COAL BASE-LOAD POWER

USING MICRONISED REFINED COAL (MRC)

MRC fuel produced from advanced coal processing technologies … can provide the overdue opportunity for the diesel engine to replace the steam engine for large-scale base-load power generation by delivering a range of superior performance attributes.

Dr Louis Wibberley – CSIRO

In a previous article the author detailed an alternative pathway that CSIRO has proposed for low CO_2 emissions electricity with coal as the key fuel. The alternative pathway aims to avoid or substantially reduce the issues facing current clean coal technologies focused on CO_2 capture and geological storage (CCS) – cost and the amount of CO_2 storage required. The alternative pathway proposes to:

- achieve the highest possible efficiency for coal-based generation at smaller scale,
- use the advantages of higher efficiency and smaller coal plants to underpin a high penetration of renewables via cost-effective backup and grid security, and
- use niche (rather than major) CO_2 capture and storage as the last step in meeting emissions targets.

DIRECT INJECTION COAL ENGINE

Size-for-size, the most efficient means of converting fuel energy to electricity is by using large diesel engines or direct carbon fuel cells. Coal could achieve a much higher efficiency if these technologies could be used, enabling a delivered efficiency (from coal in the ground through to sent out electricity) of 50% from a direct injection coal engine (DICE) in the short-medium term, and at least 65% in the longer-term future from the direct carbon fuel cell (DCFC). Both could be achieved at a smaller scale than for conventional coal technologies – an attribute that could give a number of other important advantages associated with more decentralised electricity generation, including a reduction in transmission losses (electricity transmission losses are almost always significantly higher than those from the transport of fuel). Although neither technology is commercially available, the high efficiency has been demonstrated in the laboratory and small pilot scale.

ULTRA HIGH COMBUSTION EFFICIENCY

Although never commercialised, the coal engine is not new, being the subject of a number of development programs over the last century. The early work was led by Diesel and then co-worker Pawlikowski, with engines running for many years on dry solid fuels (dust firing) ranging from lignite to coke. The most comprehensive test program was undertaken by the US Department of Energy (DOE) over the period 1978 to 1992, mostly for transportation applications. This included adapting and testing engines ranging from an 800 kW haul truck engine (1900 rpm), a 2 MW locomotive (1000 rpm), to a 2 MW single cylinder marine test engine (90 rpm). The most successful demonstrations used ultra low ash coal water fuels which were injected using modified conventional direct injection systems (*ie* solid spray injection). Although the technical issues were overcome for DICE, with combustion efficiencies of over 99% being achieved at 1900 rpm, and with thermal efficiency equal to diesel fuel, the program was eventually terminated due to persistently low oil prices and before a commercial engine was developed.

WHAT'S CHANGED?

In redeveloping this technology, it is important to consider a number of drivers and technology developments.

Changed drivers include the impending cost of CO_2 abatement, cooling water availability, the need to support a step increase in renewables, changes to the structure of the electricity supply industry and energy security issues. These give DICE a number of advantages, including its ability to achieve higher efficiency at smaller scale and capital steps around one-tenth of pulverised fuel (pf) plants while remaining competitive for base-load, peaking and providing grid security/ancillary services. DICE would also be capable of cofiring of biomass fuels (char, crude bio-oils and algae soups), which could enable biomass to be utilised at double the efficiency of current biomass plants. Also, as waste heat is at sufficient temperature to provide much of the low temperature heat energy needed for CO_2 capture, this could be added with a smaller cost and energy penalty than for current clean coal technologies (instead of converting this energy to electricity with small turbo machinery).

There have been a number of key technology changes, including developments in coal cleaning, micronising, engine technology, engine size, and cost (around 10–20% less than for pf), which are all likely to further increase the viability of the coal engine over that in previous development programs, and also reduce the time required for adoption of the technology. Currently, under the European HERCULES Project, new engine technologies are being developed which will increase the efficiency of large engines to over 60% (LHV, mech).

Although DICE and DCFC require ultra low ash coals (say below 2% ash), technologies already exist to produce suitable fuels from coals (including from Victorian brown coals).

This article gives an update on the status of fuel production and DICE RD&D over the last 12 months at the CSIRO.

ULTRA LOW ASH COAL

The alternative pathway depends entirely on cost-effective production of ultra low ash coals. Although the cleaner the better, detailed coal specifications for large diesel engines remain unclear. The DOE work in the 1980s and early 1990s concluded coal with 2–3% ash is suitable for DICE, and that this could be produced from both chemical and physical coal cleaning processes.

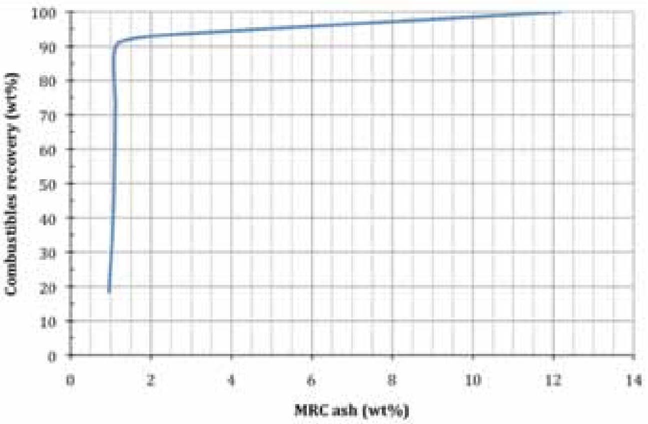
The DOE studies showed that the most suitable method for fuel delivery was direct injection of micronised coal water fuel (compared to the dust injection used in previous attempts) so drying is not required after cleaning. Depending on engine size and operating speed, the micronised coal should have a top size of around 30µm, and a coal concentration of 50-60%. This gives a viscosity of around 300mPa.s (at 100/s) which enables effective pressure atomisation.

While a number of chemical processes have been successful in producing ultra low ash coals (in particular, Ultra Clean Coal or UCC, which has been developed to a near commercial stage), these processes have been developed to compete with natural gas, LNG or heavy fuel oil, and are therefore too costly to compete with base-load conventional pf plants – regardless of efficiency improvements.

MICRONISED REFINED COAL (MRC)

For the alternative pathway a different method of coal processing is being developed based on improved physical cleaning methods. This approach involves slurrying and micronising the coal to liberate the mineral matter, and then using ultra fine flotation or selective agglomeration to remove the coal from the mineral matter. ▸

Continued from page 35



Recovery versus ash curve for flotation of a Hunter Valley coal using an L 500 J-cell

In reinventing the physical cleaning process to produce diesel engine fuel, the author acknowledges several excellent studies from the 1990's involving the ultra fine micronising-flotation sequence[1-3], and a more recent article on the complex phenomena involved in ultra fine flotation[4]. A recent CSIRO study with a range of Australian coals (including tailings) has shown that if coal is ground finely enough, flotation will give a consistent low ash product with very high coal recovery, significantly higher than obtained from most of the earlier studies. As the micronised raw coal slurry has the appearance of crude oil prior, this process has been termed micronised coal refining, and the product micronised refined coal (MRC).

With MRC comes a change in the philosophy for coal processing and marketing – ultra fine wet coal is now alright.

PROGRAM DEVELOPMENT

An R&D program has been completed by the CSIRO to develop the concept, obtain fundamental data for key process steps and to provide fuel for engine tests. This included:

- MRC production for a range of coals (including tailings and a sub-bituminous coal) by micronising with a laboratory Isa Mill, followed by flotation,
- fuel formulation – to determine viscosity and stability characteristics, and to screen additives,
- coal-engine interactions – MRC atomisation and ignition, the formation of abrasive particles, engine operation and identifying what adaptations would be required for existing engines,
- integration options for post combustion capture and oxy combustion, including new engine configurations, and
- techno-economics and development of a business case for demonstration.

Pilot development of the process is now underway with CSIRO and partners, with plants being considered for two NSW sites (details currently unavailable for publication).

MRC PRODUCTION

The preliminary study into MRC production mostly involved micronising the coal to give a d100 of 30µm, followed by flotation (for a few coals a 2-stage milling-flotation method was used). Flotation tests involved obtaining recovery versus ash curves using an Essa flotation machine and the Universal Flotation Test (the UFT tests being contracted to TUNRA Clean Coal), laboratory flotation tests using a 100mm Concorde Cell (by the University of Newcastle), and a 150mm J-cell (by Xstrata Technology). Additional studies have also been undertaken using a 500mm pilot J-cell at CSIRO Newcastle. This cell uses components from a full scale J-cell and better represents commercial-scale conditions.

The results are summarised as follows:

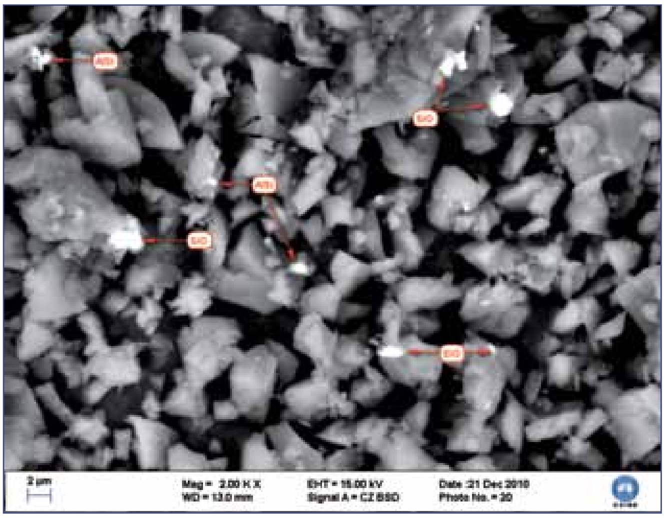
- For the laboratory Isa Mill the energy for micronising coal (comminution from -3mm to -30µm) is approximately 65kWh/t of coal. An optimised full-scale micronising plant is likely to give significantly lower milling energy.
- The laboratory Essa flotation cell and UFT tests gave 2–3% ash for all coals at a combustibles recovery of 85–93wt%.
- The larger pilot J-cell (L500) produced a lower concentrate ash (1–2%) with a similar combustibles recovery (presumably due largely to the better froth washing in the larger cell). An example flotation curve for a target Hunter Valley coal is shown below.
- Further optimisation of fuel production is expected as fuel specifications for different engines are developed.
- SEM (scanning electron microscope) analysis of concentrates showed in all cases that if the mineral matter can be liberated from the coal by micronising, it is possible to remove it efficiently by flotation, with only inherent mineral matter (*ie* ultra fine minerals locked within the coal) reporting to the concentrate. SEM showed only low levels of residual extraneous ash particles, and for the Hunter coals particles were predominantly ultra fine quartz with a smaller proportion of clay mineral particles. As the residual mineral particles were <5µm, and mostly 2–3µm, these are thought unlikely to be a major issue for engine wear.
- With the exception of the oxidised sub-bituminous coal sample, flotation reagent consumption was very low, with collector <<0.3L/t diesel, and around 30ppm of frother typically being required. Reagent consumption was significantly lower for freshly micronised coal versus that which had been stored as slurry due to slight oxidation.
- A 1.5–2% ash MRC can be produced with a combustibles recovery of around 75% from coal tailings (feed coal 54% ash).
- For bituminous coals a combustible recovery (ash based) of 85–93% was achieved. For the sub-bituminous coal a lower recovery (around 65%) was achieved, however as the coal was known to have oxidised, it is expected that a fresh sample would give a better result.

Larger pilot-scale tests are soon to be undertaken as part of a collaborative study with a large coal producer to provide fuel for larger-scale injection and engine tests.

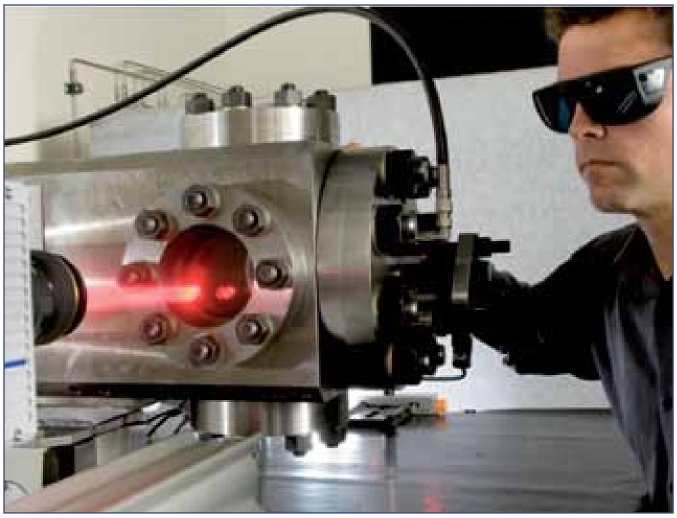
Micronising using an M4 IsaMill

FUEL FORMULATION

After flotation, the coal concentrate requires trim dewatering to increase the coal content to 50–60 wt%. Tests have shown that this can be readily achieved by a number of commercial techniques. The resulting fuel has a viscosity of 150–300 mPa.s at 100/s (and has the consistency and appearance of black acrylic paint). Depending on the application, trace amounts of additives can be used to modify MRC viscosity and stability characteristics.



SEM micrograph of MRC from a Hunter Valley coal with the main mineral (bright particles) elements identified



High-pressure spray chamber for combustion research at up to 20 MPa

For the small laboratory engine a small amount of a designer viscosity modifier was added; however for larger engine applications additives are more likely to be required to improve stability for long-term storage (*eg* several years). MRC is different from current coal water fuels in that it is finer and has a narrower particle size distribution.

MRC containing 0.8% ash and with an SE of 19 MJ/L (gar)

Although there are a number of standards for testing conventional coal water fuels, there are presently no standard tests for characterizing MRC for diesel engines, and so a range of new tests and experiments have been devised to provide performance data:

- Viscosity – measured over a wide range of shear rates (100-500,000/s at 0-150°C) using both standard instruments and calibrated nozzles. These measurements are supplemented with Zeta measurements.
- Formation of abrasive particles – initial work only involving operation of the test engine, SEM imaging of ash from plasma ashing and combustion in a high-pressure spray chamber.
- Atomisation – from both operation of the test engine for a range of injection pressures, and by direct observation of spray development using a high-pressure spray chamber. Injection pressures of up to 120MPa are used, with chamber pressures of 5–20MPa and temperatures to 1,600°C.
- Stability testing – measurement of fuel density profiles of fuel stored over a 3-month period, with settling behavior related to Zeta, surface tension, particle size and viscosity measurements.

The main findings from the work to date are that MRC is generally very stable for periods of months without the use of additives or agitation, especially for higher solids concentrations. Also, its atomisation characteristics are significantly better than would be predicted from equilibrium surface tension and low shear viscosity determinations (viscosity mostly affects the discharge co-efficient of fuel nozzles). Comparison with Newtonian water–glycerol mixtures suggests that significant shear thinning is occurring in the injector nozzles.

COAL-ENGINE INTERACTIONS

Most of the research to determine the effects of coal processing and formulation (particle size distribution, coal loading, additives and storage) on combustion behaviour is being undertaken in a high-pressure spray chamber. In this equipment MRC can be atomised and combusted at pressures up to 20MPa with optical access to enable high speed imaging and pyrometry. A modified single orifice injector is used.

Although MRC performance can only be adequately tested in very large engines for which it is being targeted, some engine tests are being undertaken with the engine shown. These tests give hands-on experience with how to adapt and operate a diesel engine with MRC, and give a comparison of engine performance and emissions relative to diesel fuel. The engine is a 3.9L single cylinder naturally aspirated diesel engine. This formerly agricultural engine has been modified with an electronic fuel injection system, crank and cylinder monitoring, plus other modifications to improve safety (*eg* steel flywheels and pressure lubrication).

A 3.9L laboratory coal engine adapted with electronically controlled fuel injection

NO ISSUES WITH FUEL PUMP OR ENGINE WEAR

Overall, the laboratory engine has been successfully operated on MRC, and has achieved similar efficiency to diesel operation. Despite the very small combustion chamber, clean combustion was achieved without the formation of tars or deposits in the combustion chamber or exhaust of the engine, and NO_X is reduced by 70%. This was achieved with an injection pressure of 100MPa and using a double-shot injection strategy, where approximately 20% of the fuel was injected early to avoid quenching the compressed air charge and to start ignition before the main injection event. ▶

Continued from page 37

Engine operation was exceptionally smooth and with slightly reduced combustion knock compared to diesel operation with the standard PLN fuel system. In large engines ignition and burnout is likely to be improved as compression temperatures would be higher and there is increased scope for injection rate shaping. Currently engine runs are restricted to around 2 hours due to the use of relatively soft steel injector tips which experience significant cavitation (not abrasion) related wear. The small size of the engine (especially the small injector orifices), do not warrant development of a diamond compact nozzle as has been successfully used for larger engines (and also for industrial high-pressure slurry spray equipment). To date there have been no issues with fuel pump or engine wear, or fouling of combustion spaces. 40-50% coal MRC has been reliably injected via 250μm fuel nozzles with no clogging problems providing the injector is flushed immediately after coal operation.

PRACTICAL IMPLICATIONS OF COAL PROPERTIES

Studies are continuing to help optimise fuel processing and formulation, as there are competing effects of fuel processing cost, fuel solids content (*ie* water content) and particle size distribution, with the quality of atomisation, ignition delay, burnout rates, engine efficiency and engine wear. The ultimate objective is to provide data for the development of MRC specifications for engines.

A detailed engine model has been developed to assist with interpreting the practical implications of coal properties, to scale the experimental data to much larger engines, and to investigate integration options for post combustion capture or oxy-combustion. As detailed fundamental data is unavailable for many of the combustion processes involved (mostly because the temperatures and pressures are significantly different to those in a pf boiler or gasification), a multi-dimensional model is not presently justified.

For this reason, a quasi-dimensional or phenomenological model has been used to describe the key processes. The model uses a number of sub-models to describe the complex processes of atomisation, evaporation, ignition *etc*, and to continuously evaluate the thermodynamic state of the cylinder charge throughout the cycle.

DICE has some interesting trade-offs in determining engine mechanical efficiency *(Refer insert).*

The calculated efficiency penalty from the fuel water content for the laboratory engine is 2% points. This is less than half the penalty in conventional pf.

$$n_{mech} = \frac{W_{expansion} + W_{tc\,\&\,cc} - W_{compression} - W_{friction} - W_{fuel\ pump} - W_{BOP}}{Q_{fuel}}$$

where:

n_{mech}	mechanical efficiency
$W_{expansion}$	work from cylinder expansion (higher for MRC due to the water content)
$W_{tc\,\&\,cc}$	work from turbo compounding and combine cycle (small differences with MRC)
$W_{compression}$	work absorbed from cylinder compression (lower for MRC due to evaporative charge cooling after atomisation)
$W_{friction}$	work absorbed as engine friction and in pumping losses through ports and valves (similar for MRC)
$W_{fuel\ pump}$	work absorbed for the fuel pump drive (increases from around 0.4% of heat input for heavy fuel oil, to 1% for MRC)
W_{BOP}	work absorbed for the balance of plant, including lubricant pumps and cooling fans (similar for MRC)
Q_{fuel}	energy content of fuel

ADAPTION OF EXISTING ENGINES

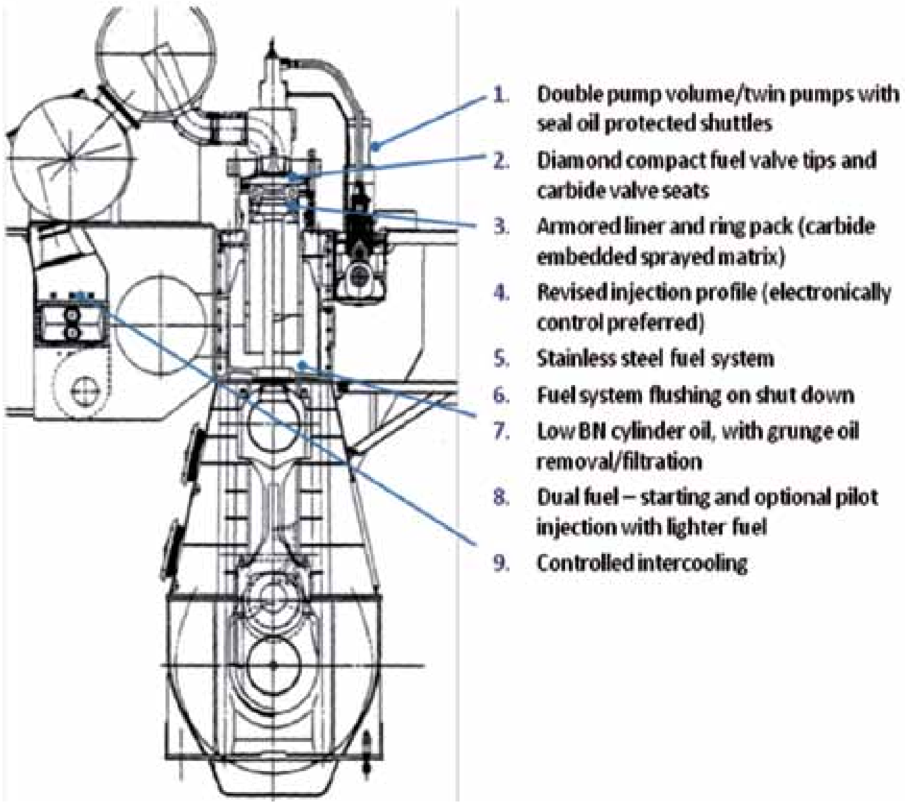
Although a wide range of large engine types could be used for MRC, it is thought that the most suitable engines are the large 2-stroke engines used for marine applications and heavy fuel oil power stations. These engines have the highest efficiency, longevity and fuel tolerance, and are available in sizes from 2-100MW. The adaptations and features required for MRC are still to be confirmed; however these are likely to include most of those in the Figure below – noting that some of these features are already available (*eg* new engines developed for bio-oils already have stainless steel fuel systems).

A fuel testing program is presently underway with a large engine manufacturer both to develop MRC fuel specifications and assist in optimisation of the fuel production processes.

A number of non-standard engine configurations have also been considered either to reduce cost, weight, or improve the integration with oxy-firing or post combustion capture. A wide range of adaptations are possible, which in the future could give significant advantages over the current engine design which has been optimised for large marine applications.

TECHNO-ECONOMICS

Preliminary calculations have shown that MRC-DICE would be cost-comparable with base-load pf, with the increased cost of producing MRC (around $1/GJ) being offset by a reduction in heat rate and a reduced CO_2 penalty – even at very small scale. For example, a mine mouth power plant (10MW) would have a nominal sent



1. Double pump volume/twin pumps with seal oil protected shuttles
2. Diamond compact fuel valve tips and carbide valve seats
3. Armored liner and ring pack (carbide embedded sprayed matrix)
4. Revised injection profile (electronically control preferred)
5. Stainless steel fuel system
6. Fuel system flushing on shut down
7. Low BN cylinder oil, with grunge oil removal/filtration
8. Dual fuel – starting and optional pilot injection with lighter fuel
9. Controlled intercooling

Cross-section through a large, low-speed, 2-stroke engine showing a probable list of adaptations for MRC out cost of electricity of $50/MWh from product coal and $40/MWh on tailings, and with a CO_2 intensity of 690kg/MWh – an excellent result for such a small power plant, and a 25% reduction over current black coal pf plants (50% for brown coal pf plants).

However, an accurate comparison requires that other factors are considered (*ie* other than increased efficiency and reduced CO_2), including location and project-specific factors such as:

- increased grade recovery, including the ability to recover MRC from tailings, and reduced tailings disposal costs,
- increased dispatchability – shorter startup time, better part-load efficiency and load following,
- reduced water consumption (equivalent to dry cooled pf),
- lower installed cost – around 10% lower than pf, increasing to 40% for medium-speed 4-stroke engines (but with 1% efficiency penalty and higher R&M), and
- project financial benefits – shorter construction time, smaller capital steps.

There are a number of other advantages which could apply if MRC-DICE became widely adopted due to the characteristics of DICE (high efficiency from small plants from fine wet coal), together with the ability to utilise a range of mine gases, and the ability to produce MRC in both liquid and cake form. These attributes could give improvements over the entire fuel cycle.

Detailed studies are being undertaken to support a number of demonstration projects, although data are presently unavailable for publication.

WHERE TO FROM HERE

It is acknowledged that the proposed alternative pathway needs considerable development and demonstration to match the level of technical development of the current clean coal technologies. Despite this, the proposed pathway has strong technical merit because of the ability to carry out a near commercial-scale demonstration at a relatively small scale. This greatly reduces development and commercialisation risk hurdles.

In addition, while the overall approach is novel, most of the component technologies are based on adapting commercial and mature processes (and many are Australian). An additional feature is the high degree of flexibility and adaptability of all of the technologies.

A number of proposals are under development to establish small-scale demonstration projects in Australia. These mostly involve a two-stage program starting with pilot testing of fuel production at around 1–3 t/day for use in large test engines, together with engineering for a larger demonstration plant. This would be followed by a 10,000 hour demonstration plant with a 7–10MW power plant.

Even at this small scale, the demonstration plant would exceed the sent out thermal efficiency of Australia's best pf plants.

In addition, this would be sufficient to scale up (through both multiples and scale) to a 100MW power plant within 3 years.

In the meantime, CSIRO, partners and several industry groups continue to undertake research on how best to prepare coal water fuels from different coals, and to better understand coal–engine interactions. A comprehensive lignite coal R&D program is also underway.

Several Chinese groups are also working in this area.

SUMMARY

Lastly, despite a number of promising developments over the last 100 years, the development of the coal engine has languished. In summarising the extremely positive results of early development in 1928, Diesel's co-worker Herr Rud Pawlikowski[5] claimed: 'The diesel engine failed to hold out its promise of out-rivalling the steam engine for large applications, in spite of its unparalleled heat efficiency.'

The author believes that at long last, MRC fuel produced from advanced coal processing technologies such as the Isamill and J-cell, can provide the overdue opportunity for the diesel engine to replace the steam engine for large-scale base-load power generation by delivering a range of superior performance attributes.

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Producing MRC at CSIRO using an L500 J-cell courtesy of Xstrata Technology