	Research, Development and Demonstration
R&M	repairs and maintenance
SCR	selective catalytic reduction; a process to convert nitrogen oxides (NOx) in flue or exhaust gases to N_2, mostly using ammonia over a catalyst at 200-300°C
SC	supercritical pf
SE	specific energy (the heating value of a fuel, relative to 25°C)
SOx	sulphur oxides
Spinning reserve	Spare synchronised generation capacity that is available to the grid in case a generator is suddenly and unexpectedly lost. This is usually provided by operating base plants at part load
Supercritical	steam pressure greater than 23.1 MPa
SwRI	South West Research Institute, Texas

Syngas	synthetic gas produced by high temperature gasification of fossil and biofuels
t	metric tonne
TDC	top dead centre of piston travel in a reciprocating engine
TIT	turbine inlet temperature
tpd	tonnes per day
TUOS	transmission use of system (leading to a TUOS or transmission charge)
Turbostratic	a type of crystalline structure where the basal planes have slipped sideways relative to each other, causing the spacing between planes to be greater than ideal
UCC	Ultra Clean Coal, trade name for ultra low ash coal from UCC Energy
ULAC	ultra low ash coal (generally below 1% ash)
USC	ultra-supercritical pf, with steam pressures over 35 MPa and temperatures of >566°C
US DOE	United States Department of Energy
USD	US dollars
UWF	UCC coal water fuel
work	used in this report to mean the rate of mechanical energy (from steam turbines or electric motors), as an electrical equivalent
YSZ	yttria-stabilized zirconia, is an oxygen ion conducting solid, which acts as an electrolyte at temperatures above about 800°C

EXECUTIVE SUMMARY

This report assesses the use of coal water fuels for high efficiency power generation, and focuses on internal combustion engines. The coal water fuels are based on UCC's ultra clean coal, and the study consider the entire fuel cycle - from coal in the ground, through to delivered electricity.

Although the production of ultra clean coals involve an energy penalty for the additional coal processing required, this would be offset by other benefits – including avoiding transmission and some distribution costs by the ability to achieve high efficiency generation at smaller scale.

The results show that, while best available supercritical pf and IGCC plants could achieve a fuel cycle efficiency of 38-40% (HHV) at a scale of around 700 MW, and natural gas turbines 48-50% (HHV) at scales between 250 and 500 MW, the highest overall cycle efficiency, 52% (HHV), is achieved by a low speed diesel engine using fuel oil, at scales around 30 MW. A key conclusion is that a direct injection coal engine using CWF should be able to achieve a similar thermal efficiency (only 2-3% lower efficiency) to that for fuel oil. The development of low speed, high capacity (up to 100 MW), 2 stoke diesel engines, provides a useful technology platform for efficient distributed generation based on CWF.

The recent development of processes that can produce ultra low ash feed coals could enable the production of much higher quality CWFs than possible in the past. Coupled with other benefits, this should give a strong incentive to develop ultra clean CWF– not just as a HFO replacement, but as a direct competitor to conventional pulverised coal in diesel engines and gas turbines.

Direct firing of coal requires micronising to <20-30µm for diesel engines, and <10µm for gas turbines, and producing a CWF containing around 50 wt% coal. Most direct fired coal studies in the past have been based on the compression ignition (diesel) engine.

Direct injection of CWF, in a similar manner to diesel or fuel oil in a conventional diesel engine, has been the most successful method of direct firing coal. Injection and combustion characteristics of CWF in diesel engines are significantly different to those for diesel fuels, due to the combined effects of poorer atomisation and the time required to evaporate the slurry water. However, combustion and thermal efficiencies matching diesel fuel have been achieved for CWF, at up to 1900 rpm.

Injectors have caused the biggest technical problems for direct injection of coal into diesel engines, and have been the subject of most R&D.

A number of successful demonstration programs were completed in the most recent DOE coal engine program from 1986-93, including medium speed 4-stroke engines in locomotive and genset applications. Although the program was highly successful technically, it was terminated due to persistent low oil prices and the US federal budget deficit.

The critical technologies developed in the final stages of the program (electronic controlled engine with its emissions cleanup system), together with a number of other engine modifications to combat wear, will allow the technologies to be packaged into commercial systems very quickly. Currently, the engine modifications required for successful direct injection of CWF are the use of a purged-shuttle fuel pump plunger, electronically timed injection, diamond compact injector tip nozzles, tungsten carbide sprayed cylinder liner and top ring set, and pilot injection of diesel (especially at low load).

Areas requiring further research are the fate of mineral matter and its effect on engine wear, and how to minimise coal agglomeration during the evaporation of individual CWF droplets.

Another potential advantage of the use of CWF, particularly if used in a diesel engine, is providing cost effective and efficient backup power and spinning reserve, and enabling efficient use of a range of liquid and gaseous biomass fuels.

The cost of supplying electricity from CWFs using direct firing is expected to be very similar to those for supercritical pf plants, and gives a significant 20% reduction in GGE. However, this does not take into account the other benefits of efficient, flexible and adaptable distributed generation.

While larger gas turbine combined cycle plants will ultimately give the highest fuel cycle efficiency and lowest GGE for CWF, development of these machines is necessarily very measured, and costly, compared to the diesel engine.

1. BACKGROUND

The use of coal water fuel (CWF) for power generation (using the conventional steam cycle), has always involved compromising overall thermal efficiency – by around 3% points. The objective of the present study was to assess ways of avoiding this efficiency loss though different power cycles.

Originally, the study was to be based on an experimental Masters degree program to investigate the phenomenon of integrated flash drying in IGCC. This program was to obtain experimental data for flash drying at elevated pressure, and to identify gasification-based power cycles that would allow efficient use of CWFs.

Integrated flash drying (IFD) for CWF is a concept which aims to achieve the advantages of dry feeding (higher cold efficiency, reduced oxygen consumption and smaller gasifier) with the advantages of allowing a high moisture coal to be used as feed. The main objective is to dry and preheat high moisture coal using the sensible heat in the hot syngases leaving the gasifier, and to feed only dried coal to the gasifier burner(s) (or injector(s)). The high pressure steam generated from the drying process then does expansion work through the gas turbine, and also contributes sensible heat to the heat recovery steam generator (HRSG).

IFD is a key feature in both integrated drying gasification combined cycle (IDGCC) and AIDG (advanced integrated drying gasification), although the processes differ, in that IDGCC uses hopper fed lump Victorian brown coal, whereas AIDG specifies slurried coal at >50% water content.

IFD in AIDG thereby gives the advantages of both slurry and dry feeding. Figure 1 shows a schematic of IFD as embodied in AIDG. As depicted, the process involves injecting a preheated coal water slurry into the hot syngases leaving the gasifier, partial atomisation of the slurry, flash drying the atomised slurry as it travels up the up-leg of the drier, separation of dried coal from the syngas using a cyclone, and conveying the dried coal to the gasifier burner(s) using a carrier gas such as nitrogen, compressed syngas or steam.

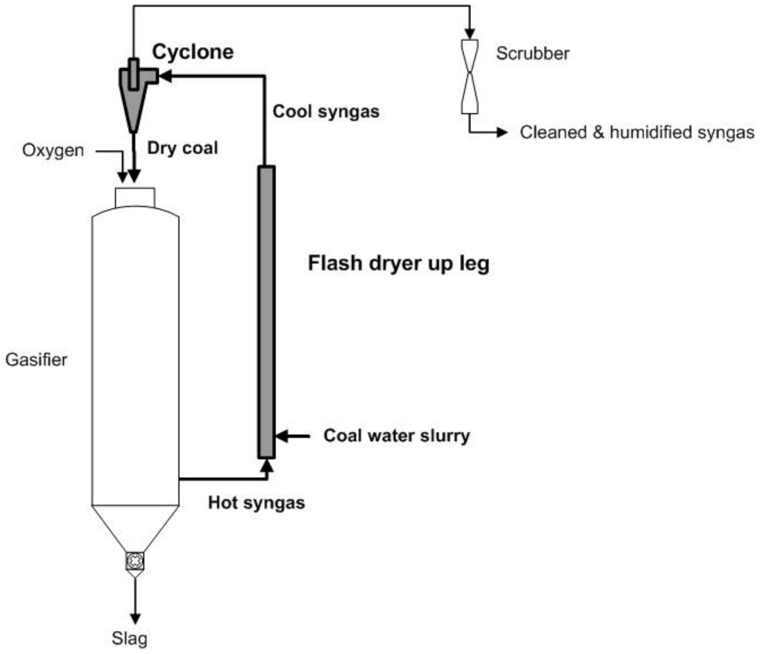


Figure 1 Schematic of a slurry feed gasifier with integrated flash drying

Although a relatively simple concept, there are significant different technical issues when applied to a slurry fed, entrained flow, gasifier. In particular, flash drying of slurried coal will require a high degree of slurry preheat (around 220-235°C) to promote atomisation in the base of the up leg of the drier. Atomisation will produce a wide range of droplet sizes (each containing many coal particles), with a wide range of drying times. This will result in a wide variation in peak coal temperatures, possibly leading to the release of tars from coal released from the finer droplets, which could cause sticking in the cyclone(s). Other uncertainties are the potential for the caking of agglomerates of coal particles formed during evaporation of the droplets (each containing numerous finer coal particles), resulting in large coal particles entering the gasifier thereby offsetting potential size reduction of the gasifier from flash dried coal.

The Masters program was to have investigated these issues and techniques for atomising high viscosity CWFs. Unfortunately this study was terminated at the literature review stage, and therefore many questions about the feasibility and technical issues around integrated flash drying remain unanswered.

The scope of the study was therefore revised to cover the alternative high efficiency uses for CWFs, namely direct firing of gas turbines and diesel engines.

It is noted that the use of CWF in gas turbine cycles was initially assessed in CCSD Technical Reports on UCC[1] and Hypercoal,[2] and the merits of both applications for achieving high efficiency power generation were further highlighted at the 2007 COAL21 Annual Conference[3].

This report assesses the use of coal water fuels for high efficiency power generation, and focuses on internal combustion engines.

2. INTRODUCTION

Internationally, developments in power plants are focussed on technologies to reduce the cost and greenhouse gas intensity (kg/MWh basis) of next generation, conventional (or IGCC) coal plants with CO_2 capture. However, when a breakdown of costs and losses in efficiency is made in a life cycle context of providing a service (*ie* delivered electricity), it is clear that improving the performance of the base plant is only part of the solution. This is shown in Table 1, which gives nominal values for a larger, best available, ultra supercritical power plant in Australia. Note that all heating values in this report are on a HHV basis.

Table 1 Nominal breakdown of costs for delivered electricity, and thermal efficiency

	Base plant	CCS	TUOS	DUOS	Overall
Cost delivered electricity ($/MWh)	$35	$35	$10	$25	$105
Efficiency (HHV) (wet cooled, delivered)	43%	-8%	-2%	-2%	31%
Efficiency (HHV) (dry cooled, delivered)	41%	-8%	-2%	-2%	29%

The basis for the present study is that alternative routes should consider the entire fuel cycle - from coal in the ground, through to delivered electricity. This will involve reducing the amount of CO_2 to be captured, through an increase in overall thermal efficiency from generation, transmission, and distribution, and consideration of the drivers and technology attributes that will be valued differently in the future. The latter include water availability, flexibility to meeting changing demand curves, adaptability to future needs and developments, such as adaptation to use a range of biofuels, and/or CO_2 capture.

To determine the overall merits of using coal directly in internal combustion engines (and gas turbines), the overall thermal efficiency of providing delivered electricity by the various technologies are shown in Figure 2. The efficiencies in this figure assume best available current technology, and that:

- Centralised plants are >300 MW, and have a transmission and distribution loss of 4.5%
- Decentralised plants have a capacity range of 30 – 300 MW, and have only a distribution loss.
- Distributed generation plants are <30 MW and have neither transmission nor distribution losses.

Using these assumptions, the very best conventional pf and IGCC plants will have an overall thermal efficiency of 38-40% at a scale of around 700 MW, and that natural gas turbines should achieve 48-50% at scales between 250 and 500 MW. The highest overall cycle efficiency is 52% for distributed generation using a low speed diesel engine at the 30 MW scale.

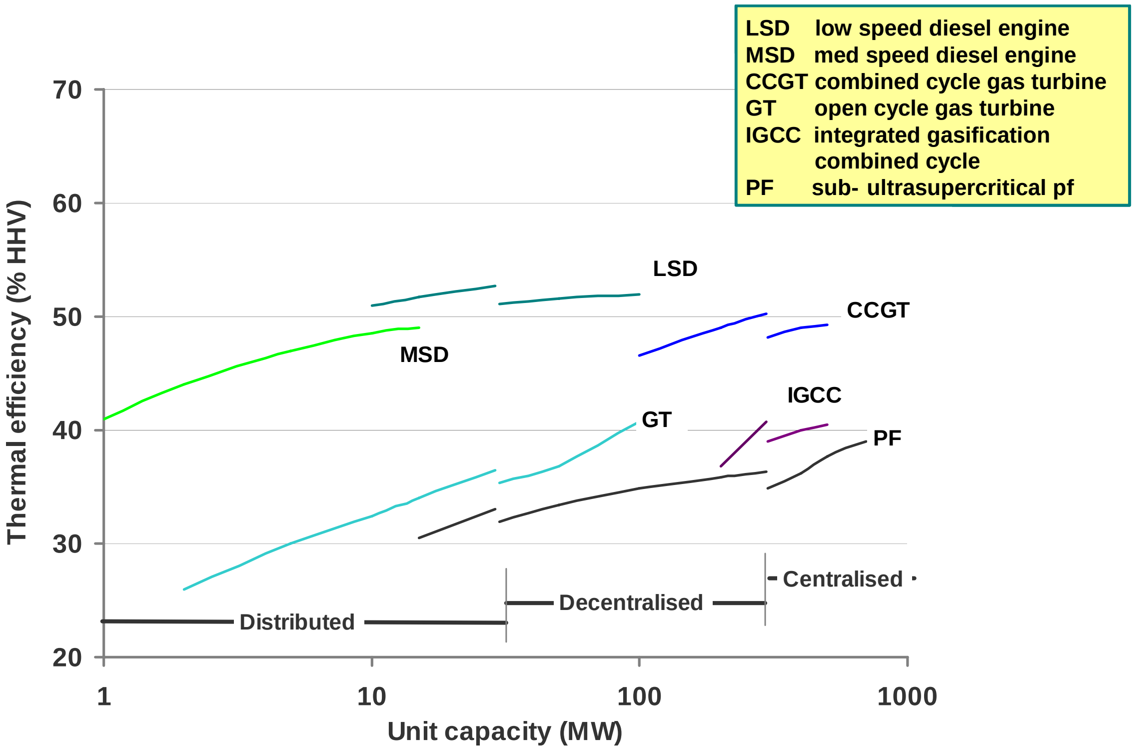


Figure 2 Comparison of thermal efficiencies

Coal water fuels

The first patent on coal-water fuels was granted in 1891, but it appears that little development occurred until the 1940s when CWF where developed in the USSR for utilising waste coal tailings in furnaces (without the need for dewatering). Research was also conducted in the US during the 1940s because of wartime constraints on oil supply, though this was mostly on coal-oil mixtures (COM). The development of coal water fuels from high quality coal commenced in earnest in the United States, Germany, and the former Soviet Union in the 1960s. Development accelerated in the United States following the 1973 OPEC oil embargo and the oil price hikes in 1979-81. Ironically, in the US, many coal-fired boilers and industrial furnaces had been recently converted to burn fuel oil following the introduction of new environmental regulations in 1970. R&D focused on producing fuels with desirable physical and chemical properties, demonstrating retrofit in existing boilers, and developing specialized equipment for handling and transporting slurries. During this period, a number of private companies were actively involved in, or planned to enter, the CWF business. All have subsequently abandoned commercialisation of slurries, as oil prices declined in the mid-1980s.

Since CWFs have always been intended as a substitute for oil, their market penetration has been heavily dependent on oil prices and oil price projections – both have experienced gross swings over the last 30 years - Figure 3 below shows historical oil prices normalised to USD2007.[4]

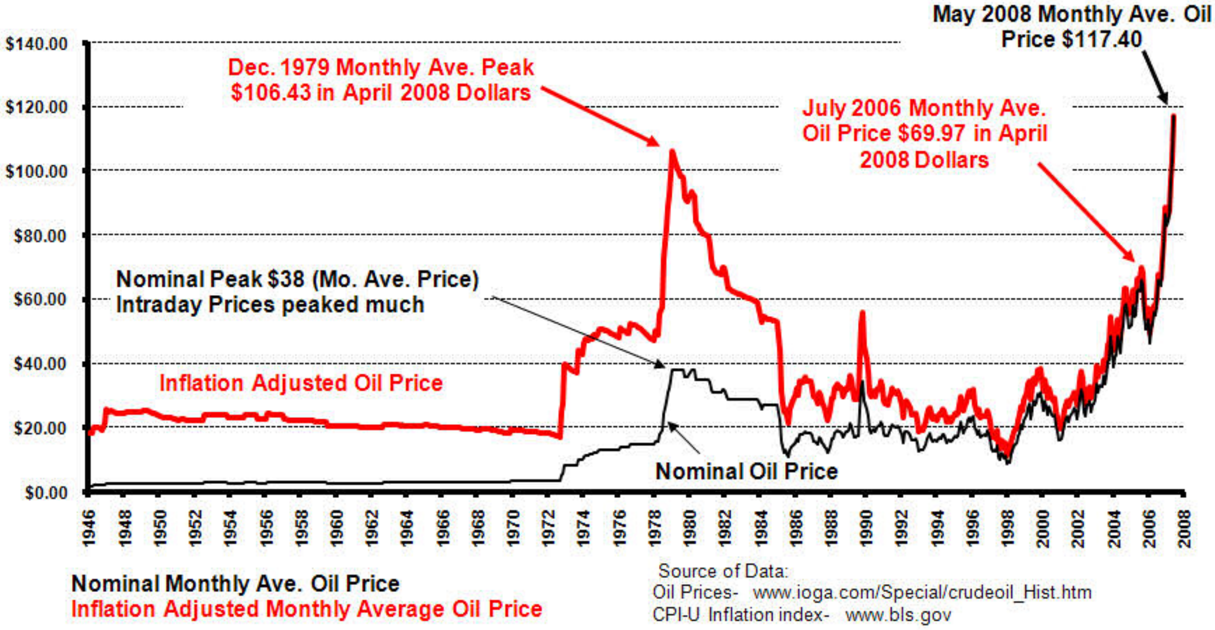


Figure 3 Historical crude oil prices

An additional on-going driver for CWF has been the lack of cost effective alternative methods for producing coal derived liquids - despite extensive research and subsidies in coal-to-liquids processes, the cost has mostly remained at least twice as much as conventional liquid and gaseous hydrocarbons.

A factor against the development of CWF in the past is that CWF has only been suitable for those applications using heavy fuel oils (HFO). As the bulk of coal is burnt directly, or with only modest treatment to remove part of the ash and sulphur, there has been little or no benefit in using a significantly more costly, albeit lower ash, CWF.

An oil price spike and adverse price projections provided the driver for the renewed development of CWF in the late 1980s, and this included an extensive coal fuelled gas turbine and diesel engine program under DOE support. Development was again terminated in the early 90s, though limited CWF production continued in Japan, Russia, China and central Europe for niche applications, including those requiring pipeline transportation.

During this period there were significant developments in fine coal cleaning (to improve coal recovery from tailings, including the mining of old tailings dams), which have continued to improve the techniques and economics of CWF production.

In the 1990s, all types of coal fuels became the subject of intense environmental pressure due to their high greenhouse gas intensity, and this was especially the case for CWF, as the thermal efficiency of boilers with CWF is around 2-3% points lower than with normal coal. Orimulsion (bitumen-water fuels with 30% water) have experienced similar strong opposition.

Up to this point, the focus has been entirely around producing low cost CWF to replace heavy fuel oils, with relatively lax specifications on the feed coal with respect to ash content – typically 3-8% ash. Fortunately, the development of CWF has been paralleled by the R&D into processes that can produce ultra low ash feed coals, especially for high value metallurgical applications, such as the production of electrode carbons. Processes include advanced physical processing to produce "super coal", chemical processes to remove fine residual ash (*eg* AMAX caustic leach, UCC and Cenfuel), and processes that dissolve coal and reconstitute it as a synthetic coal-like material minus the ash (*eg* Solvent Refined Coal and Hypercoal). Although none of these processes have reached commercial development, they could enable the production of much higher quality CWFs than possible in the past, and coupled with other drivers, result in a step change in how coal is used in the short to medium term – not just as a HFO replacement, but a direct competitor to conventional pulverised coal. A number of compounding factors are listed below:

- UCC-based CWF can match the specifications of fuel oils used in high efficiency gas turbines and low-medium speed diesel engines, and give a 20-25% reduction in greenhouse gas intensity over that from the best conventional pulverised coal (pf) power plants.
    - The water content of CWF does not have the same negative impact on cycle efficiency for gas turbines or diesel engines as it does for externally fired devices such as boilers.
    - The ability to utilize slurried fuels at high efficiency avoids the need for producing a dry fuel (difficult with current wet processing technologies), facilitates pipeline transportation and storage, and gives additional reductions in GGE.
    - Large, fuel efficient diesel engines are now available for stationary power generation, which should be especially suitable for retrofit to burn CWF – based on developments from DOE coal-engine program over the period 1984-93.
- World-wide there is a growing need to provide efficient and flexible power generation at smaller scale to match peak demands, and to underpin the intermittency of renewable energy. Gas turbines, and especially diesel engines, are ideal for this duty.
- Since the late 90s, oil (and gas prices) have experienced a sustained rate of increase that is not expected to wane due to improved estimates of finite resources, and the growth in demand for liquid fuels in China and India.
- A number of recent developments have made energy security a key issue for many nations, and coal-derived fuels are expected to underpin this energy security.
- CWF, although having a lower energy density than dry coal, is convenient and safe to transport via pipeline – an key benefit for many countries with overloaded transport infrastructure; *eg* India, China, the Eastern USA and Eastern Europe.
- Fresh water consumption is becoming a major issue for power generation in many countries, which could be greatly alleviated by use of more coal-gas turbines and coal-diesel engines.

CWF in diesel engines and gas turbines

Currently, the main applications for CWFs are industrial boilers. Gas turbines and diesel engines have been used for research and pilot project only, as both of these applications require coals of higher specification for coal than is currently being used to produce CWF for boiler and heating applications.

The issues caused by coal impurities are the reason coal turbines and diesel engines have not been commercialised. Although CWF with significantly higher specifications than coals used in previous turbine and diesel engine tests are now possible with the development of the UCC product, significant technical issues remain.

To provide a context for the report, this section briefly introduces past studies into direct fired coal turbines and diesel engines, and the range of technical issues and developments to overcome them. A more detailed description is given in the Section 4 to 5.

The history of coal diesel engines was started by Rudolf Diesel who worked on lignite dust ingested engines over the period 1898-1908. Work was terminated due to the greater success with oil-fuel engines and severe problems with wear, the accumulation of deposits on the piston and cylinder wall, and dust explosions. Pawlikowski (a co-worker of Diesel), continued the development of the dust engine until around 1928.

Pawliowski's developments included various methods for delivery of the coal dust, and for the design of rings and seals to mitigate wear issues. Ongoing development of the Pawlikowski engine apparently continued in Germany until around 1945. Technical issues addressed included methods for reducing the amount of (ingested or pneumatically conveyed) coal dust which would adhere to the oil coated cylinder walls (much more than with CWF injection), and development of harder materials for rings and cylinder liners (chilled irons and high carbon-manganese steels). Work ceased around the end of World War II due to lower cost oil and other issues.

Additional work was undertaken in the United States in the period from 1945 to 1978, mostly in attempts to operate convention diesel engines on slurries of coal in diesel fuel oil. In 1978, two programs were sponsored by the USDOE, to study in detail the effects of various alternative coal fuels on operation of diesel engines - the program by Thermo Electron was for large stationary engines, the other, by the Southwest Research Institute (SwRI), focused on coal fuels in smaller diesel engines used in transportation. The efforts in both projects involved the use of a variety of fuels including slurries of solids in diesel fuel.

Thermo Electron work[5,6] was performed in a large (900 mm bore) low speed (100 rpm) 2-stroke single cylinder Sulzer test engine.

The fuels in the initial experiments included coal-liquids and coal-oil slurries. The experiments were extended in 1982 to include the use of coal in water slurries. Four well-characterised CWFs with loadings of approximately 50 wt% coal were studied. The engine design included two separate fuel injection systems, one for pilot injection of diesel fuel and one for the slurry. The pilot system provided absolute control of the ignition timing. A new accumulator injection system was developed on this project, apparently solving the fuel metering and injection problems. The tests showed that coal/water slurry fuels can be successfully combusted with thermal efficiencies approximately equal to those obtained with diesel No. 2 fuel oil. The combustion characteristics, mechanical efficiency, and thermodynamics of this engine were investigated to show that CWF did not significantly affect engine thermal efficiency, and that the CWF was combusted in a time period slightly shorter than conventional diesel fuel oil. As a result of this program, Sulzer Brothers patented the injection system design.

The work at the Southwest Research Institute (SwRI) was performed on a higher speed single-cylinder research engine. The initial experiment consisted of screening tests of a very wide range of alternative liquids and solids, generally mixed in various concentrations in diesel fuel to provide sufficient ignition quality for auto-ignition in the test engine. The slurries included various biomass solids, coals, cokes, and carbon black. The injection system was standard pump-line-nozzle (PLN) technology with increased clearances to prevent sticking and plugging. The results of the experiments demonstrated the complexity of the rheological properties of the slurries and interactions of these properties with the injection and atomization of the slurries in the engine.

This report includes:

- Review of clean coal production - 1990 to present, scale, coals, economics, product specifications relative to those required for GT and diesel applications, market and positioning relative to alternative conversion technologies.
- Review of clean coal applications - 1990 to present, for stationary and locomotive applications and technology barriers.
- High level economics, with a comparison with advanced conventional coal technologies.
- A discussion of adaptability to CCS, and possible synergies with renewables.
- Lastly, recommendations are made for future RD&D.

3. PRODUCTION OF COAL WATER FUELS

The majority of coal is utilised in its run-of-mine state without treatment for pulverised coal power stations. Nevertheless, coal preparation plants contribute greatly to increasing the economic value of many coal reserves by removing a portion of minerals to reduce transport cost and environmental issues from SOx emissions and flyash disposal. Recent estimates indicate that there are currently more than 2,200 preparation plants in operation throughout the world, treating around one-third of the world's current production of coal.

However, conventional coal preparation plants are completely unsuitable to meet the stringent fuel quality specifications for gas turbines, or even diesel engines (in the absence of commercial markets for these fuels, specifications are only currently available as guidelines, and have been mostly adapted from those for heavy fuel oils).

There are 2 main types of coal cleaning process; physical and chemical, noting that because of reagent costs and other issues, chemical cleaning will almost always be preceded by some degree of physical cleaning.

3.1. Physical cleaning

Physical coal cleaning is typically used to reduce ash levels to around 8%, and coal preparation plants incorporate a wide array of solid-solid and solid-liquid separation equipment. The types of processes employed, and their configuration and operation, varies considerably from coal to coal and specifications for the product coal. The most notable differences in the design requirements involve the layout of the fine coal circuitry incorporating competitive flotation technologies and alternative dewatering systems.

Physical beneficiation of coal involves the separation of carbonaceous material from mineral matter by either varying the density of separation or by froth flotation. The key to the production of coal with low mineral matter content by physical beneficiation is the degree of liberation of the coal from the minerals. Mineral distribution is generally determined during the formation of the coal deposit, and can vary greatly from seam to seam. There are two basically different philosophies which can be used to produce coal with very low ash levels (say less than 3%): 1) is to isolate particular coal streams within the washery which, as a result of natural breakage, have washability characteristics which favour the production of low ash coal, and 2) crush or grind the coal to achieve liberation, followed by selective separation.

Extensive R&D into fine coal processing occurred in the 1960s, at a time when world coking coal markets were in decline and overcapacity threatened to produce lower coal prices. Many companies attempted to develop new markets for specialized coals for CWF, for combustion, as a source of carbon for electrodes, and even for possible fuelling of diesel engines and gas turbines.

In Australia, a number of potential production methods for the production of low ash coal were investigated using a variety of Australian coals, including natural fines, washed coal and washery rejects. Although it was found that selected coals could produce coal of less than 3% ash at yields exceeding 70%, the costs of comminution, beneficiation and dewatering for potential markets exceeded the value placed upon the low ash product. In addition, many coals could only produce low ash coal products with very low coal yields; many below 40%. These two factors remain to be resolved before physical cleaning alone can produce the coal quality required for gas turbines or diesel engines. This is a difficult task as the mineral matter in coal is both inherent (finely dispersed throughout the coal) or adventitious (introduced into and between the coal forming plant remains during their decomposition).

Unless the coal is milled to very small particle sizes (say below 5µm) the inherent mineral matter may only be removed by chemical means, while adventitious mineral matter can be removed by crushing to achieve liberation followed by physical (gravity separation) and physico-chemical (flotation) techniques. Figure below shows the effect of ultra cleaning on product coal recovery from early work by BHP[7].

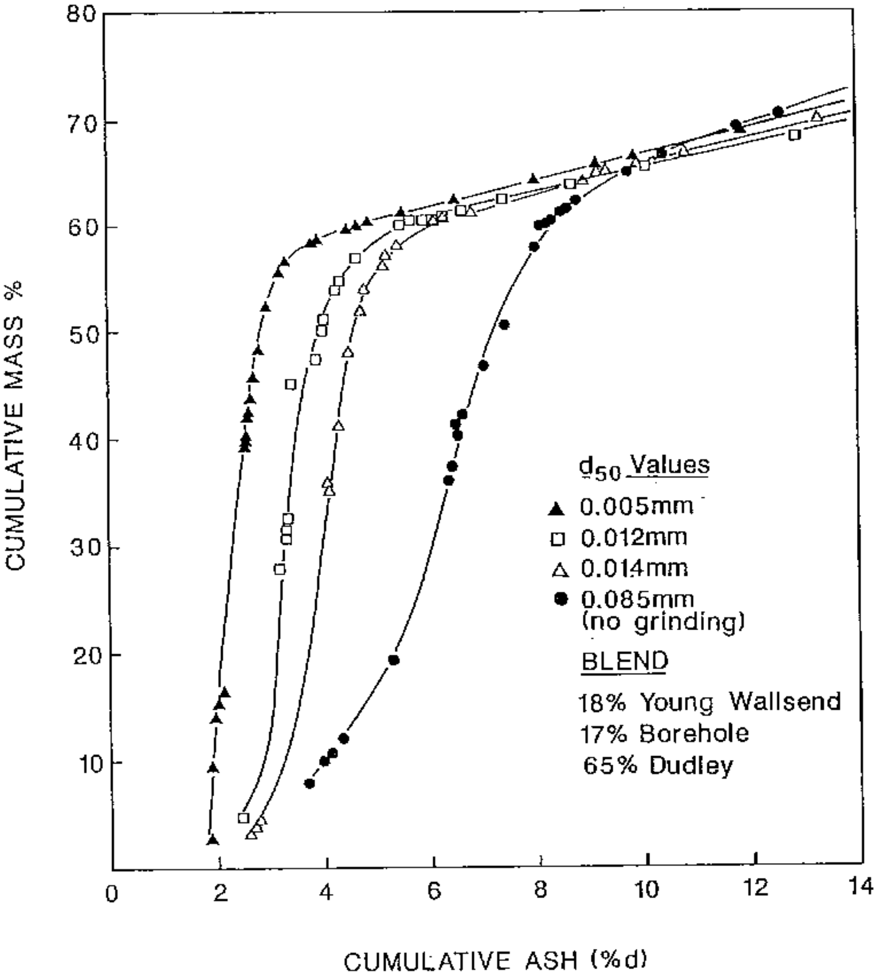


Figure 4 Liberation of coal from mineral matter for a mixed seam fines blend for the natural size distribution and 3 grinds

However, since these studies were done, there have been a number of important changes in technology (milling and fine coal treatment) and philosophy (the preference for slurry fuels) which may enable advanced physical cleaning methods to contribute more towards the production of ultra low ash CWFs.

The most promising technology for fine-coal cleaning for CWF is column flotation. Column flotation differs from conventional flotation in that columns have a much greater height-to-width ratio and do not require mechanical agitation to induce particle-bubble attachment. Columns are more effective for cleaning finer coal due to better control of bubble size, improved particle-bubble interaction, and froth washing capabilities.

There are a number of column processes that are somewhat similar in nature, with each possessing one or more unique technological advances. The most significant of these processes[8] include Microcel, Kenflote, Flotaire and the packed column. Another column, the Jameson Cell, differs from these columns in that particle-bubble contact is not achieved in the slurry column itself but rather in a downcomer tube where air and feed mixing is achieved in a venturi-type/plunging jet arrangement. Column cells have been applied commercially for the recovery of fines from both freshly mined coal and refuse ponds and also have realized significant applications in the minerals industry.

Additionally, improved cleaning of fine particles has resulted from recent advances in the design of several new water-only devices including the Kelsey Jig, the Multi-Gravity Separator, the Falcon Concentrator, and the Knelson Concentrator. Each of these devices, whether they use flowing-film or hindered settling principles, seek to take advantage of the significant increases in separation efficiency that can be achieved from the application of centrifugal force to magnify the separating forces on the particles. While none of these devices have realized any significant degree of industrial application, these, and other processes like them, are the technologies of the future as the industry seeks to improve coal recovery and minimize waste.

The development of advanced ultra-fine, dense-medium systems such as Carefree Coal and MicroMag also offer the potential of improved cleaning of coal fines down to about 30-40µm. However, neither of these processes has yet resulted in a commercial application in the coal industry.

3.2. Advanced coal processing projects

There have been a number of advanced coal processing projects over the last 10 years using essentially physical cleaning technologies. The review below includes a substantial US project using relatively conventional technologies, and 2 other which involve alternative methods.

3.2.1 AMAX

A comprehensive study of advanced physical coal cleaning for premium fuels was undertaken over 1992-97 by Bechtel and AMAX[9]. The primary objective was to develop a design base for prototype commercial advanced fine coal cleaning facilities capable of producing ultra-clean coals suitable for conversion to stable and highly loaded CWF. The main specification was an ash content of less than 2% (and preferably these than 1%). The separation technologies were advanced column froth flotation and selective agglomeration. Cleaning plant targets were to achieve recovery of >80% of the heating value in the run-of-mine, and to produce coal at an annualized cost below $2.4/GJ including the cost of the feed coal (approximately $1.4/GJ).

Following laboratory and bench-scale testing with selected coals, a 2 t/h pilot plant was designed by Bechtel and installed at Amax R&D, Golden, Colorado for process evaluation and testing. The tests successfully demonstrated the capability of column flotation as well as selective agglomeration to produce ultra-clean coal at specified levels of purity and recovery efficiency. Test results, and the experience gained, provided a valuable design basis for commercial plants, but it is unclear whether these have been built. The basis for the plant designs were:

- Feed coal: high-volatile bituminous coals with suitable ash liberation requirements. Coal included washed Taggart, Elkhorn No.3, and Sunnyside run of mine.
- CWF specifications: <2% ash, viscosity <500 cp at a shear rate of 100/s. HHV >20.7 GJ/t slurry (which equates to a coal:water ratio of around 60:40).
- Plant capacity and location: Designs were based on 1.5 Mtpa of ultra-clean coal (dry), which was deemed suitable for supplying a 500 MW power plant (note, for

continuous operation this implies a thermal efficiency of around 37%, which would represent a conventional pf plant – not a combined cycle gas turbine).

- Overall, column flotation gave slightly lower cost separation than selective agglomeration. It was concluded that the biggest uncertainity in the economic estimates was cleaning plant availability.

Whilst the final report gives detailed process flow diagrams and techno-economics, and met all of the design objectives, it unfortunately gives no information regarding the occurrence and mineralogy of the selected feed coals, or their implications on cleaning plant design, operation or performance. The report also lacks information on the preparation of the CWFs, particularly the particle size distribution and formulation.

Additional information regarding the research components of this project are described by Mahesh and Smit[10] with the ash and sulphur contents shown in Table 2 below (converted from US units of lb/mmBtu).

Table 2 Ash and sulphur content (wt% db) of selected coals tested by AMAX

Coal seam		Taggart	Winifred	Elkhorn No.3	Indiana VII	Sunnyside	Dietz
State		VA	WV	KY	IN	UT	MT
ROM							
	Ash	36.6	31.0	70.8	54.6	14.5	4.8
	S	0.48	0.94	0.97	1.14	0.54	0.32
Washed							
	Ash	1.82	7.93	5.59	8.97	4.94	5.2
	S	0.53	0.88	0.79	0.47	0.57	0.35
Advanced cleaning							
	Ash	<1.3	2.34*	2.34	2.34*	2.47	2.6*
	S	0.52	0.78	0.72	0.44	0.59	0.35

** by selective agglomeration*

The total processing costs were $6-9/t for column flotation, and $9-21/t for selective agglomeration.

3.2.2 Water jet liberation

A more novel process for the preparation of ultra-clean micronised coal has been researched in China, based around high pressure water jet milling[11]. It was found that hydraulically milled coal significantly increased liberation of minerals (97% versus 90% for ball milling) and led to improved overall mineral separation. The improved liberation was speculated to be caused by hydraulic fracturing along lines of weakness between the coal and mineral components. Milling water pressure was 70 MPa, giving nozzle velocities of 200-400 m/s. After liberation the coal was separated using froth flotation. Overall, the high pressure water jet milling resulted in an increased yield of around 10-20% points compared to ball milling to the same top size, and also gave reduced overall energy consumption. For the 9% ash Datong coal used, a 3-4% ash product was obtained at 32-39% coal yield, with an energy consumption of 84 kWh/t of product (equates to an efficiency loss of around 2% points for a coal-fired diesel or gas turbine). It is noted that as nozzle velocities of up to 400 m/s are used for milling (similar to those in diesel injector nozzles), erosive wear is likely to be a significant issue for this type of milling.

It is not possible to directly compare the advanced cleaning projects described above, due to gross differences in coals, and also because in both projects detailed mineralogical data was not reported.

3.3. Advanced coal milling

Ultra fine coal milling is an essential part of firing coal into gas turbines or diesel engines, with the finer and narrower the grind the better. For gas turbines, the upper coal particle size has been specified by MHI[22] as 10µm, and preferably finer. For diesel engines, the top size is generally specified as 20µm, though this will depend on the size (and speed) of the engine to some extent. In both cases the bulk of the coal is below 5µm, and in all cases there is a strong preference to ensure that any non-combustible material (*ie* extraneous mineral particles) is below 5µm.

This situation is greatly different to that for conventional pulverised coal firing, which typically utilises a grind with a mass mean size of 60-75µm, and with a top size of 150µm. Mills used for pf plants are normally roller table mills or ball mills with air classifiers, and with a power consumption of around 10 kWh/t. These mills would be unsuitable for commercial production of CWF due to high energy consumption, as the energy required for milling increases exponentially with reduced particle size.

Milling energy is affected by how the mechanical energy is applied, the particle breakage mode, and the energy lost in elastic and permanent deformation of the solid particles before breakage. Therefore milling energy depends on both the type of mill, and the material - especially at small particle sizes required for CWF for turbines and engines.

While ultra fine milling, say with top sizes from 0.2-30µm, is widely used commercially in the production of many common materials (*eg* paint pigments, ceramic powders, cosmetics), these are all high value applications where the cost, capacity and energy for grinding are far less important than for coal. For example, each 100 kWh/t dry coal used for milling reduces the life cycle energy efficiency of a large gas turbine or diesel engine by 1.2% points (*ie* a 2.4% reduction in energy efficiency).

A wide range of mills are available, and are briefly described below.

Ball mills

Conventional ball mills are unsuitable for micronising CWF for diesel engines due their high energy consumption, and difficulty in producing the fine sizes required. However, over the last 20 years there have been a number of high intensity stirred ball mills developed (*eg* the Isamill and Drais mill) which are able to produce -20µm grinds with much lower energy consumption, together with new ball media which gives very low media contamination. The Isamill is used extensively in the minerals processing industry, and is available with capacities up to 2,500 tpd.

Centrifical or planetary mills

In the planetary mill, the material is primarily crushed by the high-energy impact of grinding balls together with friction between the balls and the wall of the grinding bowl. The grinding bowls, together with material and balls, rotate around their own axis on a counter-rotating supporting disc. The centrifugal forces are caused by the rotation of the grinding bowls. The force resulting from rotation of the grinding bowl when the mill is started causes the rotating balls to rub against the inside wall of the bowl thus crushing the material.

At a certain point in time the stronger centrifugal force of the supporting disc causes the grinding material and balls to separate from the inner wall of the grinding bowl. The grinding balls cross the bowl at high speeds impacting with the grinding material on the opposite wall, creating size reduction by impact.

This type of mill can operate wet or dry, but is best suited to smaller capacity batch milling, and is therefore not as suitable for the preparation of CWF as the Nutating mill below.

Nutating mills

A variant of the planetary mill, and being developed commercially as Hi-com (Ludowici). The mill comprises a nutating milling chamber containing the grinding media and material. It is very compact, and generates stronger acceleration field than most planetary mills. Although little work has been done with coal, it has successfully milled flyash and quartz. Available data shows very low energy consumption, with an estimated ~50 kWh/t for CWF. It is also very suitable for wet milling which reduces energy consumption, avoids the need for inert gas blanketing, and improves the liberation of minerals for subsequent deashing. The mill can be readily equipped for continuous feed, and is considered highly suitable for preparation of CWF.

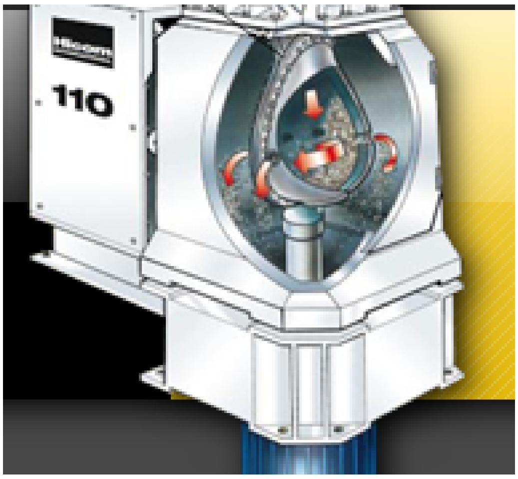


Figure 5 Illustration of the Ludowici nutating mill

Jetmill – opposed flow

Causes high speed particle impacts from opposed air jets. Most common and applicable to a wide range of materials. High energy consumption (say 200-600 kWh/t for CWF).

Jetmill – impact

Called Nippon or Anger-Muhle jetmills, which impact particle laden air jets onto ultrahard target plate (eg ceramic or boron nitride). Best for hard, inelastic particles, so probably unsuitable for lower rank bituminous coals.

Jetmill - spiral

Donut shaped milling chamber with tangential gas jets. Causes high shear to create particle collisions. Various types, with integral pneumatic classification. Generally best suited for softer materials and where the particle characteristics are to be retained (eg for milling graphite). Other variants have integral motored classifier rings (*eg* PMT Spiral Jetmill).

Energy consumption is high, around 200-600 kWh/t. Because of the natural classifying action, this mill is probably best suited for drying milling coal fuels for gas turbines with pneumatic fuel conveying.

A mill similar to this was used in the MHI combustor trials for UCC.

High pressure water jet mill (HPWJM)

Although high pressure water jet technology was introduced in the 70s, it is only now being used widely in industrial applications. The HPWJ (liquid) and hydro-abrasive jets, which make it suitable for applications in cutting soft and very hard materials, including the newest materials, which are not machinable by conventional tools. The most important benefit of the HPWJ is the ability to transport energy into the work-piece and create high-energy flux in the collision area. The collision effects are assisted by shock waves, water hammer effect, cavitation, micro-cracking and hydro wedging along grain boundaries and fracture lines. These phenomena are significantly different to those involved in the other milling technologies. Several recent studies into water jet milling of coal has been reported[12], but the energy consumption values (albeit for small mills) are higher, at over 600 kWh/t, than for nutating mills.

Overall considerations

Whilst the nutating mill appears to offer the lowest energy consumption, and can be readily constructed to supply engines at the 50 MW unit capacity (although multiple mills can be used, and would give improved overall availability and flexibility), the final choice of mill may depend on the interaction of milling with the deashing process. Preliminary research suggests that higher energy HPWJ mills may improve mineral liberation, and this may be important for coals for which physical cleaning alone can produce the required coal product. Once chemical cleaning is required, the value of liberation, is reduced (though still beneficial). Another factor affecting this choice will be the particle size distribution required for the deashing technology to be employed for each coal, and CWF product. Clearly, while technical solutions for milling, both before and after deashing exist at commercial or semi-commercial scale, a considerable amount of R&D is required to determine the milling technology required to optimise the efficiency (and costs) of the overall system.

Lastly, it is noted that as milled CWF would probably be storaged in a day-tank, this improves consistency, gives additional flexibility in the milling plant, and allows for regular maintenance without affecting the availability of fuel supply.

3.4. Chemical cleaning

Processes for chemical cleaning coal are of 2 types; 1) those that attempt to dissolve the mineral components from the coal (*eg* AMAX, UCC, CENfuel), and 2) those that dissolve the coal leaving a mineral rich insoluble coal by-product (eg Hypercoal).

UCC

The UCC production process[13] involves two main steps; a caustic pressure leach to convert silicates and clays to dissolved sodium silicates and sodalite type minerals. The sodalite material is then dissolved in acid so that it can be removed with the filtrate in a simple filtering operation. A typical caustic digestion reaction is shown in Equation 1, and the acid stage is shown in *Equation 2*. If necessary, trace levels of residual mineral components can be then removed in a high temperature washing operation.

Equation 1 $3Na_2Al_2O_5(OH)_4 + 8NaOH \rightarrow 2Na_4Si_3Al_3O_{12}(OH) + 9H_2O$

Equation 2 $2Na_4Si_3Al_3O_{12}(OH) + 13H_2SO_4 \rightarrow 4Na_2SO_4 + 3Al_2(SO_4)_3 + 6H_2SiO_3 + 8H_2O$

A simplified schematic of the process is shown in Figure 6.

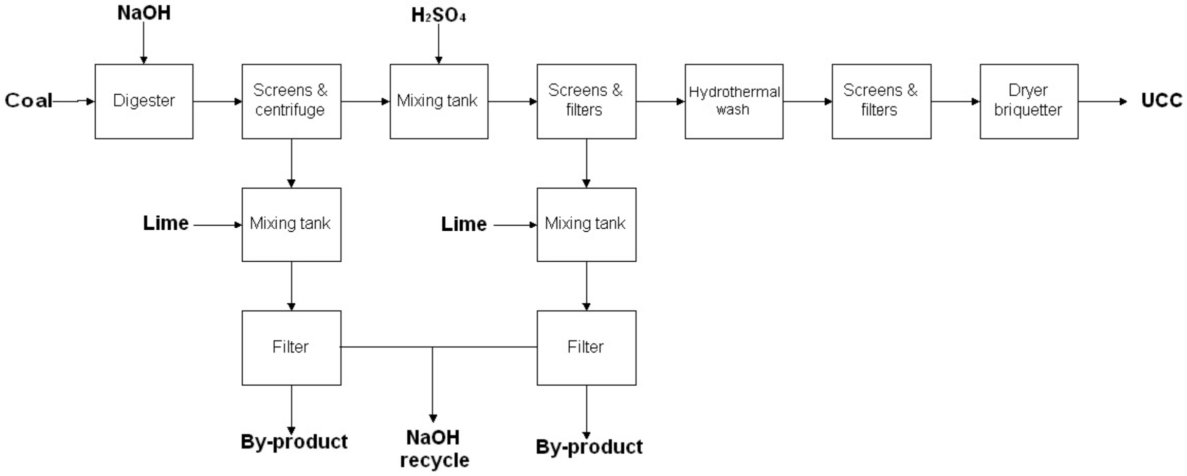


Figure 6 Simplified diagram of UCC process

Key features of the technology are:

- Pulverising of coal is not required to liberate inorganic mineral constituents for processing, which makes solid-liquid separation easier within the process.
- Digestion removes both extraneous minerals and a large proportion of that inherent in the coal particles.
- The process removes most of the alkalis (a key requirement for gas turbines), all of the inorganic sulphur, and some of the organically bound sulphur.
- The base UCC product is a friable filter cake containing around 30% moisture. This material can be handled by bulk handling systems, or further processed, eg dried and briquetted.
- The UCC process is able to treat most bituminous coals.

Properties of the UCC product are given in Table 3. The table also shows specifications of UCC set by Mitsubishi Heavy Industries (MHI) in Japan for use in their gas turbines. In general the current process configuration at the Cessnock pilot plant is capable of meeting the MHI specifications for most bituminous coals.

Table 3 UCC properties and the required levels for use in a gas turbine

Property	UCC	MHI target specification
Total ash	0.08-0.14%	<0.2%
Ash particle size	<5 µm	<5 µm
Sodium	58 ppm	<50 ppm
Ash fusion temperature	>1500°C	>1350°C

The purity of UCC has been improved to make it suitable for direct firing into gas turbines, reducing the residual ash content down to around 0.10%, with an ash fusion temperature greater than 1500°C. The higher purity has been achieved through optimising the existing process and the addition of a hydrothermal wash stage.

Important: Whilst the UCC process is highly effective in removing coal minerals down to very low levels (less than 0.1% for some coals), UCC Energy acknowledge that it is still important to minimise the ash content of the feed coal to minimise reagent and processing costs – and the overall fuel cycle GGE.

AMAX

The AMAX process was used with 3 coals in 1985-87, to produce low ash CWF as part of an Energy R&D Program for the EU Commission[14]. The process involved 3 steps as given in Table 4.

Table 4 Treatment conditions for the AMAX process

	Unit	Step 1	Step 2	Step 3
Caustic	wt.%	7		
Hydrochloric acid	wt.%		3	
Water	wt.%	58	62	65
Coal	wt.%	35	35	35
Temperature	°C	230	50	260
Time	min	25	10	25

Three types of coals were tested; Polcargo (Polish), Cerrejon (Colombia) and Smoky River (Canada). These coals were tested because of low costs and availability, and low sulphur content.

Table 5 Coal ash and sulphur content before and after treatment using the AMAX process

Coals	Unit	Polcargo	Cerrejon	Smoky River
Starting coal				
Ash	% db	12.5	2.6	9.6
Total sulphur	% db	0.47	0.43	0.75
After treatment				
Ash	% db	11.6	2.0	7.7
Total sulphur	% db	0.36	0.43	0.75

The AMAX process claims for ash removal from raw coals down to 0.2-1% were not achieved, and no further work appears to have been undertaken (AMAX lacks the final hydrothermal treatment step of the UCC process, which is fundamental to removing the last residuals of mineral content).

CENfuel

CENfuel is an ultra low ash coal produced by a process that originates from Australian inventors Lloyd and Turner. The original patents relate to cleaning coal and oil shale, with particular emphasis on acid regeneration and removal of other deleterious elements from coal.

CENfuel has had a long development history by CENtech. R&D has been undertaken for nearly 30 years, with a pilot plant producing small tonnage quantities of CENfuel and CENcarbon at Mingo County West Virginia. The pilot plant has operated in batch mode at up to 3 tpd, although there have been a number of feasibility studies for commercial scale plants linked to power projects (*eg* a 300MW gas turbine-based power plant by Asia Energy Ltd in the mid 90s), together with a number of proposals for producing carbon-based products (including graphites) with high purity alumina and silica as by-products. Included in these proposals was an offer by former Brown Boveri to provide silo-combustor gas turbines for a Chinese power project to burn either fuel oil or CENfuel – "without major design modifications".

In the process, the main ash components SiO_2, Al_2O_3 and TiO_2 are removed by leaching granular coal (-2mm) with an aqueous solution of hydrofluoric and fluosilicic acids – noting that early versions of the process only used HF for dissolution. Sulphides such as iron pyrites, are not affected by the leach, although most particles are released as the ash dissolves. The leach liquor contains soluble fluosilicates such as $Al_2(SiF_6)_3.9H_2O$, $FeSiF_6.6H_2O$, $CaSiF_6$, $MgSiF_6$, K_2SiF_6 and $Ti(SiF_6)_2$ and undissolved FeS particles. The liquor is passed to a distillation unit where metal fluorides are recovered and removed from the system. The residue is dried and stored. The spent liquor is dried and sent to the gas absorber where HF and H_2SiF_6 are recovered and excess H_2SiF_6 is passed to a hydrolyser for conversion to silica, and the HF is returned to the dissolution circuit. The process has been reviewed by several prominent engineers, Robertson Australia, and Sulzer.

In general, CENFuel production cost is claimed to be US$0.75-1.25/GJ over the cost of feed coal, giving a CENFuel price of US$2.50-3.00/GJ – similar to current cost estimates for UCC. General specifications for CENfuel are <0.3% ash, and an ash fusion temperature >1550°C. Interestingly, none of the available information contain any reference to fuel delivery systems for gas turbines, or on the required particle size of the pulverised CENfuel.

The latest CENfuel announcement relates to the conversion of gob (waste coal) to ultra low ash coal fuels in West Virginia. Up to 10 plants have been mooted, but no details are available.

The commercial use of CENfuel has been proposed on a number of grounds, including lower cost electricity from coal-fired gas turbines compared to fuel oil or natural gas, lower emissions of flyash and trace elements for use in conventional pf power plants, as a high grade carbon, and recently as a method of producing high grade fuel from gob.

The latest information relating to CENfuel is the announcement by Carbonxt[15] (now InterCarbon), with a project registered under the APP Cleaner Fossil Energy Task Force.

In general, there has been limited public information on the CENfuel process, but the process has been recently endorsed[16,17] as a new project under the company Carbonxt in the APP program - subject to proponents securing the funding that is needed to progress the work. The 2 year project is entitled "Proving the commercial and technical attributes of the Carbonxt technology", and the lead country is Australia. Target specifications are <0.5% ash.

In addition, since 2003 there has been renewed interest in the HF route at the University of Nottingham who have undertaken to develop an improved fluoride route specifically for energy coals for gas turbines, with support from the Engineering and Physical Sciences Research Council[18]. The researchers claim that fluoride chemistry offers many options, which are not yet fully realised, especially the ability to produce useful by-products from the extracted ash components. Their process differs from the single dissolution step CENfuel process in that it comprises 2 dissolution steps:

- The first leach at 65°C for 4 hours in low concentrations (3.5 molar) of hydrofluoric acid (HF), which react with most of the coal minerals. The HF does not remove pyrite and does cause small yet significant levels of insoluble fluoride compounds to form in the product coal. At this stage the aluminosilicates and quartz in the coal will have been dissolved to form complexed fluorides enabling the coal to be separated by filtration or centrifuging. The Al and Si complexes can be precipitated out of the solution as a gel and removed by filtration from the acid liquor.
- A second leach is required which preferably solves both the pyrite and residual fluoride problems. HNO_3 has been used[19], as it is able to oxidize pyrite and dissolve fluorides through the formation of HF[10]. However, HNO_3 also reacts with the coal and a way of selectively removing pyrite without oxidizing the coal has not been found. The latest research concludes that $Fe(NO_3)_3$ is a better option.

Regents are recovered by heating the product coal and precipitates obtained from the leach liquor[20].

Using this 2-step process, the ash content of Harworth coal was reduced from 5.3% to 0.09%. The leaching removed almost all of the Al, Si, Ca and Mg containing minerals and pyrite.

There would be a number of additional key processing steps, *eg* filtration of the coal product from the HF and ferric solutions, washing to remove traces of the reagents, and reagent recovery – the last step being potentially able to produce high purity silica and alumina powder.

At this stage the process is still highly conceptual, with individual steps being investigated at the laboratory/beaker scale, and it is therefore unclear whether a practical process can be developed. There are a number of severe issues to be addressed – the extremely hazardous nature of the primary leaching agent, its costs, and where residual fluorides report.

Hypercoal

This is based on Hypercoal production and use as presently claimed/expected by the proponents Kobe Steel. Many details of the process route are proprietary, or have yet to be optimised for specific commercial application. Private discussions have also been undertaken with Okuyama[21]and MHI[22] to assist in making estimates.

Hypercoal is a low ash, low alkali coal product, produced by dissolving the coal matter into an organic solvent, then flashing off the solvent for recycling to the dissolution step of the process. The insolubles (mineral matter and undissolved coal) report to a high ash by-product coal. This is deemed suitable for use in local conventional pf plants (ash content of 30% db, around 5% higher than domestic energy coals).

The Hypercoal process is therefore very different to the UCC process which aims to remove the ash from the coal matter - Hypercoal aims to separate solvent soluble coaly matter from the ash and insoluble coal, thereby also producing a high ash co-product.

A simplified schematic of the process is shown in Figure 7.

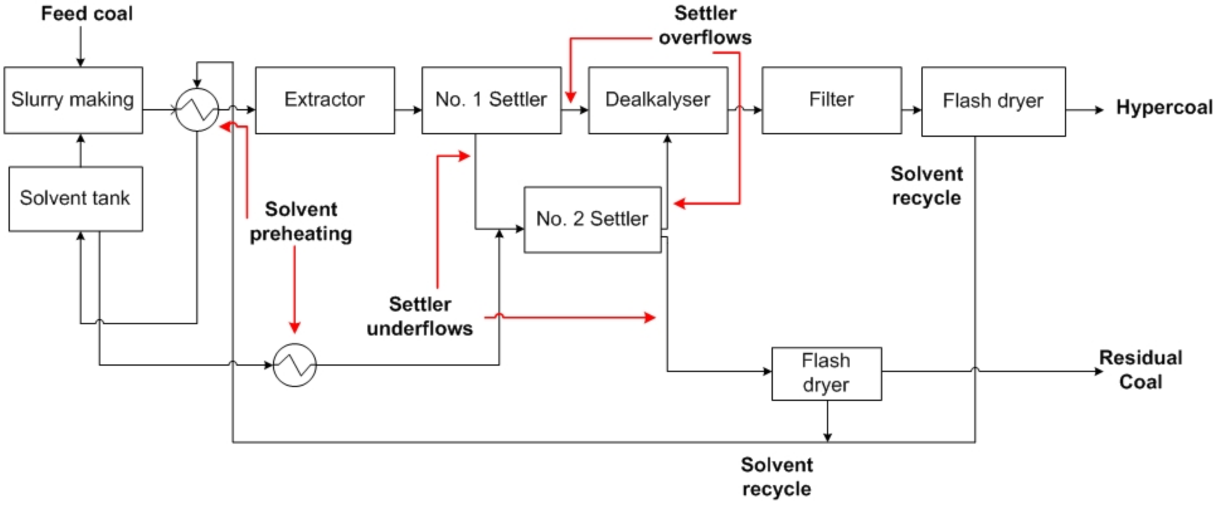


Figure 7 Simplified diagram of Hypercoal process

The Hypercoal production process involves five main steps.

1. The milled washed coal feed is slurried with a solvent.
2. The slurry is then heated to around 360°C and held in an extractor vessel. This is a batch style reactor which allows the more soluble components of coal to be dissolved into the solvent. This affects the yield of Hypercoal, and the ash content of the co-product coal residue.
3. After exiting the extractor, the mixture is passed through two clarifiers/settlers in series to separate the liquid from the solid (the residual coal). The overflow from the clarifiers contains between 0.1-0.5% ash by weight, but upon hot filtration, the ash is claimed to be removed completely[23] This settling step is key to the success of process, and it claimed to occur within minutes. Given the size distribution of the material involved, this seems remarkable, and must involve a number of flocculation phenomena. Whether these are as effective at commercial scale has yet to be proven - centrifuges may be required which will need to operate at the extraction pressure and temperature conditions.
4. The liquid component is then passed through an alkali removal system and a hot filtration stage to remove ultra fine particulates. Again, this step is key to the process and involves a difficult materials processing step, the hot filtration of ultra fines.
5. Finally, both the filtered liquid and residual coal slurry streams are passed through flash dryers to produce dry products – Hypercoal and residual coal. The solvent evaporated from the product streams is condensed and recycled to the extraction stage. Whilst the flash drying step (and the production of micro-prilled Hypercoal and recycled solvent) is commercial practice, the hot filtration (using filters with a pore size of 0.5μm) is likely to be problematic at commercial scale operation. Another key issue is that of solvent degradation. However, laboratory trials have shown that properties of the regenerated solvent from the flashing step show little change between each cycle.

A number of solvents have been used for extraction, with the overall preferred solvents being Tetralin, 1-methyl-naphthalene (1-MN), dimethylnaphthalene (DMN) and Light cycle oil (LCO).

Other solvents have been found to provide higher yields, such as N-methyl-2-pyrrolidinione (NMP), but those listed above are seen as more favourable from an economical viewpoint[23].

The claimed[24] overall features of the technology are:

- Yield of Hypercoal can be up to 80% of the feed coal on a dry ash-free basis.
- The process removes most of the alkalis from the raw coal (a key requirement for gas turbines).
- The higher ash (co-product) residue coal is suitable for domestic power generation.
- The Hypercoal process can be applied to most bituminous and sub-bituminous coals. Yields are generally lower for sub-bituminous coals than for bituminous coals.
- Research into the use of sub-bituminous coals shows some promise of increased yields by pre-treating the coal with hydrochloric or weaker acids (acetic, CO_2 in water).

Several coal quality specifications for use in gas turbines have been set by Mitsubishi Heavy Industries (MHI)[22] as part of the test program with UCC. These are also being targeted by Hypercoal, and include total ash content below 0.2% by weight, ash particle size of less than 5µm, minimum sodium content, and ash fusion temperature in excess of 1350°C.

Generally, these specifications exceed those for fuel oils currently used for gas turbines.

Hypercoal claim that the 5µm ash size specification can easily be obtained in the hot filtration stage, however this is deemed to be a very onerous requirement by the authors and colleagues. Ash particles of this size and larger are particularly deleterious for gas turbines due to their ability to penetrate gas boundary layers and impact onto the hot metal surfaces in the turbine, resulting in erosion and fouling/corrosion.

This shows an interesting difference between Hypercoal and UCC: for Hypercoal the largest ash particle size is set by the mineral matter particle size distribution in the extraneous ash and the efficiency of the hot filtration steps; however, with UCC, this size will be determined by the efficiency of dissolution of the ash during the caustic leach. It is therefore speculated that UCC should contain smaller particles of unaltered mineral particles than Hypercoal.

As Hypercoal is produced as a -20µm micro-prill, it is likely that some form of agglomeration will be needed for dry transportation, possibly binderless briquetting, as for transporting dry UCC. The best option would be to transport the product as a 65% coal-water mixture, and to deliver this to turbine or engines as a hot slurry feed without micronising. This mixture is expected to have very similar handling properties to Orimulsion (a now discontinued fuel, produced by micronising bitumen to form a stabilised slurry).

3.5. Fuel preparation and transportation

There are a number of options/strategies for fuel preparation and transportation, which depend on the location of the production site and power plants, infrastructure, the preferred method of firing for the particular power plant, and storage requirements.

It is most likely that the coal will be provided as wet cake, briquettes or CWF, with final micronising at the power station. Given the need to dilute the coal content of the CWF from around 70% solids to 50% for firing, and to micronise the CWF to below 20µm, it is probably unlikely that a CWF would be delivered in an engine-ready form. It is noted that the stability of a micronised and diluted CWF will be markedly lower than for a thicker and coarser mixture.

Table 6 gives suitable handling routes for the 3 main forms of ultra clean coals - wet cake, CWF and briquette.

Table 6 Handling schemes for ultra clean coals

	Unit	Cake	Briquette	CWF
Water content	Wt.%	30	<5	30
Energy density	GJ/m^3	21	25	18
	GJ/t	22	32	16
Processing before transportation		Nil	Flash drying and binderless briquetting	Milling and addition of surfactant
Transportation		Rail, road as for wet coal or washery refuse	Rail, road as for coal	Pipeline or tanker
Storage		Covered stockpile	Open stockpile	Tanks, intermittent or very slow agitation
Special conditions		Dust during handling and transportation	Nil	Must avoid freezing of slurry
Processing at power plant				
DFGT		Grinding, micronising with additional water to give 50:50 slurry	-	Micronising with additional water to give 50:50 slurry
DICE		-	-	Micronising with additional water to give 50:50 slurry

Other forms of transportation include bulk transportation of wet cake (*ie* directly from dewatering devices), dried product, or dried and briquetted product. These forms of transportation are likely to be only used when slurry fuels are less acceptable, for example when solid firing is required, when the efficiency penalty from CWF water (around 3-5%) is unacceptable, or when increased transportation costs or pipelining costs outweigh drying/briquetting penalties.

As the present review applies to fuels for gas turbines and diesel engines, the water penalty is much smaller and probably negligible when the overall power cycle is considered, and therefore CWF slurry transportation is presently assumed to be the preferred form of transportation.

Final preparation of CWF requires that the coal is either premilled dry before slurry preparation, or milled (micronised) wet as either part of the slurry preparation process, or immediately prior to combustion. In general, wet milling should have lower cost and lower energy consumption, but where this occurs is likely to depend on markets and end use specifications. For example, slurry stability is likely to be better with a wide particle size distribution which would enable transportation of CWF as a more concentrated coal slurry, thereby reducing transportation and storage costs. Micronising to the finer and more narrow particle size distribution, together with dilution to reduce the viscosity for atomisation in an engine would then be carried out by the end user, probably into an agitated day storage tank to ensure uniformity of supply and fuel properties (micronising equipment will be relatively high maintenance equipment and therefore buffering of micronised fuel supply will be essential for base load power plants).

Although a range of handling options are possible, as UCC is produced as a wet cake, the schemes requiring drying will slightly reduce the overall thermal efficiency (through drying energy, increased energy for micronising, and for the dust fired GT the need to produce nitrogen for pneumatic feeding).

The cake and CWF routes avoid the need for drying, but require a small increase in energy for bulk transportation. In contrast to current boiler applications, water in the fuel does not significantly reduce the thermal efficiency of a DICE or DFGT power plant - mostly due to the benefit of increased mass in the expansion stage.

Wet cake

Wet cake is the first product from the UCC process, and would be similar for coals produced by advanced coal cleaning techniques, *ie* 25-35% water, with a particle size of -0.5 mm.

This product is stable and is suitable for transportation by most normal coal transportation means – road, rail bulk carrier and conveyer belt, and using conventional loading and unloading equipment. As the surface layers may dry during transportation, it is envisaged that some dust may be lost – as occurs for coal transport by these methods.

The dust issue could be avoided by covering loads, or by micro pelletising.

Briquette

While a number of briquetting technologies could be used, the White Energy binderless coal briquetting (BCB) process[25] is currently the most cost effective, and has been used to briquette samples of UCC from the first pilot production campaign.

The BCB process has many special features, such as strong and weather resistant briquettes, is completely binderless, and has low processing cost - typically 35-50% of conventional binder processes.

The BCB process compresses fine coal particles into contact with each other under specific conditions (without heating), causing the coal particles to bond together, with bonding mechanisms much the same as exist within the coal structure itself. The process involves a combination of thermal drying and roll briquetting, and produces a strong handleable briquette with moisture levels around 2-5% for bituminous coals.

The briquettes produced from the BCB process have very little inter-particle voidage, and as a consequence have a density very close to that of the original coal. In addition, the low voidage results in very low moisture re-absorption by the briquette, helping to maintain a low moisture product.

Commercial scale operations are currently being developed in Australia and North America and other major coal producing nations.26]

Coal water fuel

Production of a ultra clean coal CWF (UWF) could employ well established commercial developments for normal clean coals (mostly 3-8% ash), and the science and technologies involved have been reviewed in a number of publications.[27,28,29,30]

Most systems involve the preparation of coal water slurries containing 60-70% coal, together with additives to provide slurry stabilisation and to lower the viscosity. Additives consist of dispersants and stabilisers. The dispersant maintains separation of the coal particles within the slurry using electrostatic repulsion effects or steric repulsion effects and sodium sulfonate of naphthalene, polystyrene, polymethacrylate and polyolefin. Stabilisers include additives such as cellulose or xanthan gums.

CWF has been produced commercially for over 30 years. In China, there are currently 20 plants, producing over 4 Mtpa of CWF (universally termed CWM or coal water mixtures in China and Japan). The 5 main companies are China West Coal Energy Inc, Tai'an Liangda CWM Co., Ltd., Datong Huihai CWM Company, Daqing Shengtai Clean Coal Fuel Co., Ltd., and Ningbo Hongyuan CWM Co., Ltd. China also has a National Engineering Research Center for Coal Water Mixture, established in 1999, with 350 staff (mostly engineering and technical personnel), to operate the 13 test facilities for CWF combustion and flow testing, a 6MW combustor and an 8 t/h atomisation test facility.

The purchase specifications for CWF for use as a boiler fuel vary from user to user, but typical requirements are given in Table 7.

Table 7 General specification for CWF for boiler applications in China

Property	Unit	Boiler specifications
Slurry		
Coal content	wt%	68-72
SE (HHV)	MJ/kg, db	22
Viscosity	mPa.s @ 100/s	500-1000
Stability		No coal stratification during transport and unagitated storage for at least 3 months
Coal content		
S	wt% db	<0.8
VM	wt% db	>30
AFT*	°C	Site dependent

* *Ash fusion temperature, of which there are a number of defined fusion points, initial deformation (IDT), softening (ST), hemispherical (HT) and flow (FT)*

For higher concentration and improved stability of CWF, the coal particle size distribution should be wide, and preferably bimodal, rather than the narrow distribution required for combustion in turbines or engines. A typical particle sizes distribution for CWF for boiler use is shown in Table *8*, along with those for a gas turbine and diesel engine.

Table 8 *Size distribution and viscosity of a typical CWF and likely values for* *turbines and diesel engines*

Property	Unit	Current CWF for boilers	Gas turbine	Diesel engine
Mass mean size	µm	10-20	4-6	5-15
Wt% passing				
-5µm	wt%	5	60	30
-10µm	wt%	35	100	60
-20µm	wt%	50		10
-75µm	wt%	75		
-250µm	wt%	95		
-500µm	wt%	100		
Coal content	wt%	65-70	55-60	50-55
Viscosity	mPa.s @ 100/s	500-1000	400	300

Wide or polymodal size distributions are usually obtained by using several mills and or recycle streams – this is shown in the process schematic from JGC Corporation[31] Japan, in Figure *8*.

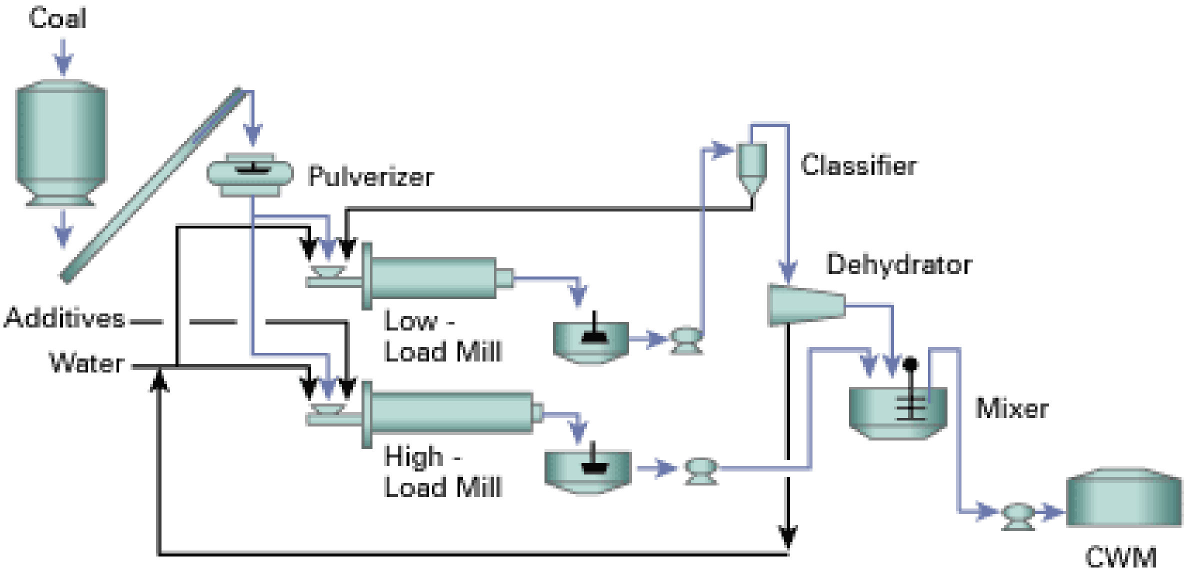


Figure 8 *Schematic of a typical CWF production process*

Whilst pourable (see Figure 9 below) and readily pumpable, CWF exhibits different rheological characteristics to fuel oils, being more like Bingham fluids than Newtonian fluids - when stationary, a CWF is plastic-like, but its viscosity decreases significantly with the shear caused by agitation or pumping. Also, unlike fuel oils, the viscosity of CWF is relatively unaffected by temperature - though temperatures below freezing must be avoided, as this degrades slurry properties when thawed. Slurry viscosities are strongly affected by coal characteristics, concentration, additives, and flow conditions, as shown in Figure 10.

Currently CWF containing 65-70% coal has an apparent viscosity of around 1,000 mPa.s (at room temperature and shear speed of 100/s). This is too viscous for the atomisation required for atomisation of the slurry (and to reduce fuel nozzle wear), and therefore the coal concentration must be reduced by 10-20% by adding water before atomisation to reduce the coal concentration to 45-55%. It is noted that atomisation may be assisted by heating the CWF before the burner or injector nozzles, which can promote flashing.

Figure 9 Pouring a CWF at room temperature[32]

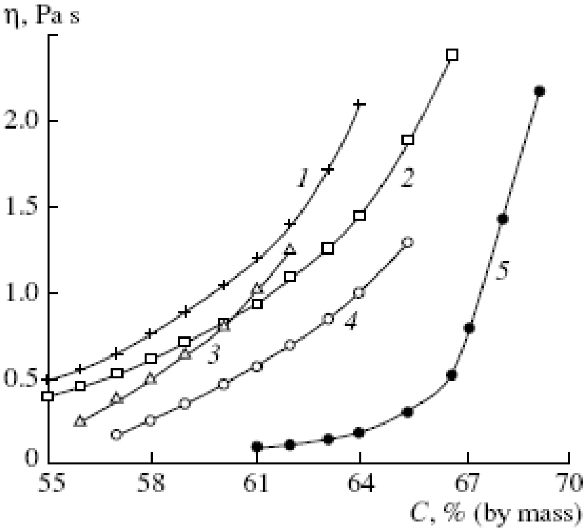


Figure 10 Viscosity of CWF with coal:water ratio (C refers to coal content) for a range of coals and methods of preparation[33]

3.6. Preparation of Victorian brown coals

Although efforts to improving the thermal efficiency of power generation from Victorian brown coals is focussed on either dewatering or drying, efficient power generation in diesel engines could be achieved using slurried brown coal.

As Victorian coals contain very low ash, and as most of this ash is very finely divided or derived from organically bound elements, it is highly probably that coal cleaning would not be required for large diesel engines. However, it is considered highly unlikely that direct firing of modern high efficiency gas turbines will be possible, due to the very high alkali content of these coals.

The main issue for use in diesel engines will be to produce a CWF with an acceptable viscosity with a water content of around 50%, or lower if possible. Although a higher water content would normally have only a slight impact on engine efficiency, Victorian coals also have a high oxygen content, which would further reduce the specific energy of the CWF. It is therefore concluded (though this requires modelling and experimental validation) that some form of dewatering and densification of the coal will be required, such as high shear milling and hydrothermal treatment/dewatering (HTD).

Both techniques have been trialled for Victorian coals both for dewatering, and for the production of cake that allows solar drying and dewatering to around 35% total moisture content. The latter also provides a degree of coalification with both a decrease in particle pore volume and a slight lowering of oxygen content. For the diesel application, only a small degree of dewatering is required, say from 62% down to 45-50%.

As HTD is a relatively simple and reversible process which has a low energy consumption, it is expected that when used to produce a CWF for a low speed diesel engine, an overall thermal efficiency of 50% could be achieved. A simplified flowsheet of a possible brown coal HTD process and engine is given in Figure 11.

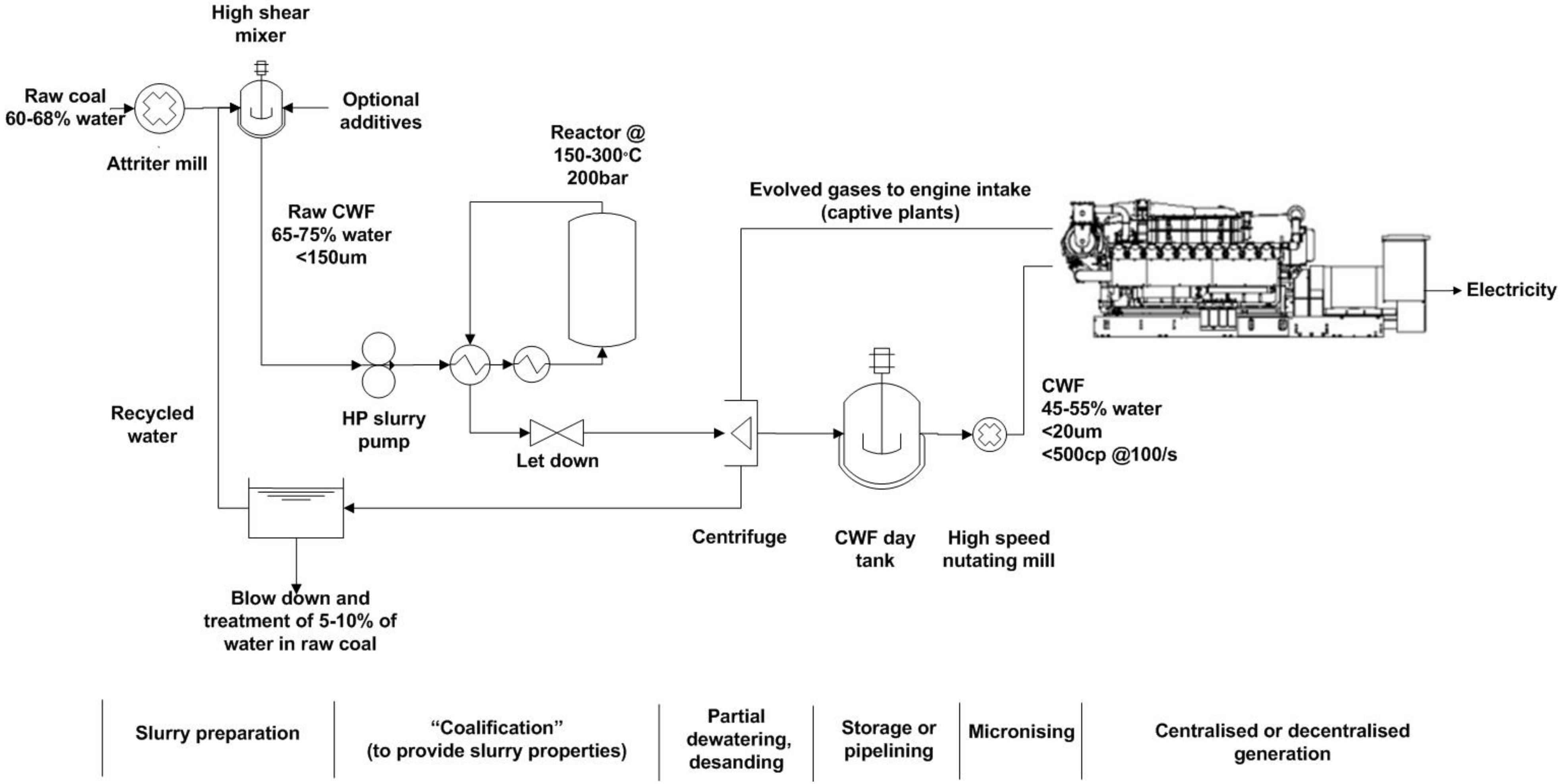


Figure 11 Possible hydrothermal treatment to produce a brown coal CWF for a diesel engine

4. COAL FIRED GAS TURBINES

There appear to have been 2 significant direct coal fired turbine trials, and 3 combustor tests over the last 30 years:

- Demonstration of a coal-fired locomotive in the USA.
- Pilot scale tests of a gas turbine with a slagging combustor.
- GE turbine simulator combustion and fouling tests with a nozzle segment.
- Pilot scale tests of a brown coal fired industrial turbine in Victoria.
- UCC combustion tests carried out by MHI in a simulator based on a M501F combustor,[34,35] supported by fouling characterisation work by Idemitsu[36].

It is important to note that all studies prior to the recent UCC-MHI work, all trials have been performed using essentially raw coals - containing up to 8% ash.

There has been significantly less development work than has been undertaken for the coal-diesel engine. It is speculated that this has likely been due to a number of difficult issues that need to be addressed for turbine tests:

- Firing a gas turbine, even using a single combustion chamber on a multi-combustor engine, will expose the entire expansion turbine section to contamination and erosion from coal combustion products. This makes full scale testing costly.
- Failure of a rotating turbine component will usually cause catastrophic failure down stream of the initial failure. In contrast, failure in a diesel engine is more likely to be over a prolonged period, and without the same dire results.
- A turbine test requires firing the entire engine, which, unless the turbine is very small (<7 MW) has a much higher rating than an individual cylinder on a diesel engine. The higher rating of turbines requires more test fuel and methods to try and utilise the generated power to offset the cost of testing. In contrast, a single cylinder diesel test engine of 150-200 kW can be readily coupled to a dynamometer and the relatively small amount of energy dumped to a cooling tower. This type of test facility is also frequently available at Universities.
- The diesel engine construction makes viewing the combustion process and its effect on the engine relatively easy to monitor. The main methods include a cylinder pressure transducer to produce indicator diagrams for the specific cylinder (which makes calculating cylinder power output and efficiency simple and accurate), injector pressure and needle lift, cylinder exhaust gas temperature and particulates.
- Long duration testing of turbines is essential to obtain erosion and corrosion data – tests in excess of 500 h being preferred for the entire machine. In contrast, much of the durability testing for diesels, especially the fuel injectors, can be performed in cold tests on the individual components, and extremely sensitive wear monitoring equipment has been developed to enable accurate wear data to be obtained within a few hours.[37]

4.1. *Direct coal-fired gas turbine locomotive*

The DFGT locomotive test was by far the most comprehensive, and successful – despite the use of a relatively high ash coal. The test involved a coal-fired 3 MW (4,500 hp) gas turbine locomotive. Union Pacific's coal-burning turbine, a two-unit set, was built between

September 1959 and December 1961. The locomotive was built using the frame and running gear from a scraoped W1-class electric locomotive 5018, with the turbine trailer unit being essentially the same as those on UP's 61-75 class gas-turbine locomotives - modified to burn coal. The coal tender was from a scrapped Mallet steam locomotive, and carried 60 tonnes of nugget coal, and equipment needed to crush and mill the coal to pf consistency.

After stationary load trials, the coal turbine made its first road trip in Oct 1962. It ran in revenue service from October 17 to November 15, and again from November 16 to March 24, 1963. After further modifications and stationary load testing, it accumulated a further 14,000 km until May 1964, when it made its last revenue trip, after which it was removed from service and stored.

The coal-burning turbine tests were unsuccessful because of excessive wear of the turbine blades caused by the fly ash from the coal, and also because of problems with pneumatic transport of the coal from the tender to the turbine unit. It is noted that all of the gas turbine locos were taken out of service after the first oil price shock as they were less fuel efficient (and noisier) than diesels.

Figure 12 Union Pacific 4,500 hp (UP80 class) coal turbine locomotive set with coal tender at the rear circa 1960[38]

4.2. Slagging combustor DFGT

The most reported work is from the USDOE advanced coal-fuelled gas turbine systems program undertaken by Westinghouse Electric, from 1986 to 1993.

The trials used 3 US high volatile coals as shown in Table 9.

Table 9 Coals used in the DOE direct fired turbine

			Eastern bituminous		Western subbituminous
			Dorchester	Pittsburgh No.8	Hanna
Ash		% ar	6.49	7.71	5.91
VM		% ar	34.0	38.9	42.2
Fixed carbon		% ar	59.5	53.4	51.9
Ultimate					
	C	% daf	86.4	84.4	78.2
	H	% daf	5.74	5.73	5.92
	N	% daf	1.53	1.47	1.69
	O	% daf	5.17	5.66	13.25
	S	% daf	1.11	2.59	0.66
	Cl	% daf	0.04	0.15	0.05

The purpose of the R&D program was to develop a technology base for the commercial application of direct coal-fired gas turbines. The combustion system under consideration incorporated a staged, rich-lean-quench, slagging combustor concept, aimed at separating molten slag particles from the rich combustion gases before the secondary combustor and expansion turbine. It is noted that a similar arrangement (but with the first stage combustor called a "pressurised gas generator") had been used by Brown Boveri[39] for an early recuperated gas turbine using German lignite during 1943-47 (in Baden).

This concept was chosen because of 25 years of experience on the development of a slagging Toroidal Vortex Combustor (TVC), originally designed for magnetohydrodynamics (MHD) applications.

The main findings were that:

- The trials showed that with CWF, the 3.5MW turbine output increased to 4.9MW (as the result of the increased turbine mass flow rate).
- Carbon burn out efficiency was in excess of 99%.
- 90% of the ash can be separated as slag in the impact separator, and a total of 98 to 99% removed with the addition of the slagging cyclone separator.
- The mass mean diameter of the fly ash entering the expansion turbine was 8-90µm – significantly above the 5µm considered acceptable for turbines.
- Measurement of alkalis in the hot combustion gases showed that 98-99% of the alkalis in the coal had been removed in the slagging section. However, this still gave an alkali loading of 0.4-0.7 ppmw (based on exhaust gas flow), which exceeded the guidelines of 0.02 ppmw - based on experiences with fuel oil.
- Significant fouling of nozzles and buckets occurred over several hours of operation, although this was readily removed by nut-shelling and/or water washing. As alkalis can combine with sulfur to form a highly corrosive agent that will attack portions of the hot gas path, trials were untaken with a number of absorbents to modify the fly

ash chemistry and absorb some of the alkalis in the bulk ash which would then be removed in the slag separation stages[40]. The absorbent trials were only partially successful in reducing the alkali load on the turbine.

There appears to have been no further development of this turbine.

4.3. GE turbine simulator trials

As part of the DOE advanced coal fuelled gas turbine systems program, GE performed combustion and fouling tests using a turbine simulator for an LM500 advanced aero derivative engine (around 3-4 MW, and intended for marine transport applications). The study involved combusting a CWF, using a range of additives to alleviate nozzle fouling.[41]

A cross section of the engine simulator is shown in Figure 13 below.

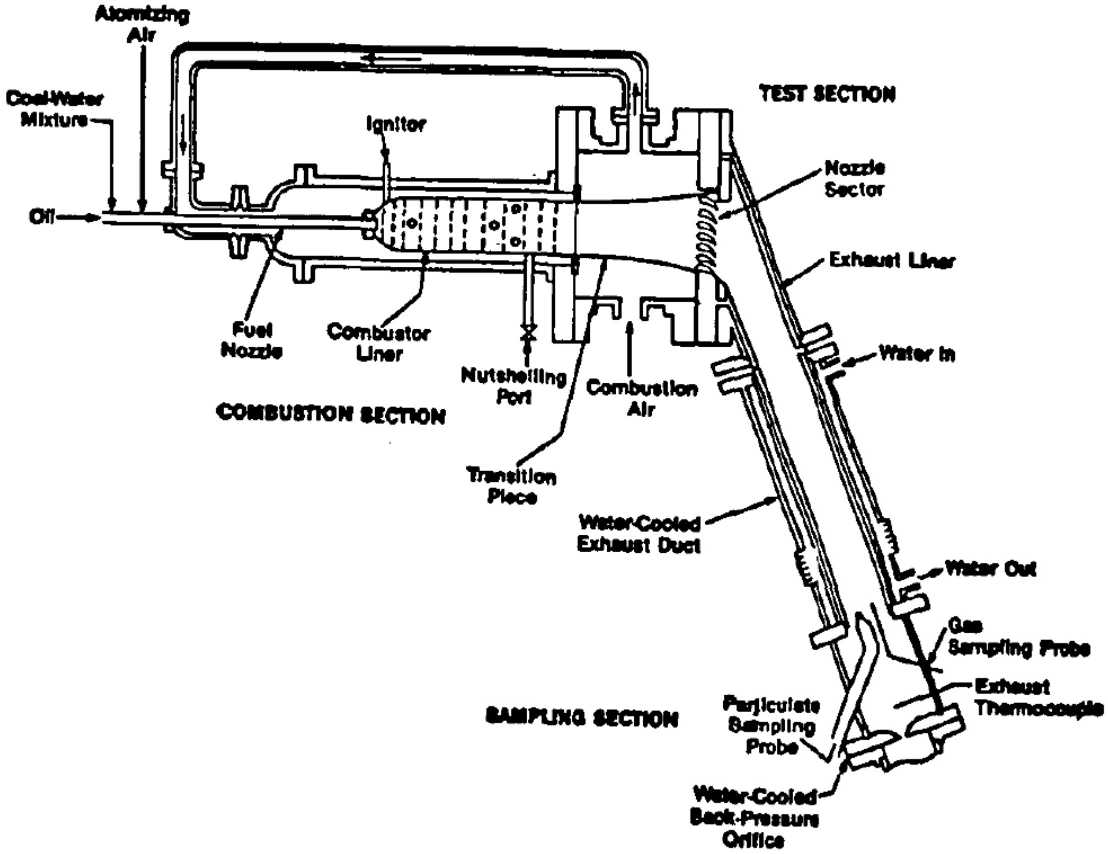


Figure 13 Cross section of the GE LM500 simulator

The CWF was a 50:50 mixture produced by Otisca Industries using Blue Gem coal. The properties are given in below.

Table 10 Properties of the coal and CWF used for the turbine simulator.

		Unit	Value
Proximate			
	Ash	% db	0.90
	VM	% db	0.80
	FC	% db	37.9
Ash			
	SiO_2		22.4
	Al_2O_3		29.15
	TiO_2		1.8
	Fe_2O_3		25.5
	CaO		9.86
	MgO		3.00
	K_2O		0.17
	Na_2O		0.54
	SO_3		0.62
	P_2O_5		0.33
PSD			
	D_{50}	µm	3.6
	D_{90}	µm	10
AFT			
	ST	°C	1400
	HT	°C	1430
CWF viscosity @112/s		mPa.s	230

The CWF was atomised using compressed air, at 16 bar, (1.9x combustor pressure). The tests were performed using 10% diesel pilot fuel to ensure flame stability.

Untreated CWF was found to produce chronic nozzle and bucket fouling after 25-40 h.

The additives used included alumina, boehmite (AlO(OH)), and a range of kaolin clay additives. Alumina-based additives were found to be completely unsuitable, and led to increased fouling by Na_2SO_4. Fouling was found to be greatly improved by small additions of kaolin materials. These rendered deposits friable, and easily removed by normal cleaning procedures of nut-shelling, and warm water washing.

4.4. Victorian DFGT

There have been several studies into direct firing of Victorian lignites over the period 1958-78; however, the relevant references were unobtainable for this report. Work was terminated due to extremely severe fouling of nozzles and buckets.

4.5. MHI combustor trials

The MHI trials did not involve firing a turbine, only a single combustor basket from a large modern turbine. These trials are significantly different from the early turbine pilot tests: an ultra low ash coal was used, and the combustion conditions were similar to those in a modern gas turbine.

In 2002, the UCC pilot plant was operated to produce 3 t of product for utilisation trials. UCC was sent as wet cake to Japan for analysis, combustion and handling trials by Idemitsu Kosan, and to Mitsubishi Heavy Industries (MHI) for combustion trials to assess its suitability as a gas turbine fuel. A sample was also sent to CSIRO to be formed into binderless briquettes which were then sent to Idemitsu for evaluation of their handling properties.

Idemitsu Kosan studied trace elements, ash properties, and combustion characteristics. This followed extensive testing of UCC samples that had been generated at a laboratory scale and sent to Idemitsu over the previous year.

The analysis of the product is given the Table 11.

Table 11 Nominal UCC properties used for MHI combustor trials

		Unit	Value
Proximate			
	Ash	% db	0.28
	VM	% db	34.6
	FC	% db	60.3
Ash			
	SiO_2		9.35
	Al_2O_3		4.02
	TiO_2		27.57
	Fe_2O_3		8.92
	CaO		2.90
	MgO		0.39
	K_2O		0.01
	Na_2O		10.41
	SO_3		13.7
	P_2O_5		0.39
PSD			
	D_{50}	µm	4
	D_{90}	µm	9
AFT (oxidising)			
	HT	°C	>1500
	FT	°C	>1500

Key properties for the gas turbine were an ash fusion temperature above 1350°C (the UCC supplied had an HT and FT >1500°C), and that fly ash particles left after combustion be less than 5µm to avoid nozzle and bucket erosion. Idemitsu's assessment of the ash particle size shows that the small quantity of ash generated when UCC is burnt is predominately less than 5µm in size.

As per normal gas turbine development practice, combustion trials were performed using a single gas turbine combustor – derived from an MHI M501F turbine. The combustor and burner were adapted to burn micronised UCC in place of natural gas, with the conventional distillate pilot being retained.

Figure 14 and Figure 15 show the gas turbine combustion basket and the test chamber in which it is mounted.

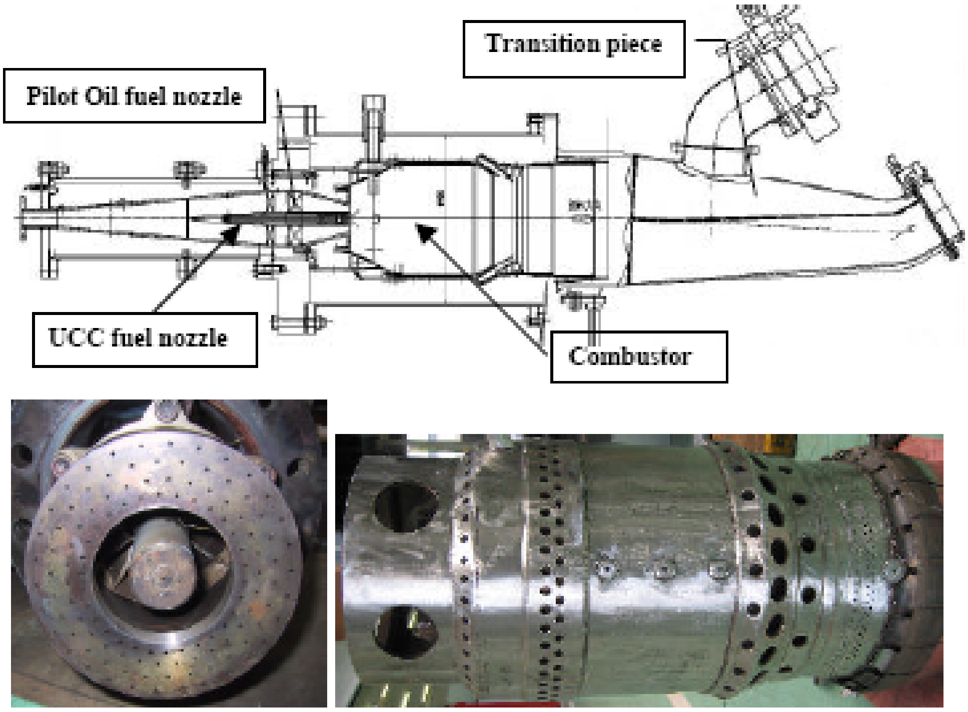


Figure 14 *Cross section and photographs of the MHI combustor basket and fuel nozzle for the UCC test program*

Figure 15 View of the assembled combustion chamber on the MHI test rig

The combustion tests were very successful - a high degree of flame stability and combustion efficiency was achieved in the first version of the UCC combustor. Stable combustion of the UCC could be maintained at normal power levels without the need for a pilot flame. Start up was made with a distillate fuelled pilot flame - as is the case for natural gas firing.

Combustion efficiency figures between 93% and 100% were generated, which is seen by MHI as particularly good for the first version of the combustor. In addition, MHI believe that the actual combustion efficiency was higher than measured, with the lower efficiency values more likely to have been the result of fluctuations in fuel delivery by the pneumatic conveying system.

Overall, UCC combustion was similar to that for liquid fuels, with increased flame radiation. The overall conclusion by MHI was that they were confident that they could modify the design of the combustor and fuel delivery system to give high performance required of a commercial engine.

Discussions with Siemens suggest that there are a number of alternative configurations for gas turbines that would be especially suitable for firing UCC fuels. This included an oxy-fired, humidified variant for CCS applications.

5. COAL FIRED DIESEL ENGINES

Most direct fired coal engines have been based on the compression ignition (*ie* diesel) engine, with variations around the method of introducing the coal into the engine. These include:

- Dry aspirated coal engines (DACE), where fine pulverised coal is ingested along with the combustion air via the intake valve.
- Direct injection of dust, where fine pulverised coal is blasted into the engine immediately prior to ignition (towards the top of the compression stroke) using higher pressure air. This method was used in Rudolf Diesel's original compression ignition engine described below.
- Direct injection of CWF, in a similar manner to diesel or fuel oil in a conventional diesel engine. This approach has been the subject of most development, and is currently the most successful.

5.1. History

The coal-diesel engine has undergone sporadic periods of development for around 105 years. It was invented in the late 1800s by Rudolf Diesel, under a 1898 patent for an "internal combustion engine", with Diesel's initial patents covering compression ignition engines that were also intended to burn waste lignite coal dust (noting that the first compression ignition engine patents were actually by Herbert Stuart in 1886). A key feature of his engines was the very high theoretical thermal efficiencies – around 75% of Carnot, compared to 10% for steam cycles of the period. The first diesel is shown in Figure 16 below.

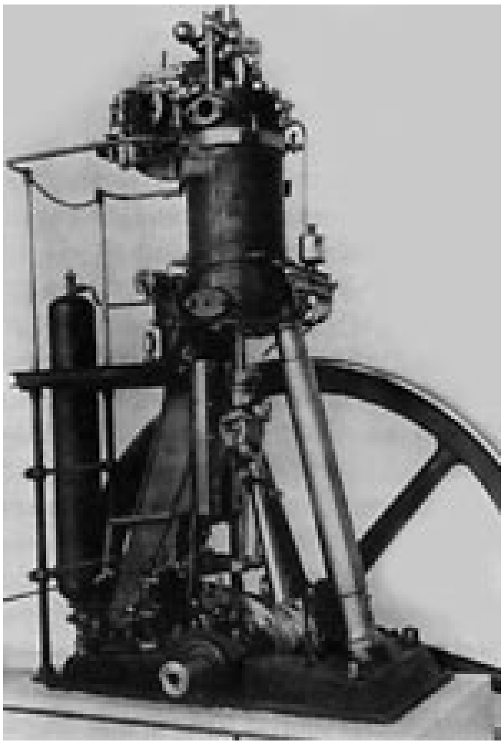


Figure 16 The first diesel from 1897[42]

Although coal was included in his original patent, it was several years before he experimented with coals. After several explosions, the issues of fuel supply, ash and safety issues terminated development of the coal diesel by Diesel; however, development was continued by others. Testing continued through the early 1900s with the work of Pawlikowski (a colleague of Diesel), Morrison, and others. This was followed by extensive German development of the use of pulverised lignite in diesels during 1920-1944. After the war, the competition to produce other equipment, together with the availability of low cost imported oil, terminated the development of the coal-diesel in Germany.

In spite of this early work, the coal diesel engine has not yet been commercialised – or operated for extended periods for demonstration. This is not due to thermodynamic reasons, but is almost entirely due to practical issues of fuel delivery and engine component durability. It is noted that although coal will have combustion differences with diesel fuels, in particular ensuring complete char burnout, for large engines these problems are considered minor compared to the fuelling and durability issues.

The most severe technical problem encountered has been injector nozzle durability, with conventional injector nozzle life of less than 5 hours on CWF. However, a comprehensive R&D program for the DOE during 1982-94 produced a wide range of technology solutions to engine, combustion and durability issues. Subsequent tests[4359] with specially hardened components indicated more promise, and this led to a detailed DOE program to address the technical barriers to commercialisation. These involved two 5-year proof-of-concept projects started in 1988. Each project involved research and financial support by major US engine manufacturers, and covered a wide range of technical issues.

Although these programs developed technically feasible engine systems and operating procedures despite relatively impure coal fuels (up to 6% ash and with particle top sizes up to 80µm), these programs were not continued, mostly due to persistently low oil prices in the early 1990s.

5.2. Diesel engine features

The main features of a diesel engine are discussed briefly with respect to their use for CWF - which is more difficult to atomise, ignite and combust than conventional diesel fuels (distillates and HFO).

The major distinguishing characteristic of the diesel engine is the compression-ignition principle, which relies on specialised fuel preparation. In contrast to spark ignition engines which use a spark to ignite a pre-mixed and homogeneous fuel-air mixture in approximately stoichiometric proportions, the compression-ignition engine relies on the spontaneous ignition of a fuel jet injected just prior to top-dead-centre (TDC). This allows higher compression ratios, higher thermal efficiency, and use of a wider range of fuels – but has issues, especially for CWF.

The spontaneous ignition occurs after a short delay needed for mixing the fuel with hot air, fuel vaporisation, and the onset of chemical breakdown and oxidation of the fuel. The mixing process is crucial to the operation of the diesel engine, and has received a great deal of attention which is reflected in a wide variety of fuel delivery and combustion systems.

Charge heterogeneity is why, at full load, diesel engines operate with 130-150% excess air for 4-strokes, and 150-200% for 2-strokes (the ratio is even higher under part load and maximum rpm as the compression ratio remains essentially constant with load).

The importance and methods for achieving fuel air mixing give rise to the 2 main classifications of diesel engines – direct or indirect injection. The other fundamental engine classification is the number of strokes/cycle, 2 or 4 stoke, noting that this relates to how gases are exchanged to and from the engine. There are a number of other engine features that are affected more by the application (required power:weight ratio, speed, size constraints, fuel flexibility) which will also be summarised. Most variants have been studied for CWF.

5.2.1 Direct injection

With direct injection (DI) systems, fuel is injected directly into a combustion chamber formed in the cylinder between the piston crown and the cylinder head in which is mounted the fuel injector with its single or multiple spray orifices or nozzles. Figure 17 shows a typical spray pattern for a large 4-stroke engine with quiescent combustion, and Figure 18 shows the spray patterns for a large 2-stroke engine with a high degree of swirl.

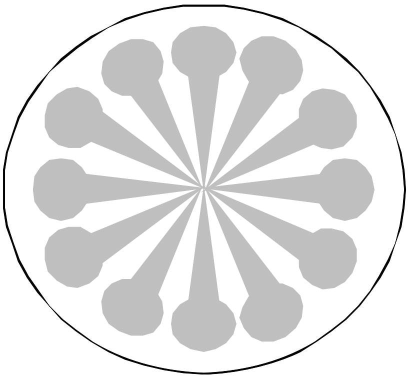


Figure 17 Typical spray pattern for a quiescent combustion system for larger 4-stroke engines with a central injector

Figure 18 Typical injection spray patterns for a large 2-stroke engine using high swirl and peripheral injectors

5.2.2 Indirect injection

Indirect injection (IDI) systems are less common, but they may have advantages for CWF. In these systems the fuel is injected into a small pre-chamber in the cylinder head. The rapid transfer of air from the cylinder into the anti-chamber gives a very high degree of air motion in the pre-chamber which helps fuel-air mixing and reduces ignition delay – especially if the chamber is insulated (*ie* adiabatic).

Although IDI is not used for larger engines, because of the increased difficulty in achieving effective atomisation with CWF (due to high viscosity and wear issues), and longer ignition delays due to the need to evaporate slurry water before ignition can occur, both DI and IDI systems, have been considered in recent studies. This is because IDI makes it easier to provide local adiabatic conditions for ignition of CWFs, compared with providing an entire uncooled head as would be needed for DI.

5.2.3 Engine cycles

This affects the periods for air ingestion, compression, hot gas expansion and exhaust gas expulsion (scavenging).

In a 4-stroke engine cycle, inlet, compression, expansion and exhaust are controlled by mechanically operated inlet and exhaust poppet valves in the cylinder head. This gives the cycle very distinct stages with only minimal (and controlled) overlap. This is the dominant engine for capacities below 20 MW.

In the 2-stroke engine, the out flow of exhaust overlaps with the start of inflow of fresh air. Although a number of configurations are used to achieve this, the uniflow scavenged engines, with an exhaust valve in the head and a belt of piston ports for pressurised inlet air, is the most common type used for very large diesel engines between 20 and 97 MW (30,000-160,000 hp). These engines have both very high efficiency, fuel flexibility, reliability and longevity, and are therefore very relevant for CWF for power generation. This type of 2-stroke engine is also usually a crosshead-type which greatly reduces contamination of crankcase lubricant with ash and combustion products. With conventional (gudgeon pin) 4-stroke engines, CWF use will require additional lubricant filtration capacity to remove ash contamination from oil washed down from the cylinders.

5.2.4 Injection and combustion

Diesel engines inject the fuel as high speed jets (300-400 m/s) of liquid into the combustion chamber. The high velocity causes atomisation of the “solid jet” by shear. Figure 19 shows a top view of the jets formed from a 6-hole injector at ~1ms intervals.

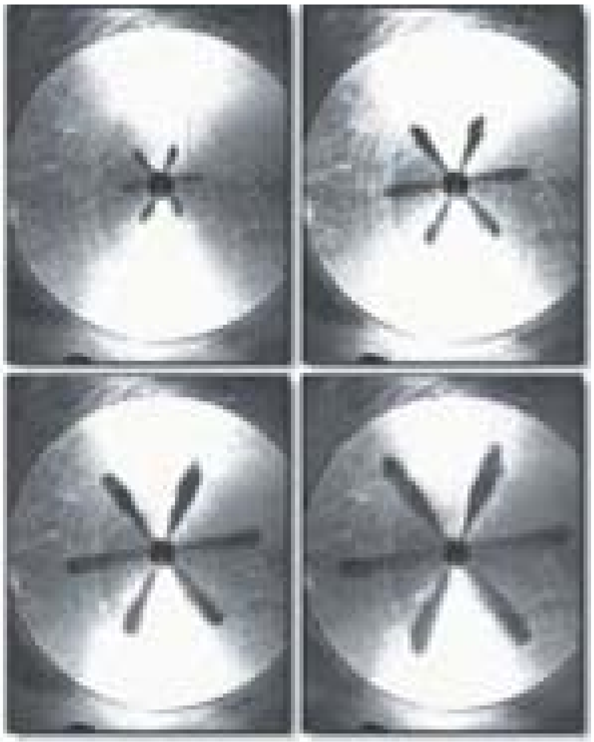


Figure 19 Spray development over a 5 ms period as viewed from under a 6 hole injector[44]

Figure 20 shows a schematic cross section of a diesel fuel jet typical of a large engine, starting with the liquid fuel, fuel vapour, through to the soot oxidation zone in the head of the jet.

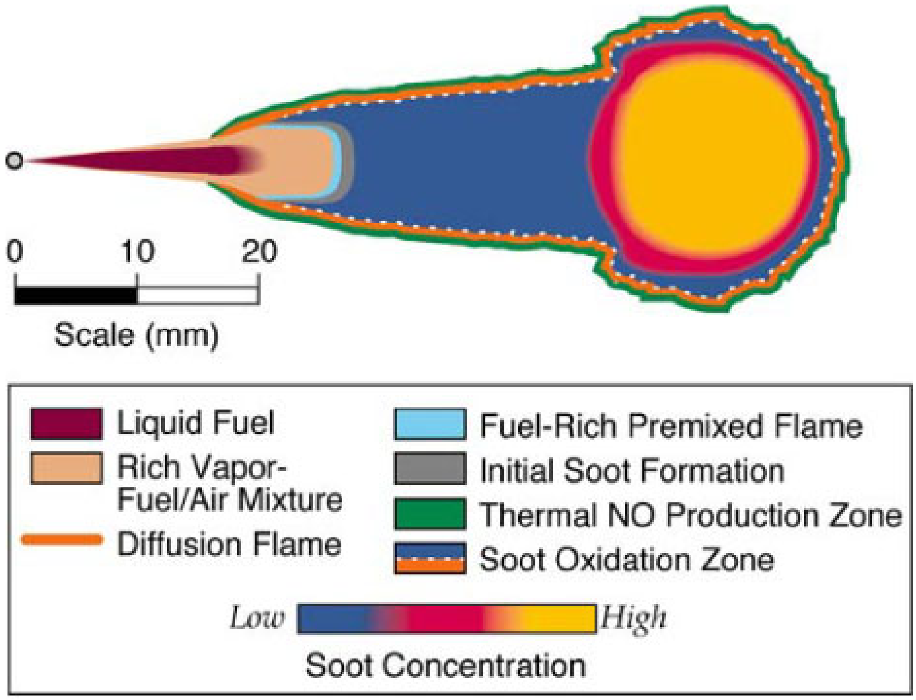


Figure 20 Zones within a diesel combustion plume[45]

5.3. Implications for CWFs

The description of the combustion phenomena for a diesel fuel jet indicates how different, and difficult, CWF combustion is in engines, especially:

- How little of the hot cylinder gases are in contact with the jets during injection, which is necessary to transfer heat to initiate combustion, especially as a CWF jet requires approximately 400% more heat transfer to evaporate the water and heat the coal to the point of ignition than is required for diesel fuel. For CWF, it is important to note that evaporation also occurs at a cylinder pressure of around 60 bar, giving a boiling point for water of around 270°C. When this is completed, the coal particles need to be heated a further 300°C, to around 600°C to achieve ignition.
- The length of individual jets - the jet schematic in Figure 20 shows that the length of a fully developed fuel jet is at least 100 mm, and so the diameter of the combustion space required to avoid jet-metal impingement is around 250 mm (especially as water evaporation will lengthen the liquid fuel portion of the jet). Although this would not be an issue for the 1,000 mm bore engines envisaged for stationary power generation, engines of this limiting bore are used in locomotives and heavy mining equipment.

From the available literature, there is much less detailed information available for CWF under similar injection conditions. *Although excellent combustion and efficiency results have been obtained in test and pilot engines, understanding how this is achieved and methods of improvement is clearly a topic for additional investigation.*

Although efficient fuel-air mixing is required for complete combustion, all conventional diesel injectors utilise pressure atomisation from small nozzles (0.3-0.8 mm). The process of atomisation being almost entirely due to the shear action between the high pressure air in the combustion space and the high velocity stream of liquid (200-500 m/s) leaving the injector nozzles. Only in liquid fuelled gas turbines (*ie* with constant combustion) is nozzle swirl used to assist in atomisation and mixing. Other measures include twin-fluid atomisation, and the addition of low boiling point fractions to assist atomisation (*eg* the use of unrefined crude oil in marine diesels), and the use of fuel-water emulsions for assisting atomisation of heavy fuels.

Recently solid injection has been used for Orimulsion where the bitumen-water emulsion is heated to invert it, to provide bitumen as the continuous phase with micro-droplets of water; inversion should assist atomisation. A similar effect was trialled in the 1980-90 period to improve combustion of heavy fuel oils by secondary atomisation from water flashing to steam in the combustion chamber. Typically 5-10 wt.% water was micronised into the fuel using a micronising mill (disc shear type). In Australia, trials were undertaken to improve combustion and reduce NOx for both boiler and marine applications[46]. Large marine engines can also add up to 50% water to the fuel for control of NOx.

Not withstanding the difficulties of atomising and igniting CWF in engines, combustion and thermal efficiencies matching that of the original engine burning diesel fuel have been achieved with the pressure atomisation system for CWF at up to 1900 rpm. This is double the maximum engine speed predicted from the studies in the 1970s.

5.4. Diesel engine fuel requirements

Normally, diesel engines can tolerate very broad fuel specifications and properties – despite the relatively short time available for fuel delivery, preparation and combustion. The most tolerant engines are the larger low speed engines for generation and marine applications, due to larger clearances in fuel delivery systems, more adiabatic compression conditions, and the longer period available for fuel preparation, ignition and burnout (marine applications have a further advantage of less stringent emissions requirements once in open water). Note, the normal cetane requirements of automotive and small engines become much less important in larger engines.

The current understanding of fuel properties remain as summarised in Table 12.

Table 12 Nominal fuel properties for industrial turbines and diesel engines.

		Gas turbine	Diesel engine (>175 kW/cylinder)	Comments
Ash content	% db	0.2	0.5 (up to 2% for very fine soft ash, say clays)	Diesel engine tests up to 3%
S	% db	0.5	<5%	MANN HFO spec[47]
V	ppm	<30	<600	“
Na	ppm	<50	Less than 30% of V	“
Ash top size	µm	10	20	Some evidence that <5 or >30 is best
VM	%	>20	>20	Based on fuels tested in the past

Additional information regarding CWF fuels is given in Section 5 below, which summarises results from coal-engine developments. These developments show that only very broad CWF specifications have been used; a mean particle size of below 20µm, a top size of up to 80µm, an ash content below 3% db, and a slurry solids content of 50-55%.

5.5. *Orimulsion fuelled engines*

Orimulsion was produced from bitumen, and the adaptation of large diesel engines to efficiently burn this fuel (and the high-viscosity bottom oils obtained from oil company refining processes) provides a significant analogue for the development of the coal diesel.

From 1985 through to 2006, Petroleos de Venezuela S.A. (PDVSA) produced a fuel called Orimulsion, consisting of natural bitumen droplets (median size 15-20µm) micronised into water (30 wt.%). In this form, Orimulsion is expected to have very similar transportation properties to a coal-water slurry.

In 2003 the Venezuelan government decided to reduce production of Orimulsion and concentrate on upgrading it or blending it with lighter crude oil – both options gave greatly increased profits, due to the increase in crude oil prices. Despite on-going supply contracts, Orimulsion production ceased in late 2006.

Figure 21 Orimulsion being poured at room temperature

Production was by pumping the bitumen to the surface using a solvent (unknown), degassing, removal of saline formation water, and storage at around 90°C. As raw bitumen has extremely high viscosity at ambient temperatures, the bitumen is micronised into water with the aid of a surfactant (nonylphenol ethoxylate added at ~0.2 wt.% of Orimulsion) to allow transportation and storage at ambient conditions; say 10-40°C. In this form, Orimulsion would have very similar properties to a stabilised UCC slurry.

In 2002, total generation capacity based on Orimulsion was around 3,400 MW, comprising steam-based power plants in Denmark, Italy and Japan. It was also under test in a 38 MW (Wärtsillä) diesel power plant in Denmark. Its use as a lower cost alternative to coal for conventional power stations has caused environmental (Greenhouse gas) concerns over the approximate 2-3% reduction in thermal efficiency due to the water content. This concern does not apply to its use in diesel engines, because the thermal efficiency is unaffected. Orimulsion was also targeted for power generation in China, Lithuania, Thailand, UK, and the USA. The main drivers were lower capital and R&M costs for the power plant compared to coal (by avoiding coal storage, handling and milling).

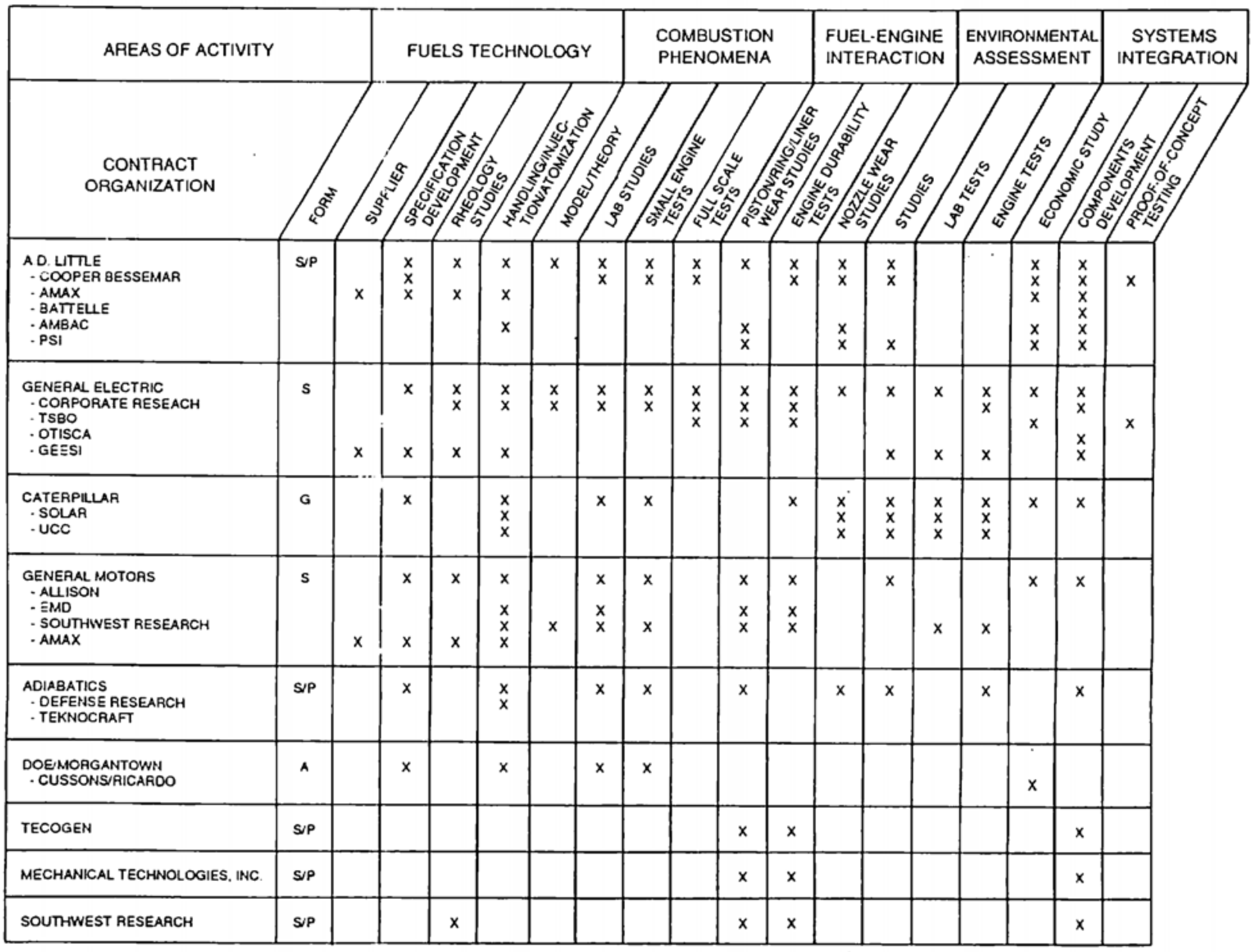
Interestingly, for diesel engine applications, Orimulsion was inverted from bitumen in water to water in bitumen. This was achieved by heating to around 160-180°C at around 18 bar. Under these conditions, the Orimulsion behaved as a HFO and could be atomised for diesel combustion. As the atomised droplets contain smaller droplets of water, the expansion of the water provides secondary atomisation of the fuel.

As Orimulsion contained a relatively high concentration of sulphur (2.8%), 0.09% ash and was highly aromatic, flue gas desulphurisation and particulate filtration were required on the exhaust gases. Technology for achieving this have been demonstrated under commercial conditions in Finland, Denmark, and Italy.

5.6. Recent coal-engine programs

The most significant reported developments involve the two 5-year proof-of-concept projects started in 1988. Each project involved research and financial support by major US engine manufacturers, and covered a wide range of aspects as shown in Table 13. This program[59] was focussed on engines with capacity below 12 MW – for locomotives and for distributed generation.

Table 13 US DOE coal-diesel program 1988-1998



AREAS OF ACTIVITY	FUELS TECHNOLOGY					COMBUSTION PHENOMENA				FUEL-ENGINE INTERACTION			ENVIRONMENTAL ASSESSMENT			SYSTEMS INTEGRATION		
CONTRACT ORGANIZATION	FORM	SUPPLIER	SPECIFICATION DEVELOPMENT	RHEOLOGY STUDIES	HANDLING/INJECTION/ATOMIZATION	MODEL/THEORY	LAB STUDIES	SMALL ENGINE TESTS	FULL SCALE TESTS	PISTON/RING/LINER WEAR STUDIES	ENGINE DURABILITY TESTS	NOZZLE WEAR STUDIES	STUDIES	LAB TESTS	ENGINE TESTS	ECONOMIC STUDY	COMPONENTS DEVELOPMENT	PROOF-OF-CONCEPT TESTING
A.D. LITTLE	S/P		X	X	X	X	X	X	X	X	X	X	X			X	X	
- COOPER BESSEMAR			X				X	X	X		X	X	X			X	X	X
- AMAX		X	X	X	X											X	X	
- BATTELLE																	X	
- AMBAC					X					X		X				X	X	
- PSI										X		X	X			X	X	
GENERAL ELECTRIC	S		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
- CORPORATE RESEACH				X	X	X	X	X	X	X	X				X		X	
- TSBO									X	X	X					X		X
- OTISCA																	X	
- GEESI		X	X	X	X								X	X	X		X	
CATERPILLAR	G		X		X		X	X			X	X	X	X	X	X	X	
- SOLAR					X							X	X	X	X			
- UCC					X							X	X	X	X			
GENERAL MOTORS	S		X	X	X		X	X		X	X		X			X	X	
- ALLISON																		
- EMD					X		X			X	X							
- SOUTHWEST RESEARCH					X	X	X	X		X	X			X	X			
- AMAX		X	X	X	X													
ADIABATICS	S/P		X		X		X	X		X		X	X		X		X	
- DEFENSE RESEARCH					X													
- TEKNOCRAFT																		
DOE/MORGANTOWN	A		X		X		X	X										
- CUSSONS/RICARDO																X		
TECOGEN	S/P									X	X						X	
MECHANICAL TECHNOLOGIES, INC.	S/P									X	X						X	
SOUTHWEST RESEARCH	S/P			X						X	X						X	

5.6.1 Cooper-Bessemer

Since 1985, Cooper-Bessemer has done extensive R&D on the coal-diesel with funding from USDOE and others.

The target application was modular power generation in the 10-100 MW size, with each plant using between two and eight engines. In the late 80s and early 90s, such systems were expected to be economically attractive in the non-utility generation market after 2000, when oil and natural gas prices were expected to escalate rapidly compared to the price of coal.

Over 1000 hours of prototype engine operation were achieved on CWF, including over 100 hours operation of a six-cylinder, 1.8 MW engine with an integrated emissions control system. Arthur D. Little managed the program, with Cooper-Bessemer contracted for the engine design and testing.

Several key technical advances were achieved: more durable injection nozzles, integrated emissions control, lower cost clean coal slurry formulations "optimised" for the engine, and a design to enable a full scale proof-of-concept test of an integrated system.

Key achievements for the program in 1992-1993 were:

- The full-scale (six cylinder, 1800 kW) Cooper-Bessemer Model LS (low speed) engine was assembled and demonstrated on coal-water slurry fuel. 200 hours of full load engine testing were achieved at the Cooper-Bessemer test facility.
- An improved, lower-cost slurry preparation approach, in which an "engine grade" coal cleaning module was integrated with conventional mine-mouth cleaning (ie conventional washery), was developed and demonstrated by QC Inc. This included a full scale, 26 kL slurry storage and handling system.
- A full-scale 1.8 MW emissions control system was installed and demonstrated at the Cooper-Bessemer test facility. NOx emissions for the coal diesel were competitive with gas turbines, and SO_2 and particulate emissions were below those of competitive, pf power plants.
- The engine achieved around 40% thermal efficiency, and it was projected that this would increase to around 46% with a steam bottoming cycle (as often used in marine applications). This efficiency is significantly better than could be achieved with a gas turbine, which, at this scale, would be recuperated and give only ~40% efficiency.
- Installed costs were similar to those of larger gas turbines.

Although these coal slurries performed well in terms of handling, injection and burning, their projected cost for use in a commercial coal-engine facility was considered too high to compete with oil and gas in the 2000-2010 timeframe.

The economic rationale at the time was to achieve a CWF cost below \$3.00/GJ delivered (which allowed around USD 1-l.5/GJ for coal processing and slurrying). At the time the study was done, however, diesel fuel would have cost around USD 0.2/L or USD6/GJ. To match the diesel fuel price, there was considerable effort made to relax the CWF specifications, and to identify alternative coal cleaning technologies that could produce engine grade CWF on a commercial scale for much lower cost.

The revised CWF specifications for the LSC 6-cylinder engine tests were: <2% ash, 88 μm top size, 12-15 μm mean size, 51% max solids, and 200 cP viscosity. Over 175 kL of slurry were produced to these specifications at CQ Inc. for engine testing. Clean coal for this slurry was produced using conventional, heavy media cyclones. The grinding circuit and additive package used by CQ Inc. to produce the fuel was developed in partnership with Energy International.

Interesting findings are that:

- The engine was fuelled with unheated slurry, and used a diesel pilot injector to ensure ignition (5% of the heat rate). It is therefore likely that a preheated slurry may have avoided the need for the pilot fuel. The effect of slurry heating is considered in a later section.
- Combustion performance was unaffected by coal size up to 80 µm (top size), and there was no contamination of the cylinder with combustion residues. This implies that a considerable relaxation of injection conditions (*ie* the pressure of atomisation) could be allowed with a finer, and narrower grind – especially if preheated.
- The report has contradictory conclusions regarding coal ash – it concludes that an ash content up to 3% had little effect on engine durability, but also claims that wear was proportional to ash content. Free silica is specifically mentioned, but (as with all other reports) there is no data provided on the occurrence, or particle size, of the mineral matter in the CWF used.

- It appears that the engine used a fairly conventional pump and injectors. The injectors (covered orifice type) had slightly larger diameter holes (19 x 0.63 mm), and experiments were done with alumina and carbide inserts to combat nozzle wear. The coal slurry did not pass through the injector pump, and, although the conventional jerk pump provided the hydraulic power for injection pressure and metering, this was transmitted via a hydraulically operated injection plunger (a shuttle) in the top of each injector. The CWF was supplied to the injector body at only 13 bar (much lower than the 340 bar required to lift the injector needle).
- Carbide coated cylinder liner and rings were used.
- Projected endurance of injector tips and shuttle, top ring, and exhaust valve were estimated at around 500 hours with the materials used. This compares with over 2000 hours for diesel injectors.
- Liner and valve seat wear was negligible.

5.6.2 GE locomotive program

The USDOE sponsored a GE RD&D program for using coal-water slurry (CWF) to power a diesel engine and to test it in a locomotive. The first locomotive system test was successfully completed in 1991 on the GE Corporate test track. The first phase coal-fuelled 12-cylinder GE-7FDL diesel engine used a modified positive displacement fuel injection system. It developed 1.9 MW at 1050 rpm in the engine laboratory before the engine was transferred to a GE Dash 8 locomotive for track testing. The final phase include an all electric controlled fuel injection equipment (FIE) diesel engine. Combustion research evaluated a broad range of CWF fuels with different source coals, particle sizes and ash contents.

A cross section of the engine is shown in Figure 22 below. The cylinder is 250 mm bore, with a stroke of 325 mm. Each cylinder generates 250 hp (180 kW) at 1050 rpm.

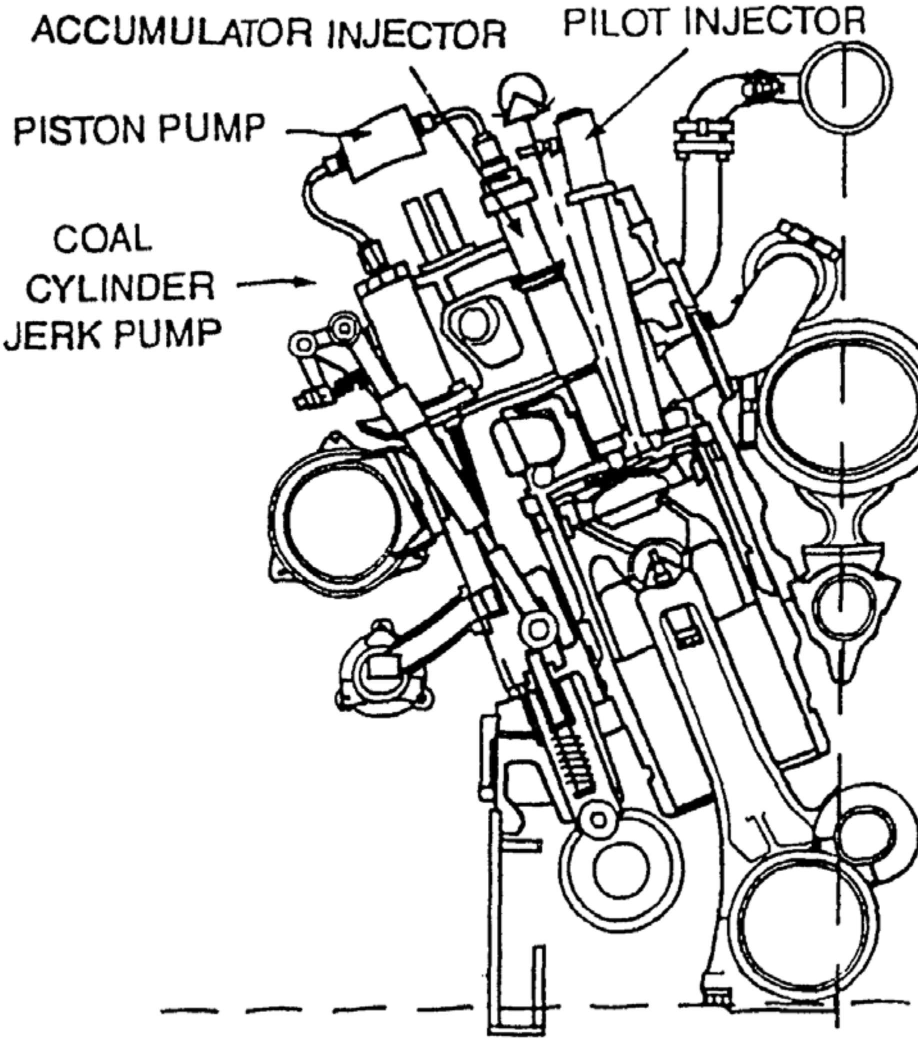


Figure 22 Section through the modified GE-7FDL diesel engine, a piston pump provided pumping and metering force to the CWF

An electronically controlled FIE single cylinder test engine gave 99.5% combustion efficiency (better than for pf boilers). A number of methods for SO_2 and particulate removal were trialled, giving 99.5% removal of particulates, and 90% removal of SO_2. The final form of the injectors used diamond compact insert nozzles that were bench tested to over 500 hours without significant wear. Tungsten carbide coated piston rings and cylinders were found to be suitable to combat abrasion wear. The study included a techno-economic assessment of the locomotive; assuming a cost for diesel fuel of USD0.20-0.25/L, the breakeven cost for CWF was USD2.9/GJ, which included allowances for increased engine component costs and increased O&M.

The coal and CWF properties are summarised in Table 14. The results show no strong trends, for the range of coals, and it is of note that Kentucky Blue Gem seam coal maintained a high combustion efficiency at a 33 μm mean size. With one exception, all CWFs gave a high combustion efficiency as shown in Figure 23.

Table 14 Coal (in CWF) properties for GE locomotive engine tests

Vendor	Coal	Seam	Type	Cleaning process	Mean size µm	Ash % db	Combustion efficiency %
OTISCA	Kentucky	Blue Gem	Bit	Physical	4.6	0.7	99.2
OTISCA	Kentucky	Blue Gem	Bit	Physical	4.8	0.8	98.8
OTISCA	Kentucky	Blue Gem	Bit	Physical	3.1	0.7	98.7
OTISCA	Kentucky	Blue Gem	Bit	Physical	33.2	0.7	99.2
OTISCA	Pennsylvanian	Pittsburgh	Bit	Physical	2.5	1.7	98.7
UNDERC	Wyoming	Kemmer	Sub bit	Physical	13.9	2.8	99.5
UNDERC	Wyoming	Spring Creek	Sub bit	Physical and chemical	14.7	2.1	99.0
UNDERC	Wyoming	Spring Creek	Sub bit	Chemical	14.9	2.8	99.2
AMAX	Kentucky	Splint	Bit	Physical	8.2	2.5	97.7

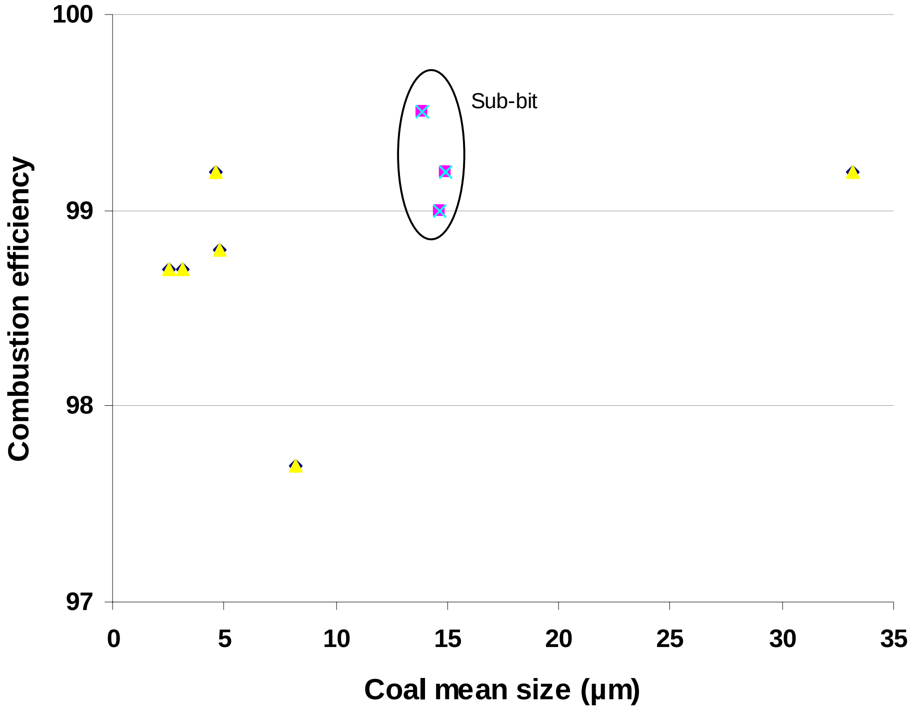


Figure 23 Combustion efficiency achieved versus coal mean size (data from table above)

The locomotive trials were supported by extensive modelling and laboratory combustion tests. The latter included high speed in-cylinder photography. This showed distinct flames from the diesel pilot injector and CWF injector. It was found that the CWF combusted only after impinging on the piston, and after secondary atomisation (the bursting of droplets due to heating). The photography also showed that agglomeration of coal particles occurred under unfavourable combustion conditions.

The techno-economic assessment of the use of CWF in locomotives[60] is summarised in Figure 24.

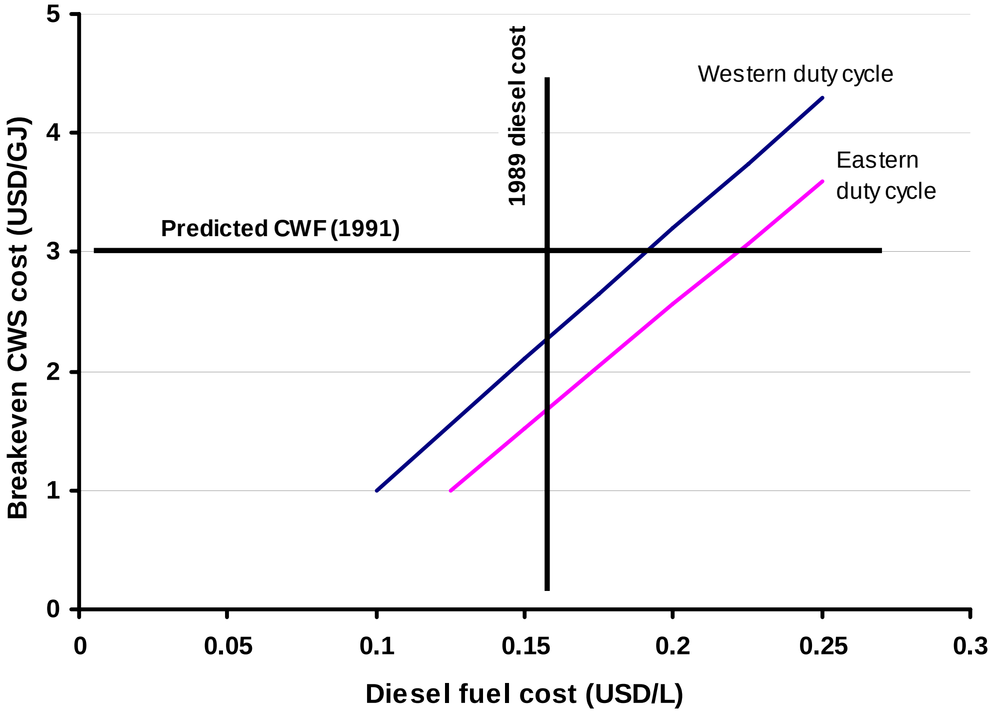


Figure 24 Breakeven costs for CWF versus diesel fuel for Eastern and Western region locomotive duty cycles, redrawn from Hsu

The analysis (based on 1989-91 costs) shows that CWF would only be economic for a 50% increase in diesel fuel costs. Assuming that crude prices comprise 75% of locomotive fuel costs, the 3 fold increase in crude prices since this study was done would make current diesel costs around USD0.5/L in the US, the breakeven price for CWF will have increased to around USD9/GJ. In addition, there is a strong move towards lower diesel engine emissions standards[48,49] which will significantly improve the cost competitiveness of CWF, which already has emissions controls for SO_2 and particulates included, and the use of CWF gives a marked reduction in NOx emissions without SCR emissions control. In the final report on the program, the authors conclude that *"due to the persistent low oil prices and the federal budget deficit, the present program scope was reduced. However, the critical technologies developed are retained and summarized in the completion of the second phase electronic controlled engine with its emissions cleanup system. When market environment becomes favourable in the future, the technologies can be further improved and packaged into a commercial system very quickly"*[50].

5.6.3 DOE CCT-V project

The general success of this program led to a larger (USD38M) DOE funded cooperative agreement for Cooper Bessemer and A D Little to conduct the Clean Coal Technology V project (CCT-V) to demonstrate the practical feasibility of operating a coal-diesel of 6.4 MW (18 cylinders) capacity for 6000 hours with 48% thermal efficiency.[51]

The 18-cylinder engine at the University of Alaska, Fairbanks (UAF) began operation on diesel fuel in September 1999, started generating power in October 1999, demonstrated 90% NOx reduction with the SCR in August 2000, and supplied all the UAF power requirements until a forced outage in August of 2004. Because the original planned source of CWF in Alaska was not viable, the unit continued to operate on diesel fuel. Eventually, CWF sources were located and a revision was made to the cooperative agreement to meet project objectives at reduced cost. In August 2003, DOE modified the cooperative agreement to execute the CWF test plan on a 2-cylinder test engine at Fairbank Morse Engine facilities in Beloit, Wisconsin, instead of the 18-cylinder engine installed at UAF. In April 2004, the 2-cylinder engine was operated on Usibelli coal-derived CWF with a heating value of approximately 9.3 MJ/kg. The CWF-fired engine produced 200 kW and emitted 150 parts per million (ppm) of NOx, which compared well with the 1,100 ppm NOx emissions on diesel fuel. Preparations were under way for operation on bituminous coal-derived CWF, however, these tests were suspended due to the need for modification of the test facility and outstanding contractual matters.

5.6.4 Dry aspirated coal engines (DACE)

In the dry aspirated engine (or the dust engine), a mixture of powered coal and air is conveyed to an intake manifold and aspirated into the cylinder with the combustion air. Dust aspiration avoids the severe wear issues of high pressure slurry injection, and the ignition delay due to droplet evaporation. However, there are issues of achieving accurate metering, mixing and avoiding dust accumulation in the inlet tract or the back of the inlet valve, which cause uncontrolled fuel-air ratios. The DACE is included because fuel delivery could be as a CWF, with flash drying of preheated fuel in the inlet tract. This would avoid the difficult issue of uniform pneumatic conveying, and give the other advantages of CWF preparation and handing.

In a parametric modelling study on a 1.4 L/cylinder engine by Khandare[52], it was found that the power and thermal efficiency were dependent on the coal particle size, engine speed, VM content and engine compression ratio – all of these factors affect the heat release profile during combustion, and burnout. The indicated or theoretical cylinder power was found to be a strong function of coal particle size. In the case of medium volatile coal, the particle size of 40μm gave maximum power, at 550-850 rpm for the particular engine simulation.

As expected, coal VM has a significant role in combustion of the coal, as it increases both the particle and gas temperatures during the combustion process. The evolution of volatiles reduces the amount of fuel that needs to be burned as char – though this will depend on the volatiles enhancement factor obtained during compression and the early stages of combustion. These effects do not appear to have been investigated. In particular, an increase in volatile matter percentage reduces unburned coal, and also results in early combustion (and reduces ignition delay) of smaller coal particles. The use of pilot ignition with diesel oil, together with higher VM content, was required to achieve efficient combustion of 75-100μm coal. The most notable results of the study are that reasonable combustion of relatively coarse pf can be achieved in a relatively small, medium speed engine - as the study assumed mono-sized coal particles, the presence of finer fractions in real grinds are expected to markedly improve combustion. The model also omitted any VM enhancement ratio with increased heat rate.

The performance of a dry aspirated coal engine was measured using a single cylinder diesel engine by Kakwani[53]. An indirect injection (IDI) Caterpillar IY73 2.2 L single-cylinder engine (shown in Figure 25) was used as the test engine (indirect injection applies only to operation on diesel fuel – not for coal). The engine was modified by the use of sprayed thermal barrier coatings on the head and piston, and was run without coolant (called TICS – thermal ignition combustion system). Coal powder was injected into the air intake port behind the inlet valve, *ie* was aspirated or ingested into the cylinder. Excellent combustion characteristics of all coal fuels were observed. It was possible to start (using a glow plug) and operate the engine on 100% coal (*ie* without a pilot fuel as is normal with slurry injection, especially below 50% load). Heat release analyses (from cylinder pressure traces) showed very rapid heat release rates and 1/3rd shorter combustion duration than achieved with diesel fuel. The P-V diagrams showed that combustion occurred at essentially constant volume – the conditions required to achieve maximum thermal efficiency. Engine speeds of up to 1,800 rpm were tested.

Overall, the heat release rate indicated very rapid combustion, 3x that for diesel fuel, which produces a significant improvement in thermal efficiency.

Ignition timing was successfully controlled by exhaust gas recycle (recycled cold) which reduced peak cylinder pressure and NOx emissions. With flash drying this could be achieved by varying the slurry preheat.

Engine lube oil filtration was improved to remove unburnt coal/char and ash. Contamination (and wear) by unburnt coal is likely to be a significant issue with this type of engine as a relatively homogeneous coal-air charge is in contact with the full length of the cylinder during the induction and compression strokes.

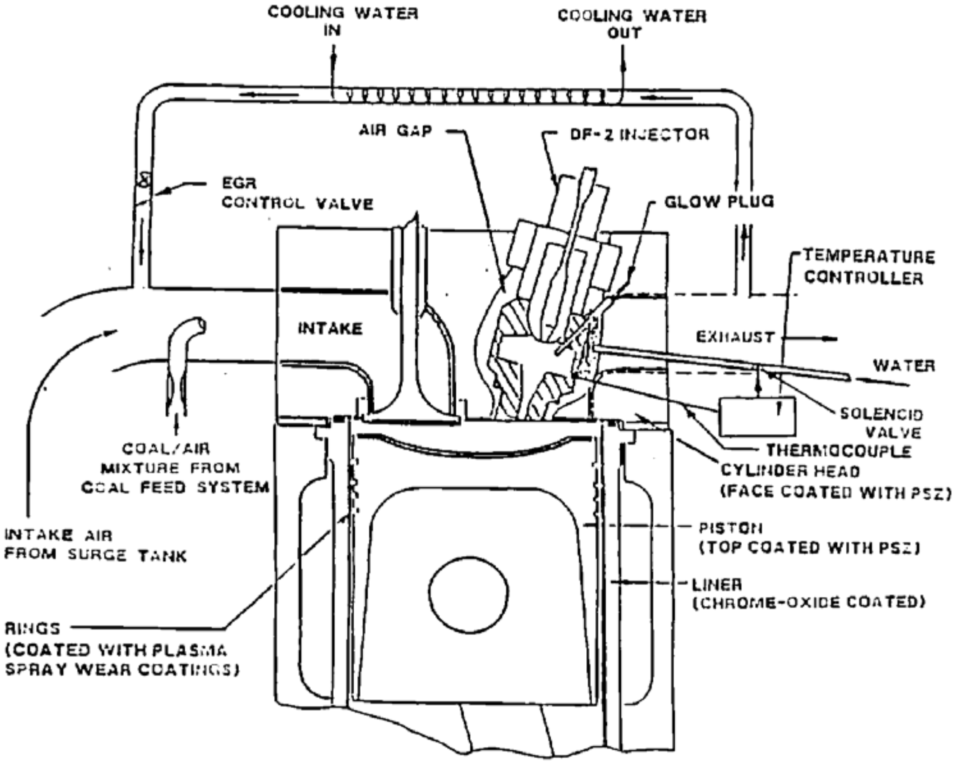


Figure 25 Schematic of Caterpillar IY73 single cylinder test engine with coated components and controlled precombustion temperature for optional pilot diesel fuel injection

The coal feed system was very simple, and based on a coal hopper, a screw feeder and an ejector. Coal rate was controlled by changing the screw speed. This very simple system was reported to have operated without any problems. The coal was a high volatile bituminous coal prepared by OTISCA Industries from Kentucky Blue Gem coal. The properties are shown in Table 15.

Table 15 Coal properties as-fired, produced from Kentucky Blue Gem coal

	Unit	Coal 1	Coal 2
Moisture	%ar	5.1	3.5
VM	%ar	38.1	37.3
Ash	%ar	0.9	1.6
Fixed carbon	%ar	55.9	57.7
Specific energy	MJ/kg	31.72	32.95
Grind			
D_{10}	µm	1.8	4.6
D_{50}	µm	5.5	17.4
D_{90}	µm	15.7	43
Top size	µm	20	75

Good engine performance was obtained, even for unbeneficiated coal which had a 75µm top size.

It is noted that these coal samples were higher in VM and lower in ash than in most of the coal slurry test programs above, but had a much coarser grind.

Although most coal engine development has been undertaken with CWF and conventional solid injection, the excellent results obtained from dry aspirated coal engines, with relatively simple systems, provides a promising alternative for briquetted ultra clean coals, especially for smaller, higher speed engines.

If integrated flash drying were used, it would avoid safety issues in fuel handling.

In this form, the engine would probably be restricted to 4-stroke engines, as control of exhaust gas recirculation is required to control ignition (with most 2-strokes, control of scavenging and exhaust gas retention would be more difficult).

5.7. Alternative and special technology components

This section summarises engine component developments for burning coal, including engine lubrication.

In the direct injection engine, CWF is injected in a similar manner to that for liquid fuels at pressures up to 100 MPa (15,000 psi). High pressure pumping, metering, and injection are the major technical issues affecting fuel system wear, ignition delay, and combustion efficiency.

A number of studies have been undertaken to understand the fundamentals of CWF atomisation for "solid" (jet) injection. For example, Yu et al[54], studied atomisation under simulated combustion chamber conditions near TDC (air charge density of 17.5 kg/m^3). Although the injection chamber was at room temperature, the results (of the behaviour of the jet core up to the head) were concluded to match those from rapid compression experiments. The CWF used was from AMAX Corporation, and some properties are shown in Table 16.

Table 16 CWF and reference diesel fuel properties for atomisation tests by Yu[54]

Property	Unit	Value
CWF		
Coal content	Wt%	53
Coal		KY Splint HVA Bit
Coal ash content	Wt%	0.2%
Grind	Mean dia µm	12
	98% passing µm	65
Viscosity	mPa.s @100/s	180
Diesel DF-2		
Density	kg/m^3	840
Viscosity	Pa.s	0.0025

Fuel type, nozzle geometry and injection pressure were varied in the test conditions. CWF formed spray patterns similar to diesel sprays, with the spray fronts (the head of the spray) travelling at steady speeds in the early stages of penetration, then decelerating with time to form a larger spray head. The most important finding was that the length of the steady penetration for CWF was 170% longer than that of a typical diesel fuel. Wider and finer sprays were obtained for lower viscosity liquids (including more dilute slurries). A larger nozzle orifice resulted in wider, shorter-lived, more poorly atomized sprays. The radial droplet size profiles depended on injection pressure, with increasing pressure giving improved atomisation at the periphery of the jet, but having only a small effect on the core droplet size.

For most conditions the Sauter mean diameter (SMD) of the spray was 20-40 µm, and injection velocities ranged from 250-400 m/s; this gave a jet penetration distance of 80-100 mm over 1-2 ms. The latter indicates that CWF requires engines with cylinder bores larger than 200 mm, to avoid the jet contacting the periphery of the combustion chamber or the cylinder wall.

Overall, the results of Yu show that atomisation quality of CWF decreased markedly with increasing viscosity of the CWF, with increasing injection pressure providing little overall improvement.

From the range of droplet sizes measured by Yu, it can be shown that each water droplet is likely to contain between 1-5 of 20µm coal particles, and 3-45 of 10µm coal particles; see Figure 26.

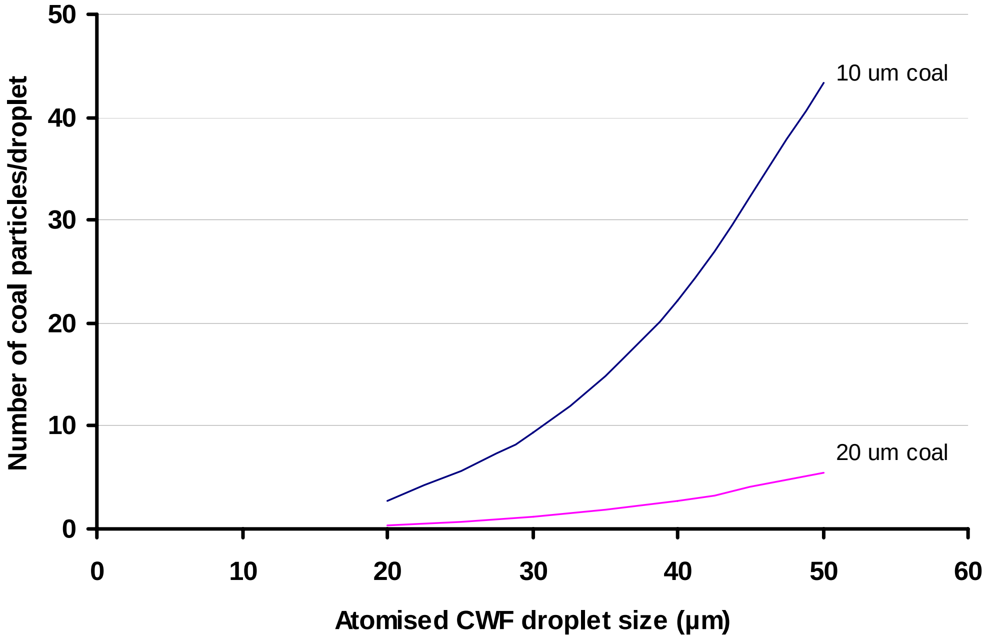


Figure 26 Theoretical number of coal particles per atomised slurry droplet

5.7.1 Fuel injection equipment

Efficient and controlled fuel injection is critical to the diesel engine. For diesel fuel, the basic equipment to achieve this is filtering, a low pressure supply pump, and variable displacement injector pump to deliver a fuel pulse to the injector. This system is generally termed the pump-line-nozzle (PLN) system.

For heavy fuel oils or sub-zero temperatures, additional equipment is needed to heat supply tanks, fuel lines and filters, to maintain a low fuel viscosity and prevent wax crystal formation (which blocks filters).

Over the last 15 years there has been marked development of the technology, mostly to improve specific output, and to reduce particulate and NOx emissions - especially for automotive applications. These improvements have been the replacement of the mechanical jerk or rotary pump systems with common-rail pressurisation and electronic injector actuation, coupled with closed loop (self adaptive) computer control. These developments have also now been applied to many larger engines, through utilising different components; *eg* some large marine diesels have no cam shafts, with all valve, fuel pump and injector actuation by hydraulic power under computer control. A further change has been the development of dual fuel delivery systems (*eg* for LNG and diesel) and hybrid Diesel-Otto cycle engines utilising low pressure gas and diesel. All of these developments have relied heavily on improved engine monitoring and adaptive computer control.

It is envisaged that most of these developments should have positive implications for the use of CWF.

A number of different CWF injection systems have been trialled, mostly as part of the 1989-94 DOE program. These systems included variations of the conventional PLN system, with shuttles and diaphragms being used to separate the pressurisation fluid (diesel) from the CWF, and integrated systems with unit injectors (combined pump and injector unit), accumulator injector bodies, and various electronically controlled fuel pressure-time (P-t) systems. Most of the R&D was undertaken as follows:

- AD Little-Cooper Bessemer-AMBAC worked on the PLN system with an in-line shuttle piston, and alumina injector nozzles.
- SwRI trialled several systems, including PLN systems with increased clearances and the Cummins P-t system[55].
- GE worked mostly with the diaphragm system and accumulator injector body and used diamond compact nozzles[56] and electronic servo-controlled needle lift.

These are described under the headings of:

- **Injection pumps**; the device for pressurising and metering of the CWF.
- **Injectors**; the device for conveying the CWF into the cylinder as atomised spray. The injector may also provide metering.
- **Injector nozzles**; the holes through which high velocity CWF is injected into the combustion chamber, the velocity being >300 m/s in order to cause atomisation. The nozzles are also positioned to provide optimum fuel-air mixing and flame development whilst minimising fuel impact with the piston, cylinder walls or head, and valve surfaces.
- **Novel systems**; include those cited in a number of patents, and which, if achieved, could provide significant improvements over the more conventional fuel delivery systems.

5.7.2 Injection pumps

As fuel pumps are high precision devices with very small clearances (typically <2μm), the presence of particulates results in extremely rapid wear, jamming of pump plungers, and rapid erosion of spill ports.

For CWF, this difficult technical issue has already been overcome, mostly during the DOE test programs in the early 90s. The basic method is to retain the normal jerk-type fuel pump to provide the force for fuel pressurisation and metering, but then applying this force to the CWF via a shuttle piston or a metal diaphragm. A successful fuel pumping system is shown in Figure 27 below. This system uses a conventional slurry pump to supply CWF to the high pressure circuit, with CWF pressurisation to 700 bar via a shuttle, in which particle wear and jamming is prevented by a high pressure purge oil applied into the clearance space between the shuttle and the pump body. This purge oil also protects the injector needle from sticking in its upper guide. Pumping pressure and metering is therefore achieved using diesel fuel as the hydraulic fluid. In the system depicted, an accumulator injector is shown, which uses 270 bar servo oil pressure via an electronic servo valve on the injector to control needle opening and closing. Although this pumping system has been used in a number of trials, there have been some problems with the shuttle piston sticking.

In a separate development program involving GE, the piston pump shuttle has been replaced with a metal diaphragm[57]. In the test version of this device, the diaphragm was less successful, and limited injection pressure to 700 bar (lower than the intended 830 bar); however, this was sufficient to give excellent CWF combustion at 1050 rpm in the GE7 FDL locomotive test engine.

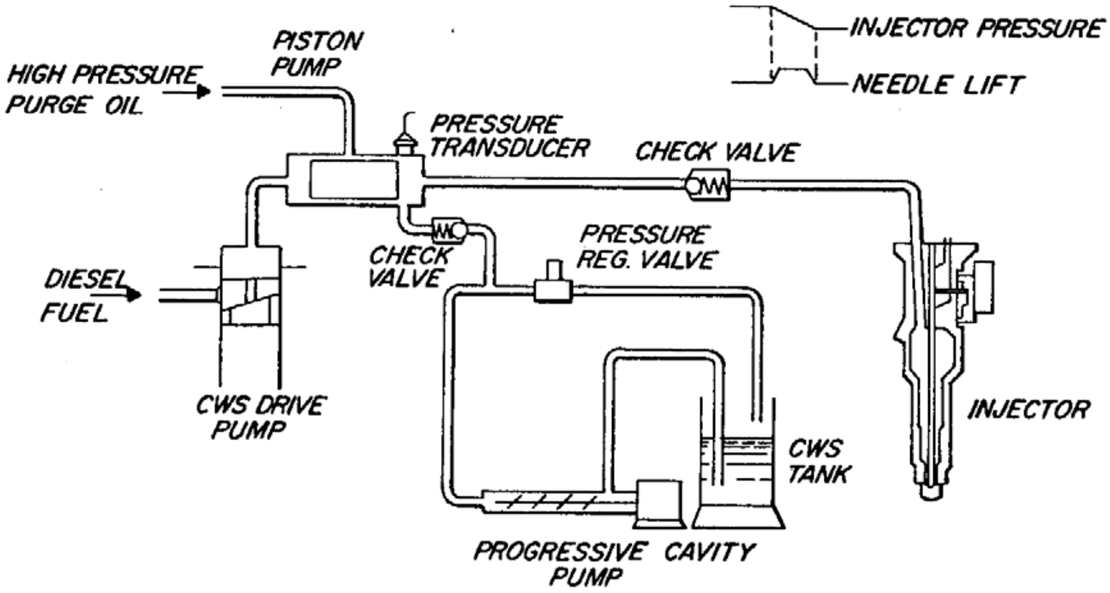


Figure 27 A CWF fuel injection system using a shuttle pump and accumulator injector[57]

Overall, the shuttle pump system has proven to be the most suitable.

5.7.3 Injectors

While injectors are critical to effective atomisation, they have caused the biggest technical problems, and have been the subject of most R&D. There are a number of factors which have compound affects on combustion:

- CWF is more difficult to atomise than diesel fuel due to its much higher viscosity.
- Effective atomisation is more critical to combustion due to the effect of droplet size on ignition delay (increased by the time required for water evaporation) and burnout.
- CWF causes chronic wear of injection nozzles, with wear being exacerbated by cavitation effects.
- Pressure atomisation can be improved by increasing the liquid velocity through the nozzles; however, this is prevented by increased nozzle wear and high viscosity.

Wear can be reduced by increasing the nozzle diameter, thereby reducing the liquid velocity (which is normally 300-400 m/s); however, this results in less efficient atomisation. Atomisation efficiency is particularly important at the start of atomisation, as this fuel needs to ignite first. Poor atomisation can result in large droplets reaching the cylinder wall where they collect without burning, and cause ring/liner wear and oil contamination.

This problem is most evident with conventional fuel pumps and injectors, where atomisation is worst as the injector opens and shortly afterwards (due to the fuel not being fully pressurised), and also due to pressure fluctuations caused by the pressure waves along the pump to nozzle fuel line (which can cause the injector needle to chatter).

The GE accumulator injector has been developed to help reduce these effects, by providing maximum atomising pressure on opening, and rapid needle opening and closing. This injector was successfully trialled on a GE7 FDL engine at 787-1050 rpm. A cross-section of the accumulator injector is shown in Figure 28.

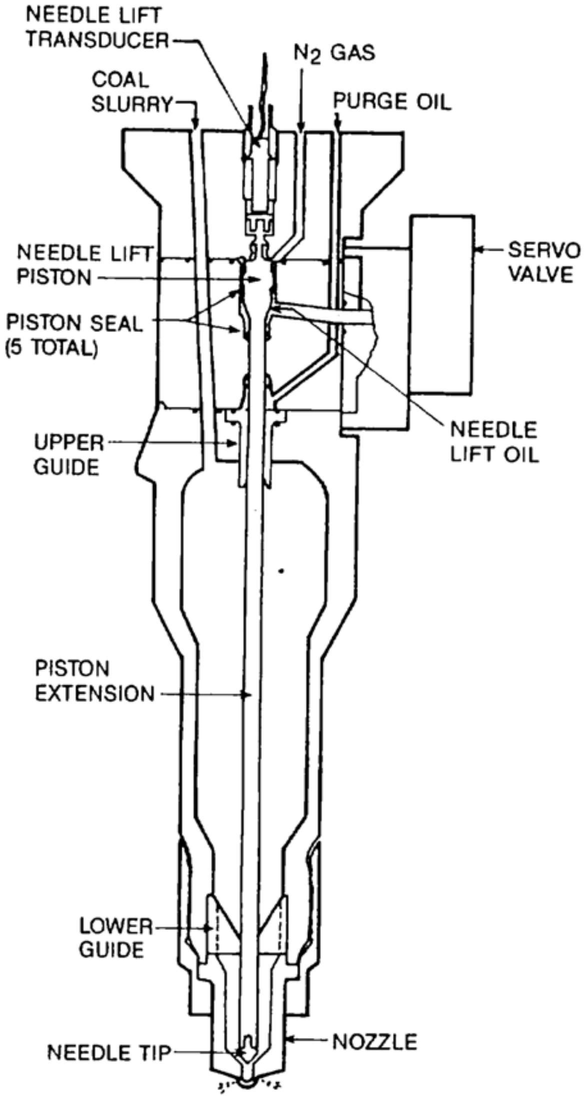


Figure 28 CWF accumulator injector[61]

The accumulator volume of this injector was approximately 235 cm^3, and the system was sized to inject 3 g of CWF per injection, with the pressure in the injector falling from approximately 83 MPa to 48 MPa as injection occurred. The lower injection pressure limit of 48 MPa was found to yield good combustion efficiency, and allowed the peak injection pressure to be kept at 83 MPa. The injection cycle proceeded as follows:

The jerk pump was stroked, pushing CWF into the injector and raising the pressure. The injector shutoff needle was kept from opening by high pressure gas on top of the needle assembly. At the injection shutoff time specified by the electronic control, an electronic servo valve allowed the needle to reset.

During testing it was found that the injector needle opened fully in about 0.5 ms and closed in 0.75 ms, fully meeting the requirements for the locomotive engine used for testing. The performance of this injection system enables CWF to be used in medium (1,000 rpm) speed locomotive engines.

An alternative approach was developed by the South West Research Institute (SwRI) with an integrated shuttle-nozzle injector, shown schematically in Figure 29. In this design, the low pressure CWF is delivered directly to the injector body, as is the pressurisation pulse from the fuel pump. This system was used in a 2-stroke engine at up to 1,900 rpm.

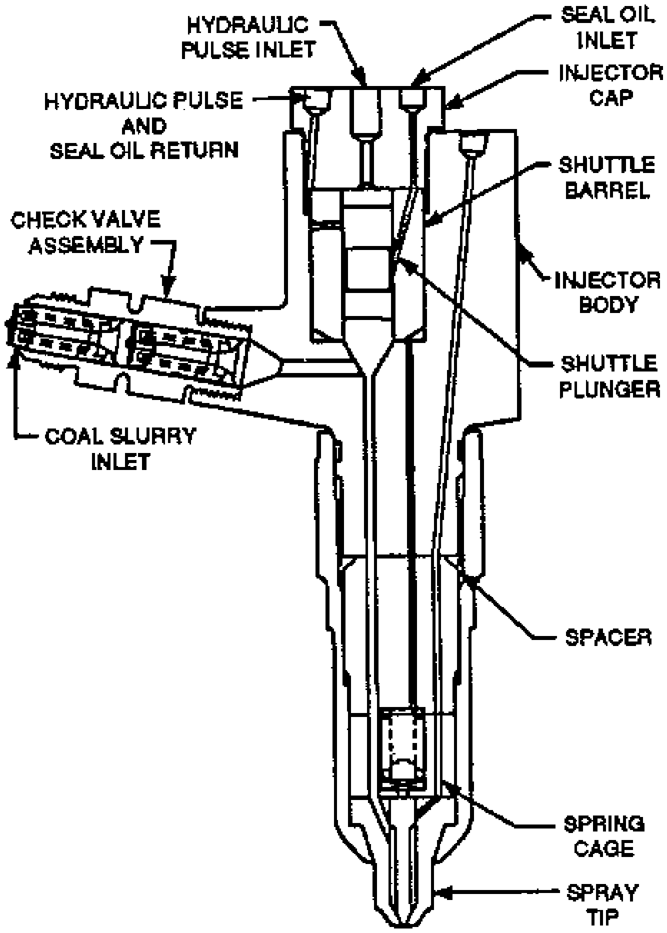


Figure 29 Integrated shuttle piston and nozzle injector assembly developed by SwRI[55]

5.7.4 Injector nozzles

Conventional diesel injectors usually achieve efficient atomisation of the fuel by creating high velocity liquid jets of fuel from fine holes or a fine annulus in the injector tip. The different types of tips are shown in Figure 30 to illustrate the subtleties in design,[58] and the potential for technical difficulties involved in injecting CWFs at supersonic velocities.

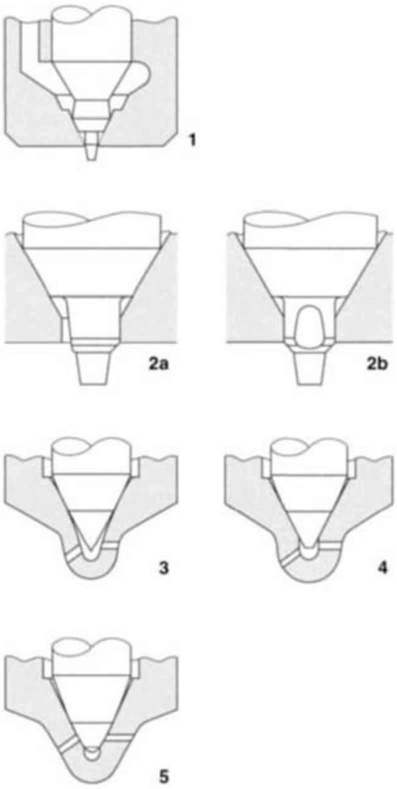


Figure 30 Nozzle types[58]: 1) throttling pintle nozzle, 2) throttling pintle with flat-cut pintle, 3) hole nozzle with conical blind hole, 4) hole-type nozzle with cylindrical blind hole, 5) seat-hole nozzle

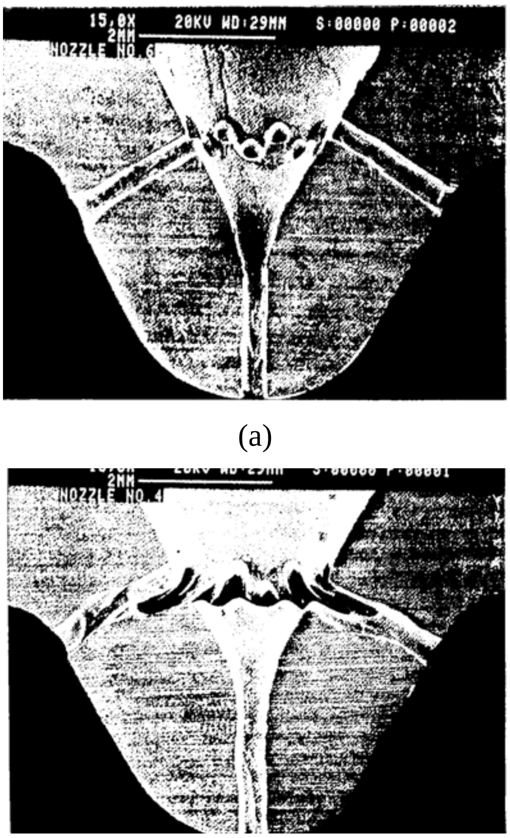
The basic objectives are to:

- Open rapidly at the required injection pressure without oscillation.
- Direct a number of high velocity jets (typically 300-400 m/s) of fuel into the combustion space (for pintle-type injectors only a single jet is produced), with the fuel rate being usually controlled by the pressure drop across the nozzle(s) (not the valve seat).
- Close rapidly and completely at the end of injection, contain no minimal residual fuel in the injector tip (which can drip or coke), and achieve complete sealing against ingress of combustion gas once closed.

Injectors are expected to do this for at least 2,000 hours without servicing, which equates to up to 60-100 million injection cycles (equivalent to atomising 20-30kL from a 0.6 mm orifice).

Whilst CWF can be injected via conventional hardened steel nozzles (usually 30% larger in diameter to pass the required volume of higher viscosity CWF), this causes extremely severe wear, leading to injector tip life of a few hours at best. An example of this extreme wear is reported in detail by Rao[59] for a conventional multi-hole injector with a 3.4% ash coal.

Wear after less than an hour of operation is shown in Figure 31. The injector trials were undertaken in a single cylinder 4-stroke Cooper-Bessemer research engine[59] after operating at 375-450 rpm. During the tests the injector tips had only experienced around 10,000 injection cycles, indicating that tip wear with the CWF used was 1,000-10,000x greater than for diesel fuel.



(a)

(b)

Figure 31 Cross section of multi-hole injector nozzle (8620 carbo-nitrided steel) (a) before and (b) after 40 min of operation on 3.8% ash CWF[59]

Testing at GE with super hard materials for injector nozzles has given much better results. GE used alumina, diamond compacts, and titanium boride (TiB_2), using both a single cup insert and with separate components electron beam welded into the injector cap. The best overall results were obtained for individual diamond insert orifices[61] with a carbide valve seat (see Figure 32) as originally trialled by Hsu. Although these have only been tested for 100 h on an engine, they have been successfully bench tested for 500 h. As nozzle wear had resulted in a flow increase of <0.5%, the test GE team concluded that a satisfactory injector tip solution had been developed, and further development of wear resistant nozzles, including the TiB_2 coated nozzle, was discontinued.[60]

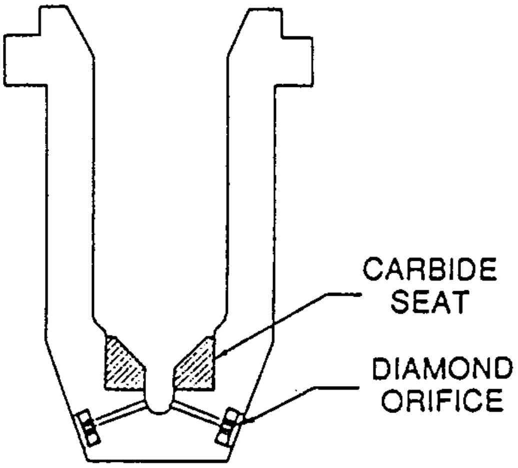


Figure 32 Schematic of modified injector tip with a carbide valve seat and diamond compact nozzle inserts[61]*(expected life of up to 5,000 hours)*

5.7.5 Engine longevity

In all reciprocating engines, particulates in the fuel or combustion air can cause excess wear, especially of the rings and liners. For CWF, even with ash contents below 1%, wear rates have been observed at 20-150x that experienced for heavy fuel oils. Wear on the piston rings and liners is due to both the ash and residual char. For dry aspirated engines, coal will greatly increase the amount of contamination of wear surfaces with abrasive particulate matter.

For conventional engines (*ie* non-cross head engines), additional filtration capacity is required for the crankcase lubrication system to cope with the increased particulate loading for coal engines, and to prevent accelerated crankshaft wear. This is especially the case for ash particles larger than 10µm.

Although there are conflicting test results, wear appears to be worse for particulates in the range 5-30µm (*ie* smaller than, or much larger than, the thickness of the hydrodynamic oil film).

In most of the engine tests described previously, wear rates have been reduced to acceptable levels by using ultra-hard coatings on both the rings and liners, especially plasma sprayed tungsten carbide. An additional improvement can be achieved by the use of special high viscosity oils for cylinder lubrication to maintain a thicker hydrodynamic lubrication layer and therefore prevent 3-body wear (when abrasive particles contact both metal surfaces simultaneously). Note, the softer piston is generally unaffected by the presence of the abrasive particles, as these usually embed themselves into the piston which then abrade the cylinder.

The wear is worst near TDC where the piston/ring velocity is zero, which destroys the hydrodynamic lubrication film. This area is also subject to higher temperatures and ring pressures (due to peak gas pressure), and will contain the largest amount of cylinder debris scraped up from the bore lower down. With CWF, this is also the area where slurry impingement has been observed.

The implications for CWF from ultra clean coals are particularly promising, because analysis by Idemitsu Kosan have showed that most of the ash particles are below 5µm. As most of the remaining particles are acicular in form – the effect of combustion in changing the morphology of the residual ash (*eg* spheroidisation) needs to be investigated. This has received little consideration in the numerous previous engine test programs.

5.8. Novel engine systems

The engine systems for CWF and dust described above have all been used in successful pilot trials, and are based on relatively small modifications to conventional technologies. Over the last 20 years there have been numerous other novel systems proposed or patented. These are described briefly to indicate the scope for development, and also to indicate systems that could be adapted to the DFGT.

5.8.1 Superheated CWF

As the water must be evaporated from each droplet before the contained coal can be ignited, it causes long ignition delays, and recent tests with medium speed engines have required pilot injection of diesel fuel at below half load. The delay also increases the risk of impingement on the cylinder walls and broadens the heat release curve which decreases the thermal efficiency to some extent.

Preheating the slurry significantly reduces these heat effects, and can utilise waste exhaust heat. A fuel injection system using this principle was patented in 1985[62] using a GE accumulator-type injector, and is shown in Figure 33 (the same method of fuel delivery has been proposed for slurry fed coal gasification[63]). The patent suggests operating at 300-360°C for fuel delivery pressures of 100-250 bar. Preheating to 360°C will cause half of the water in the fuel to flash (instantaneous evaporation) in the combustion chamber. It was also proposed to combine this injector with a refractory coated (adiabatic) precombustion chamber to further improve ignition.

This method of enhancing atomisation would be especially advantageous for direct firing of CWF into gas turbines, as flashing provides most of the atomisation energy. A more viscous CWF could be used (*ie* with a lower water content), which would further reduce the time and volume required for combustion.

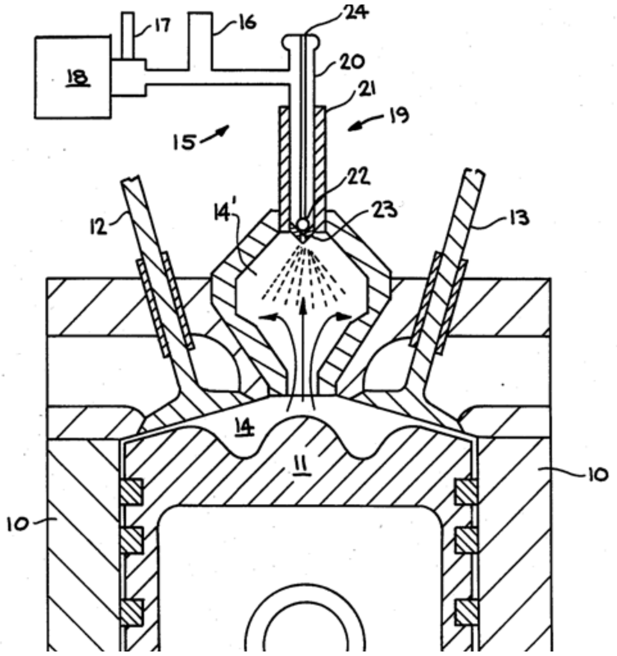


Figure 33 Schematic of engine head showing heated accumulator injector and adiabatic precombustion chamber[62]

Despite the lack of practical tests on preheated slurries, the objective of reducing the effect of the heat required for fuel evaporation remains a key consideration for direct firing of CWFs.

5.8.2 Air atomisation

A number of patents have proposed atomisation using compressed air - a variant of the original gas-blast method for atomising and injecting fuel oil into diesel engines. The basis of twin fluid atomisation is the ability to greatly increase the energy available for atomisation, without using high pressure CWF. Twin fluid atomisation is used in many other applications, including liquid fuelled gas turbines, boilers, and spray painting. Twin fluid atomisation is likely to be very effective for DICE, if it can be implemented.

Although marked improvements in wear have been achieved by the use of ultra-hard coatings, a number of research programs were carried out in the early 90s to investigate powder lubrication. Drivers for this work also include the potential for lubrication breakthroughs to enable efficiency improvement through the development of the adiabatic engine (*ie* no cylinder cooling). A range of suitable lubricants, mostly based on sulphides and graphite, have been used. Significantly, the work of Heshmat[64,65] using combinations of graphite and coal fly ash and a range of ring contact surfaces, showed that fly ash is a viable lubricant, either in combination with graphite, or in pure form. Tests with the latter showed “zero” wear was possible. The main significance of this work is probably the fact that fly ash between the ring and liner does not automatically result in severe wear.

6. SYNERGIES WITH RENEWABLES

6.1. Backup power

Backup of, and synergies with, renewables is a key driver for the development of CWF fuels. CWF has many potential advantages, based on the ability to generate electricity at much higher efficiency at smaller scale than using conventional pf- or IGCC-based technologies.

The DICE option has additional benefits which make it the most preferred engine for this role. These include:

- Superior part-load efficiency. This attribute is further improved by the relatively small scale of individual engines, enabling engines to cut in and out as demand dictates. The efficiency penalty is much smaller than that achievable with all other conventional power plants, with the exception of similar gas engines.
- The ability to provide short start up times which avoids the need for extra spinning or hot reserve as is the current practice. In addition, these engines are far more tolerant of rapid and frequent starts (gas turbines accrue significant engine hour penalties for rapid starts, trips and load changes). For large diesel engines, rapid start will require maintaining hot coolant, which could be readily achieved in a number of ways, particularly by using a common cooling system with an installation of several engines. Solar heating could also be used.
- Unless the steam cycles are maintained hot, gas turbines can only achieve open cycle power output and efficiency until the steam cycle is fully heated – this can take 4-8 hours from cold.
- Ease of dry cooling.
- Tolerance to hot weather (gas turbines can lose 20% of rated output on a 40°C day, unless inlet air cooling is utilized – fogging with deionised water).
- The ability to store fuels as cake, briquettes or CWF (compared to NG, or even LNG), together with the above advantages, enable generators to be located strategically around the grid.
- Integration with algal fuel production systems, using capture of CO_2 and nitrogen/sulphur compounds from the engine exhaust to enhance biomass production.

The issues for renewable power are well understood, and issues other than installed cost are major blockers to increasing the uptake of the various technologies – these are short and long term variability and intermittency. Energy storage to cover short term variation is possible, but is costly - more than doubling the cost of electricity, and incurs the round-trip efficiency losses of 30-40%.

Although some of this variability can be reduced using a mix of renewable technologies (together with various load shedding strategies using SmartGrid-type technologies), there is also great variability in the suitability of different locations for the different renewable technologies which make mutual support a complex problem.

6.2. Provision of spinning reserve

Short term variation is a particular issue for wind. For example, the annual power produced by Danish wind turbines over a year[66] is less than 25% of their installed capacity for 70% of the time. The same reference shows the rapid fluctuations possible (Figure 34) - this shows swings in German wind generation of over 80% of installed capacity over several hours. As concentrating solar thermal receives energy only when the mirror collectors have an unobscured exposure to the sun, even greater daily swings will occur (0-100%) unless heat storage is used.

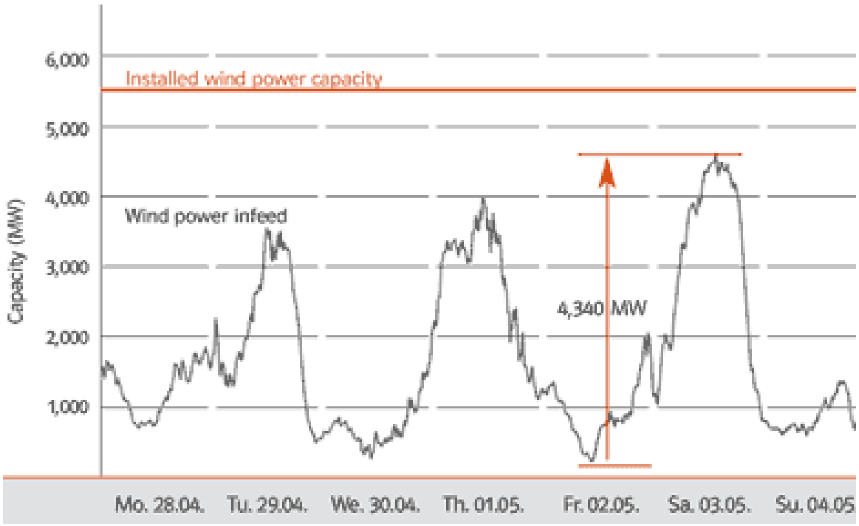


Figure 34 Example fluctuations in German wind generation

A number of strategies are possible for DICE power generation to underpin high penetration renewable energy, mostly by avoiding the issues outlined above. For this application, it is presently envisaged that DICE would be the preferred ultra clean coal generation technology, as it is the most flexible, could be available at 30-100 MW scale, and maintains a high efficiency at greatly reduced load.

6.3. Cofiring and dual firing

The use of smaller capacity DICE (and to a lesser extent DFGT) around the grid may be highly synergistic with renewables, by providing a very high efficiency application for a range of biomass fuels (relative to use in stand-alone power plants).

Suitable fuels include all forms of biodiesel, waste oils of any type, fats, waxes, staches, glyercols, ethanol, biogas (from landfill or biodigestion) and algal matter. This would reduce the cost (and emissions) from longer transportation of these fuels to centralised power plants, or from needing to process into higher quality fuels, as well as providing a higher conversion efficiency to power.

Purpose dual fuelling based on DICE could involve coal providing top-up fuel to maintain output and maximum efficiency during seasonal variation (*cf* coal-bagasse dual firing of 70 MWe steam plants in Mauritius). Examples could include biogas from ethanol production, or close coupling with algal production systems.

7. CO_2 CAPTURE

While the primary aims of CWF are to provide a step reduction in GGE via a step improvement in the thermal efficiency of delivered electricity, together with supporting increased penetration of renewables, it may also be necessary to combine CWF generation with some level of CO_2 capture and storage (CCS).

Figure 35 below shows that a 30% reduction in the GGE intensity of delivered electricity is possible in the short term from ultra clean coal into DICE alone. The facilitation of high penetration renewables (assumed to be 15%) would increase this improvement to 40%, now, and give a 55% reduction with the efficiencies expected from the direct carbon fuel cell[67] (DCFC) – without CCS.

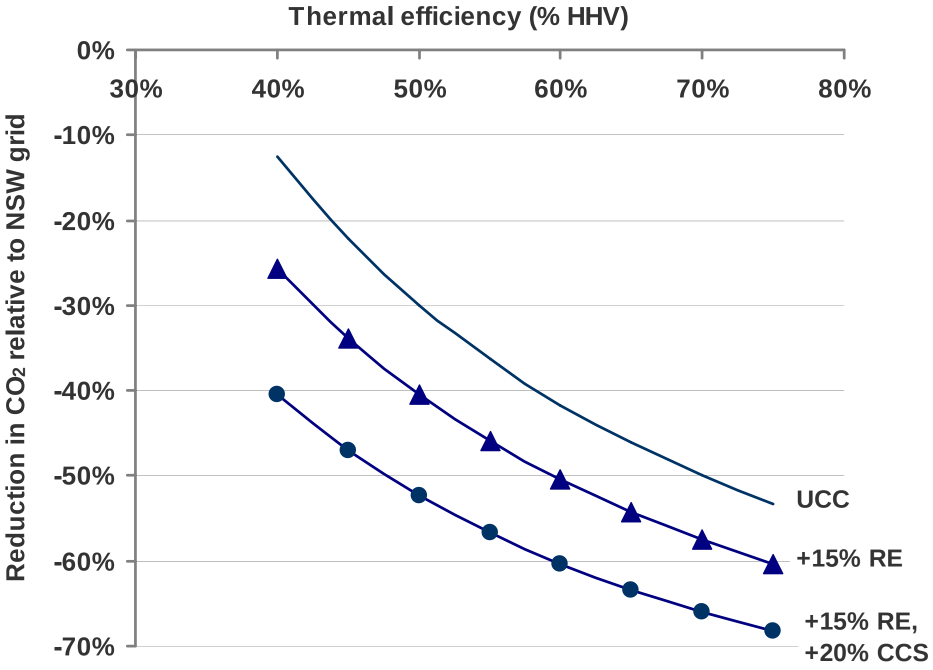


Figure 35 GGE intensity vs fuel cycle thermal efficiency for delivered electricity

Figure 35 also shows the overall reduction possible through the addition of 20% CCS to ultra clean coal technologies; over 50% reduction could be achieved in the short term, increasing to 65% reduction with the introduction of the DCFC. Clearly a high delivered thermal efficiency, together with a practical level of renewables, can achieve a large reduction of emissions without using CCS. The benefits of the latter are that the amount of CO_2 which must be stored is greatly reduced, and the effectiveness of smaller niche storage sites is increased. Figure 36 shows that with the introduction of the DCFC, together with 15% renewables, only 17% of the CO_2 emissions will require storage to achieve a 65% reduction of emissions from delivered electricity from current NSW levels (this equates to around 100 kg CO_2/MWh).

Important: Although the comparison appears to be comparing new with old (ie based on a delivered efficiency of 35%), this efficiency is equivalent to a sent out efficiency of around 40%. In the future it is expected that improvements in thermal efficiency will be reduced by the introduction of PCC capture, coupled with other likely changes, and the delivered efficiency is not likely to increase; eg the *best projected base plant efficiency of 47-48% (HHV), will only result in a delivered efficiency of ~35% after dry cooling, capture, transmission and distribution losses are taken into account.*

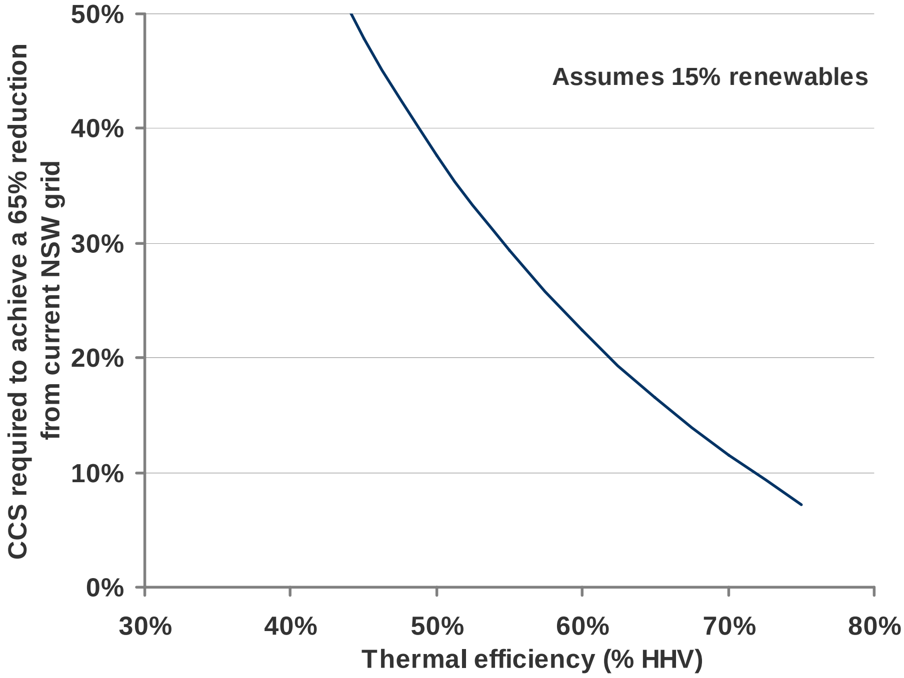


Figure 36 CCS required for a 65% reduction in GGE intensity

For DICE and DFGT, the flue gas composition will be similar to that for conventional pf, with the exception that the O_2 and N_2 concentrations will be significantly higher due to the higher excess air levels used in engines and turbines. Expected flue gas compositions are compared with those for pf in Table 17, based on a nominal UCC composition for production of UCC water fuel (UWF) and dry (5% water) UCC.

Table 17 Comparisons of wet flue gas compositions

Fuel		USC pf Feed coal	NGCC NG	DICE 50:50 UWF	DFGT 50:50 UWF	DCFC Dry UCC
CO_2	vol. %	14.0	3.4	5.86	5.5	65
O_2	vol. %	3.3	13.2	12.3	12.8	
N_2	vol. %	73.6	74.2	72.0	72.2	1
H_2O	vol. %	8.6	8.73	9.2	8.7	34
Ar	vol. %	0.7	0.7	0.7	0.7	-
NOx	ppmv	350	20	600	50	-
SOx	ppmv	250	20	250	250	250

The biggest effect of a more dilute CO_2 concentration is the increase in the size of the absorber, and a slight increase in stripping energy. However, this will probably be offset by the reduction in the amount of CO_2 captured per unit output. In the case of the DICE, it is interesting to note that most of the wasted heat energy is rejected at temperatures above 95°C, which means that the energy penalty in percentage points loss of thermal efficiency is likely to be less for this type of heat engine – around 3% versus 8% for pf.

The DCFC is unique with respect to CCS potential, as the device uses air for combustion, but produces essentially pure CO_2 flue gas - slightly purer than for oxy-combustion at around 98% CO_2 on a dry basis. In this case, the energy penalty will be likewise very low – around 3% of lost efficiency – and would only require cooling, compression, dehumidification and liquefaction.

The choice of capture technology will be similar to that for USC pf. These are currently amine based, with aqueous ammonia and hindered amines solvents under development or demonstration.

A preferred development would be for coal engines and turbines to be located adjacent to algal farms, whereby the engines could sequester CO_2 directly into enhanced biomass growth and either offset CO_2 emissions by avoiding the combustion of fossil transport fuels, or partially closing the C-cycle by co-firing with algal matter

8. ECONOMIC AND GREENHOUSE BENEFITS

This section gives a brief techno-economic analysis of supplying electricity from direct fired coal engines, compared to centralised generation from a new dry cooled USC, and decentralised generation using heavy fuel oil in a 100 MWe diesel generator, and NG in a 400 MWe GTCC.

The purpose of this analysis is to show that ultra clean coal used in smaller and more efficient power generation cycles is cost competitive with the best currently available technologies, and with a significantly reduction in GGE over USC coal.

It is acknowledged that comparison at this stage requires broad assumptions, and these are discussed below.

The base assumptions and results are summarised in Table 18. The results in the lower half of the table are showing graphically in Figure 37 through to Figure 38. The series in the figures are grouped from the left as base, alternative, and ultra clean coal cases with direct firing. Note that the last 2 cases are for a low and high ultra clean coal cost for the DICE.

The key assumptions include:

- USC assumes conventional centralised generation with losses in both transmission (TUOS) and distribution (DUOS), whereas for the smaller diesel engine- and gas turbine-based technologies the TUOS penalty is avoided.
- The thermal efficiency assumes dry cooling and warmer Australian conditions.
- The 100 MW diesel engine using HFO (HFO-DE) uses a large marine 2-stroke engine.
- The gas turbine cases are based on high efficiency combined cycle technology (equivalent to a thermal efficiency of 60% LHV basis, minus 3% for warmer Australian conditions).
- Fuel costs are intended to be representative of current or near future NSW prices – coal at \$1.25/GJ is equivalent to \$35/t, CWF is based on and is assumed to have a nominal cost of \$3.2/GJ (or \$100/t).
- A loss for fuel extraction, preparation and delivery has been included – for most fuels other than run-of-mine (ROM) coal for the USC pf, this ranges from 0.2% for ROM pf to 12% for turbine grade ultra clean coal. CWF for the diesel engine has a slightly lower energy and cost penalty, due to reduced processing and milling for this application.
- A \$40/t charge has been assigned to CO_2 produced, and is intended to be equivalent to the cost of capture and storage. The energy losses (and CO_2 emissions) in the fuel production chain are assumed to have the same CO_2 intensity (kg/GJ) as for the fuel used in each case.
- Power plant R&M for the direct fired coal has been set at 200% of that for conventional technologies.
- A capacity factor of 75% has been used for all technologies. In practice, the higher fuel cost HFO and NG cases may have a lower factor.
- The cost of electricity is given as a cost of generation sent out (COG_{so}), cost of electricity delivered (COE_{de}), with and without the CO_2 charge. As above, the COE includes TUOS and DUOS for USC, but only DUOS for the smaller capacity cases which are considered as decentralised generation.

Table 18 Techno-economic comparison of direct fired coal with best available conventional routes to electricity generation

		USC 700MW $1.25/GJ TUOS	HFO-DE 100MW $11/GJ	NGCC 400MW $8/GJ	DFGT 400MW, $3.2/GJ	DICE 100MW $3.2/GJ
Basis						
Unit size	MWe	700	100	100	400	100
Fuel cost	$/GJ	1.25	11	8	3.2	3.2
OTE base plant	%	41%	54%	51%	51%	54%
Fuel delivery loss	% of SE	0.2%	8%	14%	12%	8%
OTE_{so+fd}	%	41%	50%	44%	45%	50%
TUOS loss	%	4%				
DUOS loss	%	3%	3%	3%	3%	3%
TUOS charge	$/MWh	10	0	0	0	0
DUOS charge	$/MWh	25	25	25	25	25
OTE_{de}	%	38.1%	48.0%	42.7%	43.7%	48.5%
GGE_{de}	kg/MWh	882	591	452	769	695
Capex	$M/MW	1.8	1.4	1.2	1.4	1.6
LCC	%	10%	10%	10%	10%	10%
R&M	% capex	2%	2%	2%	4%	4%
Other operating	% capex	2%	4%	3%	4%	4%
Capacity factor	%	75%	75%	75%	75%	75%
Cost of CO_2	$/t	40	40	40	40	40
COE delivered						
Capital charge	$/MWh	29.5	22.0	18.8	22.0	25.1
Fuel cost	$/MWh	11.8	82.5	67.5	26.4	24.0
R&M	$/MWh	0.6	0.4	0.4	0.9	1.0
Other operating	$/MWh	0.6	0.9	0.6	0.9	1.0
COG	$/MWh	42.5	105.8	87.3	50.1	51.1
TUOS charge	$/MWh	10.0				
DUOS charge	$/MWh	25.0	25.0	25.0	25.0	25.0
COE, no CO_2	$/MWh	77.5	130.8	112.3	75.1	76.1
CO_2 cost	$/MWh	35.3	23.6	18.1	30.8	27.8
COE, with CO_2 charge	$/MWh	112.7	154.4	130.3	105.9	103.9
Change relative to USC with CO_2 charge	ΔCOE		27%	13%	-6%	-9%
	ΔGGE		-33%	-49%	-13%	-21%

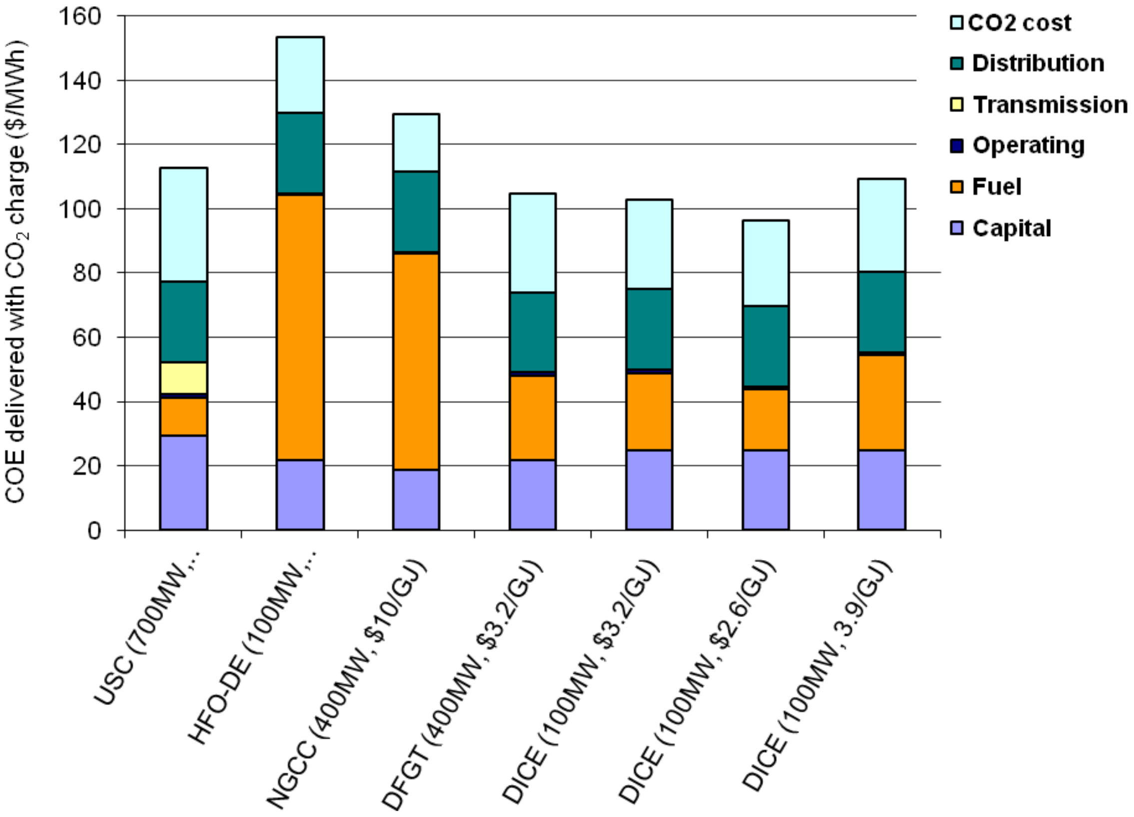


Figure 37 Breakdown of costs for delivered electricity with a $40/t CO_2 charge

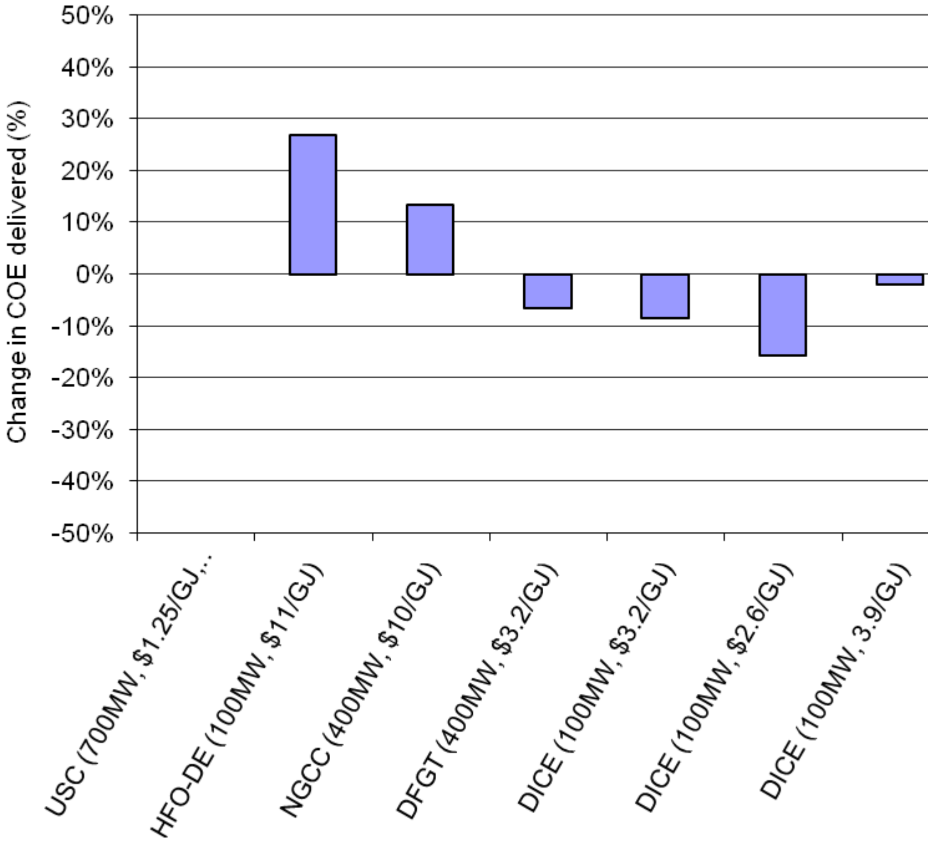


Figure 38 Change in the cost of delivered electricity relative to USC with a $40/t CO_2 charge

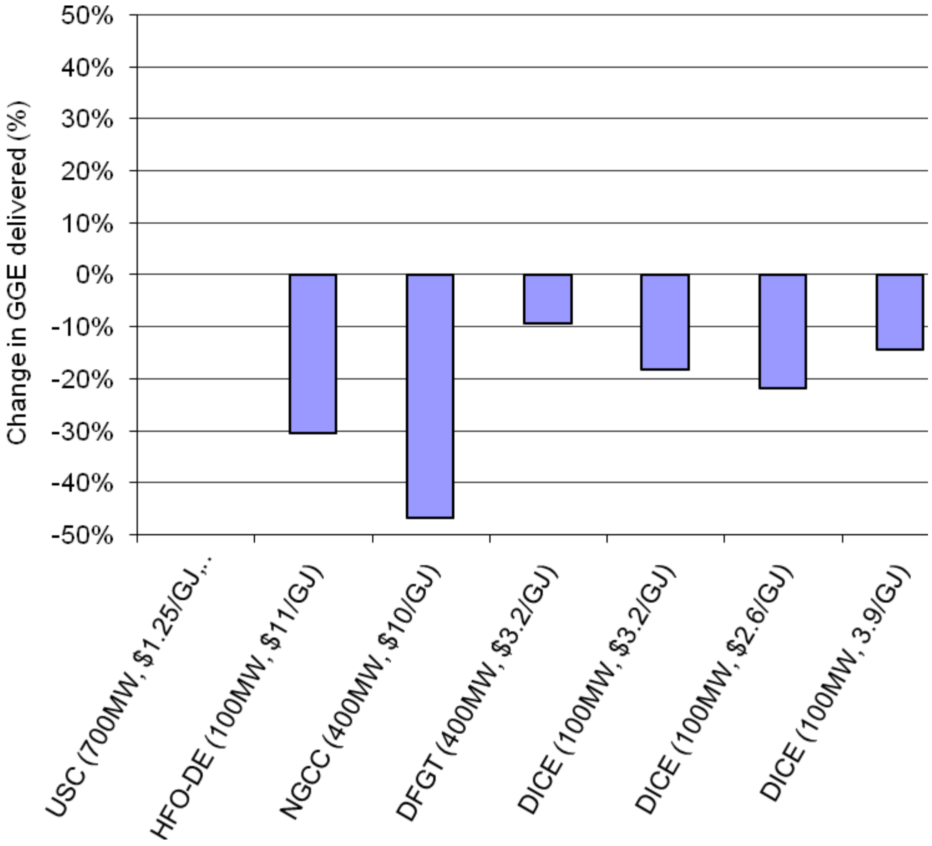


Figure 39 Change in the GGE for delivered electricity relative to USC

The main findings from the analysis are that:

- The base technology gives a delivered COE of $78/MWh without a CO_2 charge, and $113/MWh with a CO_2 charge.
- The CO_2 charge ranges from $35/MWh for USC, down to $18/MWh for the NG case.
- Diesel-based electricity is by far the most costly at $131/MWh, almost entirely due to the high cost of HFO.
- The delivered COE for the NG is $112/MWh, despite the higher efficiency, lower capital cost, and avoidance of TUOS ($10/MWh) in the present analysis.
- The direct fired coal cases are similar to that for USC.
- DICE would give a marked reduction in COE over that for generation using HFO.

None of these findings is contrary to previous studies, with the exception that most studies only give the cost of generation and the conversion efficiency of the base power plant. In addition, previous studies for UCC by the CCSD have been based on UCC delivered to Japan.

The inclusion of these factors penalises conventional USC pf mostly by the $10/MWh TUOS charge. It is noted that this charge can be significantly higher – for example, in Japan in 2006, TUOS charges ranged from $22-42/MWh.

Overall, the analysis shows that ultra clean coal-based electricity is competitive with USC for base load, and gives a significant 13-21% reduction in GGE. Note, that the variation in GGE benefit for the UCC cases in Figure 39, is due to the additional processing for the higher cost (higher quality) product.

9. DISCUSSION

The report has presented many technology components for coal cleaning, milling, power plant configurations, and strategies for underpinning a large penetration of renewables.

A key uncertainty is whether the DFGT can be developed to utilise CWFs. The attributes of the DFGT are therefore discussed briefly and compared with those for the DICE.

Although the DICE is likely to have issues with high pressure fuel injection and possibly unacceptably high wear rates of cylinder components, it is concluded that this type of engine has key fundamental advantages that will give it the best chance of successful commercialisation:

- Thermodynamic advantages – in a diesel engine, the combustion comprises a series of batch processes in the diesel engine, whereas the gas turbine uses continuous combustion. This means that higher initial temperatures and pressures can be used in the diesel engine, since the exposed components are cooled between power strokes – this increases thermal efficiency for a given scale, and reduces the effect of water in the fuel.
- Combustion – in a low speed diesel, the time available for combustion is around 10x longer than in medium speed engines or gas turbines, which overcomes ignition delay issues for low quality fuels, and enables more complete combustion.
- Tolerance to fuel impurities - batch combustion followed by cooling prevents slagging, fouling and corrosion associated with high temperature combustion of lower purity fuels. Fuel impurities do, however, cause issues:
  - wear from ash on sliding surfaces must be controlled by hard surface coatings.
  - the potential turbocharger fouling is increased, but low temperatures involved make this manageable.
  - emissions control will be required – for land-based engines (SCR, FGD, particulates).

Table 19 gives additional detail on both the similarities and differences in key combustion conditions and technical issues for the 2 types of engine, with the most difficult conditions and issues warranting further R&D shaded in yellow, and areas which remain uncertain or a serious difficulty are shaded in red.

Overall, there seem to be no show stoppers for the development of the coal diesel engine, with the most difficult issue of wear and atomisation being substantially overcome. Given the relative ease in which diesel engines may be modified to burn CWF, including being able to modify only one cylinder of a multi-cylinder engine, it is apparent that DICE gives the best option for early demonstration.

In comparison, there is a serious issue and uncertainty for the DFGT around fireside fouling and corrosion. Development and demonstration of the DFGT is likely to require a much higher level of commitment and support, and an order of magnitude more CWF.

Table 19 Comparison of key combustion conditions for a diesel engine and gas turbine, with conditions most difficult for coal fuels shown shaded

Combustion condition	Diesel engine	Gas turbine
Similar conditions		
Combustion intensity	5 MW/m^3.atm (on clearance volume where combustion most occurs)	20-50 MW/m^3.atm
Combustor pressure	45 bar at the start of fuel injection, 75 bar at the end	25-40 bar
Combustion air temperature	570-600°C	450°C (industrial) 600°C (aero derivative)
Excess combustion air	150% full load (4-stroke) 180% full load (2-stroke)	200% full load
Time for combustion	7 ms at 750 rpm	<10 ms
(after ignition)	50 ms at 100 rpm	
Ignition delay	3-5 ms chemical control, (aim to minimise)	<5 ms, mixing controlled
Peak combustion temperature	1500°C	1600°C (aim to avoid high peak temp to reduce NOx)
Exhaust temperature	650°C (400°C after turbocharger)	480-550°C (for combined cycle)
Dissimilar conditions		
Combustion mode	Intermittent, 7/s at 750 rpm (4-stroke) 1.5/s at 100 rpm (2-stroke)	Continuous
Combustion pressure	Peaky, starting at 50 bar, increasing to ~180 bar	Aim to be constant at 20-35 bar, (combustion fluctuations can cause chronic engine vibration)
Combustion chamber cooling	Water cooled head, maximum surface temperature is piston crown at ~300°C with coatings	Air or steam cooled to give surface temperatures up to 1300°C
Liquid fuel atomisation	Pressure via multi-hole nozzle	Pressure via swirl nozzle, or twin fluid atomisation using compressed air or steam
Combustion gas velocity against cooled engine surfaces	Low, protective stagnation layers	Up to 300 m/s, usually film cooled with air for surface temperatures above 1100°C
Ash interactions	Wear due to 3-body mechanisms – ash between sliding surfaces	Erosion from impact, fouling due to fine particles, alkalis, S and V, with fouling leading to corrosion

10. CONCLUSIONS AND RECOMMENDATIONS

While best available supercritical pf and IGCC plants could achieve a fuel cycle efficiency of 38-40% (HHV) at a scale of around 700 MW, and natural gas turbines 48-50% (HHV) at scales between 250 and 500 MW, the highest overall cycle efficiency, 52% (HHV), is achieved by a low speed diesel engine using fuel oil, at scales around 30 MW. A key conclusion is that a direct injection coal engine, using CWF based on ultra clean coals such as UCC, should be able to achieve a similar thermal efficiency to that for fuel oil. The development of low speed, high capacity (up to 100 MW), 2 stoke diesel engines, provides a useful technology platform for efficient distributed generation based on CWF.

In the past, CWFs have always been intended as a substitute for oil, which has been a factor against their development. The recent development of processes that can produce ultra low ash feed coals could enable the production of much higher quality CWFs than possible in the past. Coupled with other benefits, this should give a strong incentive to develop ultra clean CWF– not just as a HFO replacement, but as a direct competitor to conventional pulverised coal in diesel engines and gas turbines.

Direct firing of coal requires micronising to <20-30µm for diesel engines, and <10µm for gas turbines. In the past this has been difficult, costly, and energy inefficient. A variant of the planetary mill has been developed commercially by Ludowici, and is considered highly suitable for preparation of CWF. This mill should reduce the energy penalty for micronising by 75%.

There has been significantly less development of the direct coal fired gas turbine than has been undertaken for the coal-diesel engine. The most recent, and most successful, tests were carried out by MHI using UCC. Overall, UCC combustion was similar to that for liquid fuels, but with increased flame radiation. MHI concluded that they could modify the design of the combustor and fuel delivery system to give high performance required of a commercial engine using CWF.

Most direct fired coal studies in the past have been based on the compression ignition (diesel) engine, with variations around the method of introducing the coal into the engine. Direct injection of CWF, in a similar manner to diesel or fuel oil in a conventional diesel engine, has been the most successful method of direct firing coal.

Injection and combustion characteristics of CWF in diesel engines are significantly different to those for diesel fuels, due to the combined effects of poorer atomisation and the time required to evaporate the slurry water. Not withstanding the difficulties of atomising and igniting CWF in engines, combustion and thermal efficiencies matching that of the original engine burning diesel fuel have been achieved with the pressure atomisation system for CWF, at up to 1900 rpm.

Injectors have caused the biggest technical problems for direct injection of coal into diesel engines, and have been the subject of most R&D. There are a number of important factors:

- CWF is more difficult to atomise than diesel fuel, due to its much higher viscosity.
- Effective atomisation is more critical to combustion due to the effect of droplet size on ignition delay (increased by the time required for water evaporation) and burnout.
- CWF causes chronic wear of injection nozzles, with wear being exacerbated by cavitation effects.
- Pressure atomisation can be improved by increasing the liquid velocity through the nozzles; however, this is greatly increases nozzle wear.

A number of successful demonstration programs were completed in the most recent DOE coal engine program from 1986-93, including medium speed 4-stroke engines in locomotive and genset applications. Although the program was highly successful technically, it was terminated due to persistent low oil prices and the US federal budget deficit.

The critical technologies developed in the final stages of the program (electronic controlled engine with its emissions cleanup system), together with a number of other engine modifications to combat wear, will allow the technologies to be packaged into commercial systems very quickly. Currently, the engine modifications required for successful direct injection of CWF are the use of a purged-shuttle fuel pump plunger, electronically timed injection, diamond compact injector tip nozzles, tungsten carbide sprayed cylinder liner and top ring set, and pilot injection of diesel (especially at low load).

Areas requiring further research are:

- Effects of mineral matter; despite extensive tests, there are no firm conclusions on the effects of mineral matter occurrence (type, size and morphology) on the mechanisms of flyash formation in the combustion chamber, or its effect on engine wear.
- The mechanism of atomisation of CWFs; this is unclear, as are the effects that this may have on agglomeration of coal particles during the evaporation of individual CWF droplets. A number of novel methods for atomisation have been proposed, but without practical testing.

Another potential advantage of the use of CWF, particularly if used in a diesel engine, is that it may give important synergies for high penetration renewables, by providing cost effective and efficient backup power and spinning reserve, and enabling efficient use of a range of liquid and gaseous biomass fuels. The Commonwealth government has announced a target of 20% renewables by 2020, and this will require cost effective support by fossil fuel power plants – a role which could be played by the direct injection coal engine.

The cost of supplying electricity from CWFs using direct firing is expected to be very similar to those for supercritical pf plants. However, this does not take into account the other benefits of efficient, flexible and adaptable distributed generation. Overall, the analysis shows that CWF-based electricity (using either diesel engines or gas turbines) is competitive with USC and NGCC (at the assumed production costs on a fuel cycle basis and with a TUOS charge only for USC), and gives a significant 20% reduction in GGE.

While larger gas turbine combined cycle plants will ultimately give the highest fuel cycle efficiency and lowest GGE for CWF, development of these machines is necessarily very measured, and costly, compared to the diesel engine.

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