100 MWe COAL-FIRED DIRECT INJECTION CARBON ENGINE (DICE) COMPOUND REHEAT COMBINED CYCLE (CRCC) WITH 90% POST-COMBUSTION CO_2 CAPTURE

VOLUME III: TECHNOLOGY GAP ANALYSIS REPORT

U. S. Department of Energy (DOE)

Contract No. 89243319CFE000025, Coal-Based Power Plants of the Future

By

Nexant, Inc

And

Bechtel Power and Infrastructure

Table of Contents

List of Tables

List of Figures

Section 1 Introduction

1.1 CURRENT STATE-OF-THE-ART POWER PLANT

The current state-of-the-art in coal-fired power generation comprises supercritical (SC) and ultra-supercritical (USC) pulverized coal (PC) boiler-steam turbine generator (i.e., Rankine steam cycle) technology. Due to the nature of the main prime mover plant equipment and auxiliaries used and the underlying thermodynamic cycle (and the working fluid), the technology is cost-effective only at very large, utility-scale (almost gigawatt) installations. Even then, the strict environmental regulations governing criteria pollutants and other harmful emissions resulting from coal combustion impose very expensive coal treatment/preparation and flue gas treatment equipment, which negatively impacts plant cost and performance. On top of those challenges faced by conventional coal-fired power generation technologies, such mega-facilities are not amenable to fast and flexible operation requirements imposed by the rapidly changing nature of power generation portfolio with increasing penetration by renewables. Especially vexing is the clash between advanced alloys which are requisite to facilitate USC steam conditions for high efficiency (i.e., austenitic steels), which are less resistant to thermal stresses imposed by rapid load ramps and plant starts and shutdowns. A further challenge is faced during construction because of the need for skilled welders to handle pipes and valves made from such exotic (and expensive) alloys.

Even when all the practical challenges associated with advanced USC steam technology are ignored, the proverbial *"pot of gold at the end of the rainbow"* is more like copper – i.e., net lower heating value (LHV) efficiency that can be hoped for is worse than that of an E-class gas turbine combined cycle (GTCC).

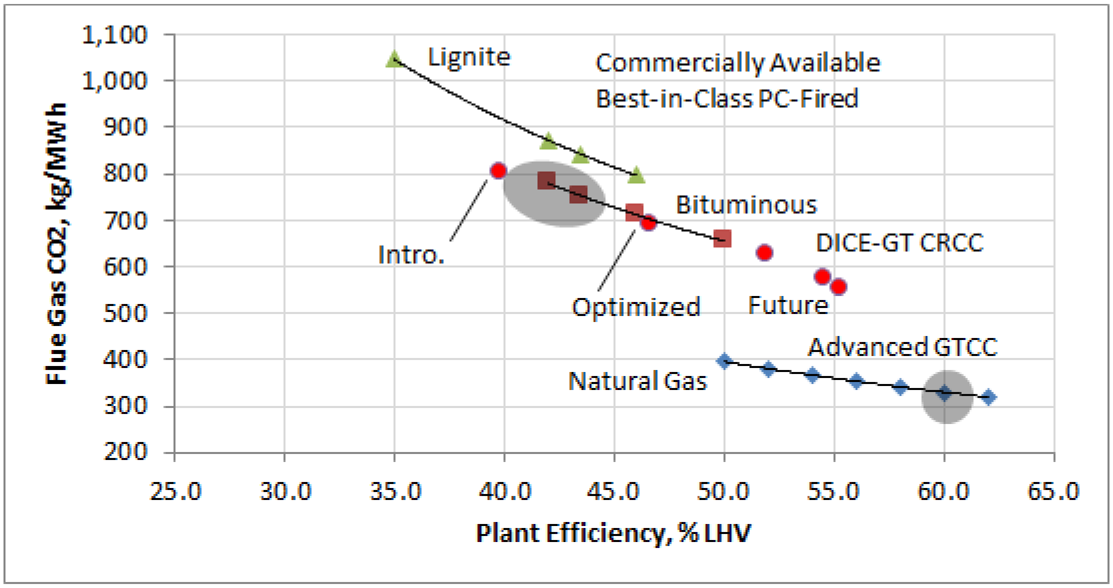
1.2 PROPOSED CONCEPT

The proposed concept, the **Direct Injection Carbon Engine Compound Reheat Combined Cycle** (DICE CRCC) delivers the predicted and achievable efficiency by the most advanced USC technology while being:

- Modular
- Flexible
- Small (120 MW base, about 80 MW with post-combustion capture, PCC)

This is clearly highlighted and illustrated by the chart in Figure 1-1, which shows the CO_2 emissions and plant efficiency of PC, GTCC and DICE CRCC (without PCC and including their best embodiments) technologies.

Figure 1-1
Efficiency-CO_2 Emission Comparison of Fossil Fuel-Fired Technologies



The DICE CRCC delivers the promised capabilities by combining mostly standardized, off-the-shelf, and commercially mature equipment with proven technology in a thermodynamically optimum manner. The combination of reheat with constant volume heat addition delivers the most efficient heat engine cycle, which can be implemented in the field with multi-equipment configurations for maximum modularity and flexibility with high efficiency at small ratings. The DICE CRCC with post-combustion carbon capture (PCC) is a low emissions, coal-fired power plant comprising three "blocks" or "islands":

- Coal beneficiation and coal-water slurry (CWS) fuel processing and production
- Modular electric power generation
- PCC

The basic operating principles and overview of the DICE CRCC can be found in Section 1 of the **Performance Results Report**.

1.3 TECHNOLOGY GAP ANALYSIS – THE PHILOSOPHY

The PCC Block utilizes amine-based chemical absorption technology, which is currently available and is not considered for technology gap/risk analysis. Detailed description of the PCC Block is provided in Section 4.8 of the **Performance Results Report**.

The Power Block also comprises of commercially mature and proven technology *except for the DICE*. Thus, the main focus of the technology gap analysis presented herein is on:

- DICE R&D and development pathway
- CWS processing and production.

The approach and methodology for the technology gap analysis presented herein is guided by the USDOE definition of **Technology Readiness Level** (TRL) is outlined in Appendix B. There are **three** areas of focus in the analysis:

- Technology Gap
- Technology Risk
- Development Pathway

The "gap" is determined by the TRL of a particular technology. *If the technology in question is at TRL 9, there is no gap*. If the technology is at, say, TRL 5, the technology gap is defined by the difference between TRL 9 and TRL 5.

As far as the distinction between technology "gap" and technology "risk" is concerned, in a nutshell:

- The "gap" is associated with the question "can we do it?"
- The "risk" is associated with the question "can we do it safely and economically?"

The "development pathway" is the key driving **stratagem** to be followed to bring the technology in question from TRL X < 9 to TRL 9 in the shortest time possible while mitigating the risks identified along the way.

The term "technology" can refer to a single system or a subsystem of a system. For example, the **Power Block** of DICE CRCC comprises the following "technologies" (not a *comprehensive* list):

- Reciprocating Internal Combustion Engine (RICE)
- Gas Turbine
    - Gas Compression
    - Combustion
    - Gas Expansion
- Waste Heat Recovery
- Steam Turbine
- Alternating Current Synchronous Machine
    - Motor
    - Generator

It should be highlighted that there is interchangeability between the terms "technology" and the "equipment" representing a particular technology. *All technologies enumerated above are at TRL 9 when used with a conventional liquid or gaseous fuel*.

From a subsystem perspective, the technology gap is inherent in RICE when burning an *unconventional* fuel (i.e., coal-water slurry in this case). In this particular case, the technology is referred to as *Direct Injection Carbon Engine* (DICE). Even then, note that DICE comprises various "subsystems", which are "technologies" in their own right, i.e.

- "Stock" engine comprising
  - Engine block/cylinders
  - Pistons
  - Crankshaft
  - Camshaft
  - Fuel injectors
- Turbocharger
- Synchronous alternating current (AC) generator
- Lubrication system
- Engine cooling system
- Charge air cooling system

The vast majority of all "subsystem technologies" in DICE are at TRL 9. The exception is the fuel (MRC) preparation and fuel injection system, which is discussed in detail below.

For N subsystems in a system with N – 1 subsystems at TRL 9 and one system at, say, TRL 4, can one take the average (it can even be a somehow "weighted" average) and state that the system is at, say, TRL 8.2? This may not always be the case because a system is like a chain, *it is as strong as its weakest link*.

The other key vexing question is this: If the subsystem in question is developed from TRL X < 9 to TRL 9, can it be introduced into *any existing system framework* (with all other subsystems at TRL 9) so that the new system will be at TRL 9? Specifically:

- If the fuel injection system is brought to TRL 9 by using a RICE platform from OEM[1] X, can one say that any RICE (from OEM Y or Z) can be transformed to DICE at TRL 9?
- If DICE is brought to TRL 9, can one say that DICE CRCC can be deemed to be at TRL 9?

The answer to the second question is ***NO***, because, while individual subsystems are at TRL 9, their seamless integration into a fully functional system may ***NOT*** *work and may require system modifications*. Due to the modular nature of DICE CRCC, however, moving from TRL 6 (pilot plant) to TRL 9 should be relatively straightforward. The focus is primarily on the interaction between the DICE and the expander in turbocompound configuration. There is field experience

---

[1] Original Equipment Manufacturer (OEM)

in very similar applications (see Appendix A). The development path is more of a “risk elimination” exercise rather than closing a “technology gap”

The answer to the first question is ***NO*** as well due to the other “risks” (not “gaps” *per se*) involved in the DICE (enumerated and discussed in detail in section 1.3), i.e.:

- Combustion, specifically, ignition characteristics of the CWS fuel
- Wear and tear of components (cylinder walls, rings, pistons) due to ash particles
- Fouling of components

Finally, production of the CWS fuel itself is a technology, which is not at TRL 9 either. This is discussed in detail in Section 1.5. In this case, additional technology risks are present due to the variances in reliability among the different coal feedstock (i.e., bituminous, subbituminous or lignite with differences in quality and composition from mine to mine in each category).

1.4 DICE CRCC (POWER BLOCK) TECHNOLOGY GAPS AND RISKS

A partial list of the technology OEMs for major equipment including standard, off-the-shelf equipment, and commercially mature in the power generation block (DICE CRCC) are listed below.

- Major equipment needed:
  - Reciprocating internal combustion engines (RICE)
    - Medium-speed, large-bore
    - MAN, Wärtsila
  - Hot gas expander (HGE)
    - Baker Hughes
  - Main air compressor
    - Integrally-geared, centrifugal process compressor with intercooling
    - Kobelco, Dresser-Rand
  - Heat recovery steam generator (HRSG)
    - Single-pressure, non-reheat with duct burner and SCR/CO catalyst
    - NEM, Nooter Eriksen, Vogt
  - Steam turbine generator
    - Back-pressure (non-condensing)
    - GE, Siemens (Dresser-Rand), Elliott
  - Particle removal equipment
    - Third Stage Separator (TSS) used in FCC applications
    - Honeywell UOP
    - Shell

All of the major pieces of equipment are off-the-shelf and commercially mature products (i.e., representing TRL 9) *except* the RICE, which requires the following modifications to DICE:

- New fuel injector
- Cylinder/piston coating (with carbide)

The project team is planning to cooperate with CSIRO to further the development of these modifications in the next phase of work (CoalFIRST Critical Components Development).

The definitive associated technology gaps and risks as well as the development pathways are discussed in depth in Section 2 and Section 3.

It is also highlighted that:

- Bechtel has worked with all of the major OEMs of major equipment used in power generation and process
- Bechtel has access to data and information on the equipment included in the proposed concept

Section 2 DICE Technology Gaps and Risks

Prima facie, technology gaps and risks associated with the DICE CRCC concept are not overwhelmingly large. The least-proven part of the cycle is DICE, which is a *reciprocating internal combustion engine* (RICE) fired with a coal-water slurry fuel (roughly 45 weight percent (wt %) water). Even DICE has ample R&D and field operation history behind it (e.g., please refer to Nicol [1] and the extensive bibliography therein). One prominent example is medium-speed, large-bore RICE by Wärtsila, which has been successfully operated with Orimulsion in Finland [2].

2.1 LIMITATIONS AND ADAPTATIONS OF CURRENT ENGINES FOR DICE

While atomized MRC burns well in diesel engines, the engines require several essential modifications, and the engine also need to be low-medium speed (preferrably <500 rpm) to allow for longer combustion time and to reduce the fineness of atomization required to achieve efficient combustion.

To some extent these modifications are already used for commercial engines using Orimulsion and MSAR (bitumen-water emulsions – a close proxy for coal-based slurry in terms of combustion), high pressure gas, liquefied gases and alcohols. However, additional essential modifications are required for DICE. While most of these modifications involve straightforward engineering, several critical components will require redesign. The limitations and adaption of current engines for DICE is discussed for the following aspects:

- Cylinder size and speed
- Wear coatings
- Piston
- Ring shape
- Dual injection
- Injector
- Exhaust ducting
- Cylinder drains
- Turbocharger

2.1.1 Size and Speed

For coal, the cylinder size should be as large as possible and the engine speed as low as possible – larger and slower, respectively, than economically optimal for comparable installations using fuel oils and gas. Although low-speed engines cost proportionally more per MW, the benefits for coal are a reduction in cylinder wear and an increase in wear tolerance due to larger component sizes. In addition to increased wear tolerance, large bore and low speed mean that fineness of MRC atomization is less critical, and this allows both larger orifices (resulting in longer fuel jets) in the atomizer nozzle and lower injection pressure. Both are essential to reducing nozzle wear. A larger bore also increases the space available for the injector, which for MRC will likely be larger to accommodate ceramic components.

2.1.2 Fuel Supply System

Conventional fuel supply systems are unsuitable for MRC and will require redesign to avoid clogging and wear issues. The MRC supply system should provide a small, controlled circulation flow around the fuel rail and through the injectors to enable rapid flushing of the system and to eliminate clogging of the fuel system when the engine is not in operation. This circulating flow should be down through the injectors suction valve to the seat of the needle valve and be controlled either electronically or from the same oil that actuates the fuel pump plunger. The spring-loaded inertial valves often used with HFO are not recommended desirable due to the variable flow properties of MRC (shear thinning) and seat wear.

It is recommended that a twin pump low-pressure fuel system is used, with one pump controlling the pressure in the circulating flow, and the other used to control the return flow – as described in more detail in Section 3.1 of the Performance Results Report.

2.1.3 Injectors

Conventional injection equipment, including pump-line-nozzle, hydraulically actuated electronically controlled unit injectors (HEUI), mechanically actuated electronic controlled unit injectors (MEUI) and common rail injectors are completely unsuitable for MRC due to instantaneous jamming of sliding parts with coal particles, clogging of fuel galleries, and rapid wear due to erosion/cavitation. Required modifications are summarized as follow:

Jamming of any sliding surfaces wetted by the fuel -- This is especially the case for the fuel pump plunger and the cut-off needle valve spindle, which will jam solid within several injection cycles unless protected by a higher-pressure seal oil. This also precludes the use of a conventional jerk pump with spill ports to control injection rate.

Clogging of fuel ways if the fuel is allowed to remain stagnant – This will occur especially if the engine is hot and the fuel has been repeatedly pressurized to injection pressure (which can destabilize the fuel). This means that flushing of the fuel system is necessary either before or immediately after stopping of the engine.

Erosive wear of fuel system components – This occurs not just to the atomizer orifices, but also for the non-return valve seat and the needle valve seat. The size of fuel galleries must also be increased to reduce fuel velocities to below 10 m/s if possible. Velocities over 20 m/s will cause galleries to wear. Erosive wear is further accelerated by corrosion-erosion mechanism if materials subjected to high-velocity fuel are not sufficiently hard and corrosion-resistant.

Cavitation wear is increased with MRC due to the higher vapor pressure of the fuel's continuous phase (water), and also due to its higher viscosity. Other fuel properties may contribute to cavitation, including the high particulates loading and the strongly shear-thinning nature of MRC, which tends to channel flow.

2.1.3.1 Piston

The piston bowls of modern engines are shallow and wide for less intense fuel-air mixing to reduce peak combustion temperatures and NOx formation: NOx should not be an issue due to the cooling effect of the fuel water – but requires full scale demonstration. Although the optimum shape for MRC has not been identified, it is probable that the older-style, deeper bowl, higher squish piston will give better results by providing faster and more complete fuel air mixing, which effectively increases the combustion time and allows the use of lower excess combustion air. The latter will also result in a higher charge temperature at the start of injection, further improving both ignition and combustion. Fuel-air mixing for DICE is also likely to be enhanced by the need for additional nozzle orifices to pass the higher fuel volume of MRC. A deeper bowl piston is also expected to reduce fuel contamination of the upper cylinder bore.

2.1.3.2 Piston Rings

There has been little published R&D on ring design for MRC. Conventional ring designs with hard coatings have given reasonable performance with MRC – but tests appear to have been of short duration (a maximum of 200 hours continuous). It is speculated that an optimized ring design will be necessary to minimize wear via 1) additional cylinder lubrication to carry away char and ash contamination of the cylinder wear surface, 2) avoiding Brinnelling by hard ash particles means that pressure equalisation across the ring pack will be more important which also increases the minimum oil film thickness, 3) ring porting/draining needs to be increased to allow for a step increase in particulates (ash and char) in the lubricant film, 4) ring shape may need to be changed to increase down scrap of contaminated lubricant to collection points. Piston ring rotation would also assist in evacuating contaminated oil grunge from behind the rings.

2.1.3.3 Materials

In general, the materials used for the critical components in the fuel system, piston rings and cylinder liner in conventional diesel engines are unsuitable for MRC. High hardness is essential to avoid abrasive wear from coal ash. Although ceramic coatings are available for piston rings and liners, conventional hard coatings are generally too thin to prevent the Brinelling effect of large hard fly ash particles – i.e. indenting through the hard coating into the softer substrate. Thicker, more monolithic coatings will be necessary with binders that are resistant to corrosion and grain plucking. The injector nozzle is particularly challenging. Although conventional polycrystalline diamond compacts have been shown to be effective in managing nozzle abrasive and cavitation wear of nozzles, the newer nanoparticle compacts of polycrystalline diamond or cubic boron nitride are expected to give an even better performance – and are tougher. These materials should also be used for fuel system valve seats and needles/poppets. A redesign of the injector is required to utilize these ceramics, in particular, as the ceramic components require an increase in component cross-section to compensate for lower tensile strength.

MRC can be handled using conventional steels (as for coal water fuels); however, it is recommended that components downstream of the fuel strainer are constructed from stainless steel – especially the engine fuel delivery system and high-pressure injection system. This is to reduce scaling and erosion-corrosion. For pump and injector bodies, steels recently developed for biofuel should be considered (e.g. Duval TN15 or similar).

2.1.3.4 Exhaust Ducting

Conventional horizontal ducting between the turbocharger turbine outlet and emissions control equipment will likely result in ash deposits on the lower surfaces of ducting – especially from shed ash deposits. Minimizing horizontal runs, live bottom ducts (e.g. equipped with drag chains), dropout boxes, soot blowers, and other measures will need to be used to prevent deposition from becoming an issue.

2.1.3.5 Dual Injection

A dual injection system will be necessary to allow the engine to start and warm-up on diesel or lighter fuel oil, and to enable pilot injection to control ignition (depending on the MRC quality). For some engines, the fuel oil side of the existing dual-fuel system may be used - possibly downsized to match only starting and pilot rating.

2.1.3.6 Cylinder Lubricant Drains

To accommodate increased particulates contamination of the cylinder lubricant film, increased cylinder lubrication is required, with provision to collect contaminated down scrap of lubricant (e.g. using a spiral/circumferential oil collection groove(s) near the bottom of the stroke). This arrangement will enable dirty lubricant to be routed out of the engine for separate deep cleaning using a centrifuge, thereby reducing the filtration load on the crankcase lubricant system.

2.1.3.7 Turbocharger

Coarse particulate matter in the engine exhaust will cause inlet vane and turbine erosion, especially for particles larger than (say) 10µm. While the bulk of the flyash is likely to be finer than this value (larger cenospheres are unlikely to be an issue as they are spherical and being hollow have a small equivalent aerodynamic diameter), ash deposits shedding from inside the engine and exhaust ducting will be larger. For this reason, turbines and inlet vanes will require hard facing – as used for large low-speed 2-stroke marine engines using heavy and residual fuel oils.

2.2 DICE TECHNOLOGY GAPS

While it is believed that there are no technical limitations concerning adapting an engine for DICE (this is an engineering issue only), there are a number of technology gaps that continue to hamper development. As these involve both the fuel and the engine, these gaps are discussed under that of a new fuel cycle involving the production of new fuel, for adapted engines for new coal generation markets

- For the fuel, this includes producing a suitable slurry fuel from coal that is exclusively used in boilers, and for which no experience with DICE exists
- Measurement of parameters requisite to predict coal suitability
- For the engine these involve items critical to producing a commercial engine with acceptable longevity and RAM[2] requirements
- Overall, there is a lack of logistics/infrastructure for a DICE fuel cycle
- Emissions prediction, especially, particulate matter (PM) 2.5, NOx and CO, requires significant field experience and system tuning

While all of the issues were considered to some extent in the comprehensive USDOE program from 1978-92 (which focused on bituminous coal replacing diesel fuel), this data is only partially relevant to the present initiative which is for a sub-bituminous coal particle size distribution, new abrasion-resistant materials, manufacturing techniques, and larger capacity stationary generation. Also, there has been a range of new technologies and business drivers over the last 25 years, for example, more efficient mills, new abrasion-resistant materials, manufacturing methods, electronic control, the rise of the reciprocating engine for both decentralized and baseload generation.

What is lacking is an understanding of the trade-offs between fuel quality and engine modifications, and this balance should be reassessed in the context of developments in ultra-hard materials and manufacturing techniques introduced over the last 25 years.

Table 2-1 summarizes the currently known technology gaps. .

---

[2] Reliability, Availability, and Maintainability (RAM)

Table 2-1
Perceived DICE Technology Gaps

Technology gap	Description	Importance
Processing and formulation of subbituminous coal	• De-ashing by flotation or selective agglomeration may result in a higher product ash • Lower rank coals can make excellent MRC if the surface properties are altered and any porosity reduced (e.g. by hydrothermal treatment or low temperature carbonization) • Cost effective additive packs to provide optimal solids content and rheology	High (trade-off between fuel cost and engine cost)
Fuel logistics	• Fuel quality standards including suitable performance tests need to be established • Pulverized coal and fuel oil standards do not apply for DICE • CSIRO has a number of DICE fuel tests which could be used	High
Fuel-engine interactions	• Very little data for subbituminous coals • The occurrence of mineral matter in the processed coal will have a big influence on the required engine adaptations (armoring) and repairs and maintenance (R&M) costs • However, expect only a small increase in engine capital cost due to special componentry (for the Nth engine)	High
Engine design	• Current designs and materials of construction assume clean fuel. This limitation applies to the fuel supply system, the injection system, cylinder components, exhaust valve seats, exhaust system, turbocharger turbine, and heat recovery systems.	High

Technology gap	Description	Importance
	• Engine maker philosophy – the fuel needs to match the engine	High – potential large new markets using lower cost fuel needs to be valued
Next generation DICE fuel systems	• Atomization and atomizer longevity is the absolute essential requirement/obstacle to DICE • The existing practice of pressure atomization is a quick fix – it works, but not for very long • Air blast atomization can solve this problem but requires more adaptation to the engine systems • A change in engine philosophy is required: new air blast could be much better than that of the 1920's, the benefits of DICE warrant extra effort on the engine, MRC is a different fuel that requires a different engine	Medium in the short term, but could eliminate the atomizer problem and result in relaxed fuel quality requirements High Engine manufacturers currently adopt the view that the fuel must match the engine. The opposite could be optimal for DICE
New coal philosophy – life-cycle analysis (LCA) based	• DICE is a higher value market for coal. A new philosophy around quality and optimizing the overall coal fuel cycle is required. For example higher ash MRC could be used as a boiler low load or light-up fuel, creating operations for MRC with higher ash fractions to PC boilers, mining of tailings dams, other higher value end-uses for MRC quality coals • The highly flexible nature of DICE could directly underpin a high penetration of intermittent renewables	High Potential to reinvigorate the industry High New system boundaries need to be established – with coal and DICE

2.3 TECHNICAL RISKS AND ISSUES

The key technical risks and issues associated with developing DICE – based on recent CSIRO experiences, are as follows, in decreasing order of importance:

2.3.1 Commitment

Ensuring commitment of both the engine manufacture and fuel supplier/fuel chain as this involves producing and using a fuel that is new to the world – this requires industry backing and commitment to not only undertake the engineering RD&D, but also to establish new logistics (including tests for quality, OH&S, public perceptions). If a holistic development approach is not taken, development could stall due to a chicken-and-egg situation between fuel supply and availability of suitable engines.

2.3.2 Tradeoffs

Establishing at the outset nominal trade-offs between fuel quality and engine modifications. The engine manufacturer will likely insist that the fuel is produced to suit the engine and the fuel supplier that the engine is adapted to suit the fuel. Although a full-scale demonstration is required to quantify the optimum quality-engine adaptations, an early decision should be made on fuel quality targets to give an acceptable overall generation cost. Other changes are also required: For the coal supplier, MRC must be regarded as a premium fuel and prepared and handled accordingly; for the engine manufacturer it should be accepted that MRC is not a fuel oil, and that DICE will require substantial changes to engine manufacturers to incorporate new materials and changes to the base engine (e.g. a new fuel system, revised cylinder heads to accommodate a larger injector, increased crankcase lubricant cleaning, revised exhaust ducting and turbine materials etc)..

2.3.3 Development Philosophy

Ensuring that both the engine manufacturer and fuel supply parties agree with the engine development program. There are two diametrically opposite pathways to achieving a commercial engine: 1) develop and test what is considered to be key components prior to undertaking the engine tests/demonstration, or 2) undertake engine tests early with adapted components to identify and prioritize component development needs and learn by doing. This single issue was the cause for termination of the recent CSIRO project with an engine manufacturer and the Australian coal industry: The coal industry disagreed with OEM's approach (which was a 3-5 year program based on early engine trials prior to component development) to develop a commercial engine for DICE. It is emphasized that the program was not terminated on technical grounds – only conflicting philosophies on how development should proceed.

2.3.4 Supporting R&D

Including a parallel program to develop and establish fuel cycle logistics. This should include identifying/developing suitable tests for the fuel – which will likely involve a hybrid of fuel oil and coal type tests. It is recommended that a high degree of importance is placed on understanding how the inorganics in the as mined coal report to the MRC fuel, the exhaust gases, and the wear implications – especially for the injector nozzles and cylinder components. For example, depending on the coal and the cleaning methods used, around one-third of the ash content (in, say a 2% ash coal) could be derived from organically bound or finely disseminated mineral matter which will have different wear implications that coarser extraneous quartz particles. Another key area is MRC rheology: If this is correct the relatively high viscosity fuel will inject as well as fuel oil and will be safe to store without agitation. If not, fuel system and injector nozzle blockages will result, and fuel tanks settle to form a compacted sludge.

2.3.5 Engine-ready MRC

Developing a cost effective, engine ready fuel. For bituminous coals fully commercial technologies are available to do this. For lower rank coals such as Powder River Basin coal, some development is required to ensure sufficiently low mineral content and to allow an MRC with over 50% coal to be produced with acceptable rheology.

2.3.6 Engine Modification

The minimum modifications to enable an engine trial, for example, to obtain combustion and heat release data, and to identify other issues, is a seal oil protected injector and fuel pump. Using a standard tool steel nozzle should enable 5-10 hours of consistent operation to gain early engine performance data and to refine the component development program.

2.4 KEY R&D REQUIREMENTS FOR DEVELOPMENT

The technical R&D requirements are discussed below in the context of developing an overall fuel cycle that is ready for commercialization by 2030:

- Fuel development (elaborated in detail in Section 3.1)
- Engine component development
- Logistics.

2.4.1 Engine Component R&D

Engine component R&D is mostly for fuel delivery and injection systems, including materials selection. Key areas include:

- Wear coatings for the piston rings and cylinder walls
- Piston bowl shape
- Ring shape
- An MRC injection system with seal oil protected sliding surfaces and ceramic valves and atomizer nozzle.
- Exhaust ducting - reengineered to manage ash dropout
- Cylinder lubricant drains to remove contaminated oil
- Turbocharger armoring
- Reengineered fuel delivery system

These are described in more detail under development imperatives and the development pathway below.

2.4.2 Logistics R&D

DICE is a potential new market for both coal and reciprocating engines that requires the establishment of new fuel cycle logistics, especially fuel quality standards, and fuel supply logistics. These are described in more detail under development imperatives and the development pathway below

Section 3 Fuel Production Technology Gaps And Risks

The fuel burned in DICE is in the form of a “slurry”, which is defined as a “semi-liquid mixture, typically of fine particles of solids *[in our case, coal]* suspended in water”. The *coal-water slurry* (CWS) fuel has to be prepared before being used in DICE. This process can take one of the two forms:

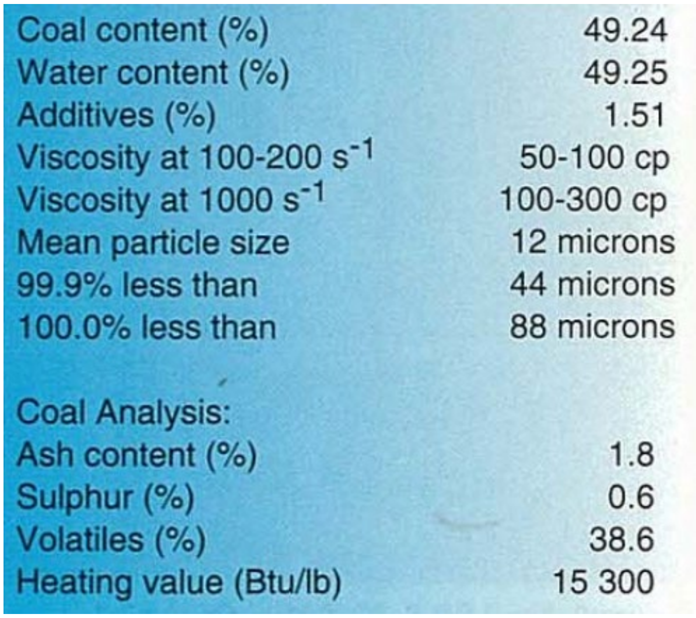
- A central fuel processing plant (analogous to a petroleum refinery producing gasoline and diesel fuel among other products) serving many CWS-fired power plants
- A dedicated fuel processing plant serving each CWS-fired power plant

The CWS fuel processing power plant has two major functions:

- Creating “coal powder” to be mixed with water
- “Cleaning” the coal powder (commonly referred to as “beneficiation”) to reduce sulfur and ash

In the literature, cleaned, pulverized (or “powderized”) coal is also referred to as *micronized refined coal* (MRC) because of the size of the fine coal particles (mean size of the order of 10 to 15 *microns*). Typical, CWS is a mixture of MRC and water in roughly equal amounts by weight and has a consistency similar to that of paint. As an example, CWS properties from the USDOE’s *Clean Coal Technology* program in 1994 are provided in Table 3-1 [3]. (Additives such as xanthan gum and surfactants are used to control slurry viscosity; dispersants are added to prevent agglomeration.)

Table 3-1
CWS Properties



Coal content (%)	49.24
Water content (%)	49.25
Additives (%)	1.51
Viscosity at 100-200 s^{-1}	50-100 cp
Viscosity at 1000 s^{-1}	100-300 cp
Mean particle size	12 microns
99.9% less than	44 microns
100.0% less than	88 microns
Coal Analysis:	
Ash content (%)	1.8
Sulphur (%)	0.6
Volatiles (%)	38.6
Heating value (Btu/lb)	15 300

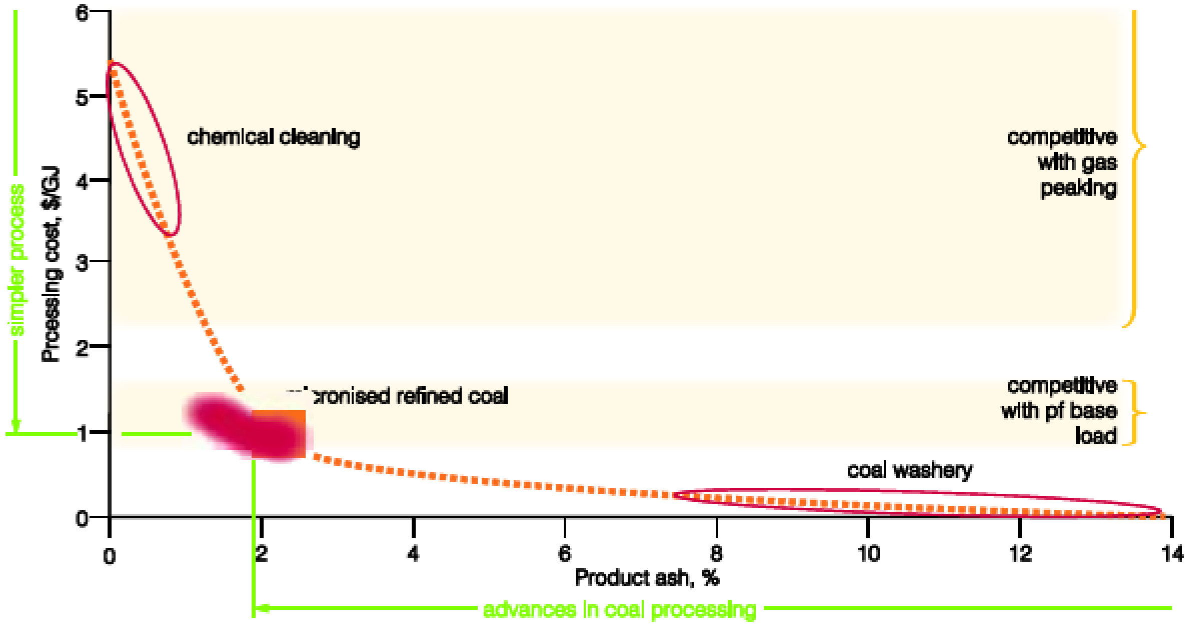
Ideal MRC properties for *black* ("high rank" or bituminous) and *brown* ("low rank", subbituminous or lignite) coals are provided in Table 3-2 [4].

Table 3-2
MRC Properties

Property	Black	Brown
HHV (MJ/L)	21-25	16-19
Mineral ash (wt% dry)	1-2	0.2-1
Total ash (wt% dry)	1-2	2-3
Viscosity (apparent, mPa.s)		
@100/s (pumping)	200-500	400-700
@100,000/s (injection)	100-300	200-400
Unstirred settling rates(stagnant) mm/month	1-5	1-5
Particle size d50 µm	10-15	10-15
d95 µm	50	70
Cost including coal ($/GJ)	$4-6	$2-3

Neither coal pulverization nor coal cleaning/beneficiation requires "invention" of new technologies. Currently available physical and chemical cleaning technologies can readily eliminate ash (including mineral sulfur) but there is a cost-performance trade-off as illustrated in Figure 3-1 [1]. Reducing the MRC specification from 2 wt% to 1 wt% can easily triple the coal processing cost.

Figure 3-1
Coal Beneficiation Cost (in Australian Dollars)



3.1 FUEL DEVELOPMENT NEEDS

3.1.1 Fuel R&D

Cost-effective fuel processing to meet a specification that is suitable for DICE is essential. For most coals, this will require producing a finer and lower ash product than for existing markets – but without the usual moisture constraints. Three steps are involved, and all require R&D and testing to optimize the processing for the specified feed coal.

1. Demineralizing and densification
2. Micronizing and slurry production
3. Blending

The steps and nominal targets for both R&D and test work is described below, based on CSIRO's experience with 48 coals.

3.1.1.1 Demineralizing and Densification

The first step is to produce feed coal with sufficiently low ash, and without coarse, hard minerals such as quartz, pyrites or rutile. It is important to recognize that this requires low temperature plasma ashing (LTA), followed by quantitative X-ray diffraction (XRD), to determine the mineral species. This complements a standard coal ash analysis. From recent experience, this step will be challenging for the sub-bituminous PRB coal proposed, as deep cleaning by a highly selective process, such as flotation or selective agglomeration, is likely to be less effective than for bituminous coals –resulting in both higher product ash and lower recovery. Ideally, cleaning would be undertaken on densified material – e.g. after pretreatment by hydrothermal treatment. Hydrothermal treatment is also known to reduce hydrophilic surface groups and oxygen content (slightly), which further assist in both cleaning and by increasing calorific value of the fuel slurry.

3.1.1.2 Micronizing and Slurry Production

The second step is to micronize the cleaned feed coal. Ideally, this is by higher efficiency wet milling with the required slurry water plus additives. For a 500 rpm engine, a conservative top size (d_{97}) is 65μm. The aim is to produce a size distribution that will have a good packing efficiency, which maximizes the coal loading and therefore calorific value of the fuel.

Unless a cleaning step follows micronizing (as would be the case for bituminous coal), micronizing should be undertaken with steel mill media, as ceramic media can chip and cause unacceptable contamination. If steel media is used, the fuel will pickup some Fe, but as discussed below, this iron pickup can improve fuel rheology.

3.1.1.3 Blending and Trimming

It is unlikely that a fuel freshly micronized and slurried in Step 2 will have acceptable rheology. A significant improvement in fuel rheology requires a combination of further blending and aging. Blending is most efficiently undertaken using a combination of a high shear mixer (eg Eirich-type paddle mixer) followed by a longer period of low-intensity mixing (*eg* a Visco-jet or similar). Experience has shown that the energy required for the high-intensity mixing stage can be as high as 30-50% of that of micronizing. The low shear mixing could also be provided by storage tank agitation. During the blending and trimming step, the rheology of the MRC should be measured for the shear rate range 0.1-3000/s (or higher) to ensure the shear thinning behavior of the MRC. Additional trim additions of a surfactant or thickening agent may be required to achieve these properties.

Examples of additions for Australian bituminous and lignite coals are shown in Table 3-3.

Table 3-3
Nominal Additives Used to Produce MRC

Purpose	Example	Range wt%[1]	Comment
Dispersant	Polystyrene sulfonate	0.1-0.5	Needs to be optimized for the coal. Other dispersants may be more economical
Stabiliser	Carboxymethylcellulose	0 0.1	Often not required, can interfer with the dispersant
Auxillary	Soluble Fe or Ca	0.01–0.1	Bridging agent. Most effective for bituminous coals. Not required for alkaline ash coals
Biocide	From vendors	0.0-0.1	Usually not required

1 active ingredient, dry coal basis

As a general comment, processed lignite and sub-bituminous coal usually produce excellent fuel slurries from a stability and shear thinning perspective; however, porosity and residual surface groups reduce the coal content and, therefore, the calorific value of the fuel for a given viscosity. The other factor that affects the coal content of the slurry is the particle size distribution, which determines the packing efficiency (can be calculated).

3.1.2 Further Research Studies

Suggestions for research studies that would assist in de-risking the fuel technology for bituminous and sub-bituminous coals are given below. It should be noted that not all of these studies may be required – as work progresses, the research will be amended to achieve the goal cost effectively

3.1.2.1 Mineral Matter

- Identify the mineral species in the coal (LTA plus XRD, and the size distribution of the various minerals by SEM - very useful in considering beneficiation issues and options.
- Optimize mineral removal from micronized coal(with and without hydrothermal treatment), using flotation or other physical separation procedures- how much of which mineral species is removed?. This study will include the effect of flotation aids/chemicals on slurry rheology.

Dewatering is required after flotation, which requires a dilute (~5%) slurry. Research is required to develop the most cost-effective dewatering technology and to optimize dewatering aids, prior to fuel slurry formulation.

3.1.2.2 Surface Groups

- For lower rank coals, the level of carboxylic acid/carboxylate surface groups should be measured (e.g. by a titration procedure).
- If insufficient surface groups are present to achieve stability and shear thinning studies will be undertaken to determine how can they be generated at minimal cost for bituminous and sub-bituminous coals (eg by increasing surface oxidation using chemicals or electrolysis).
- Additives such as calcium ions have a very beneficial effect on bituminous coal slurries, with small additions (<0.02%) changing slurries from shear thickening to shear thinning. Is this effective for the target coal, and what is the effect when combined with a dispersant?
- What is the effect of hydrothermal treatment (and perhaps other treatments such as compression, or low temperature pyrolysis) on the coal properties such as surface groups and porosity may need to be assessed, as coal characterization proceeds.

3.1.2.3 Milling/Micronization

- It may be possible to wet micronize the coal to achieve the final slurry coal. concentration. This would have the benefit of avoiding an additional trim dewatering step, especially if a dry beneficiation process was used

3.1.2.4 Slurry Generation

- Mixing conditions (time, intensity, dispersant, type of mixer) are known to affect the properties of the slurry, but this depends on the coal and additives used. Experimentation is required to optimize mixing for the particular coal

3.1.2.5 Fuel Stability

- Coal slurries can be adversely affected by bacteria and may need biocides to maintain stability. Work is required to determine if biocide, if required, and identify formulations that do not negatively affect slurry rheology. CSIRO has had a bacterial problem with only 2 coals to date (out of 48). However, other research groups have experienced significant bacterial issues.
- Stability tests - many of the tests in the literature are focussed on comparatively short term stability (days to weeks). There is a need for tests that are relevant to commercial operations associated with storage and transport (months)
- Stability tests – many of the tests in the literature are focused on comparatively short-term stability (days to weeks). There is a definitive need for tests that are relevant to commercial operations associated with storage and transport (months)

3.2 CWS PROCESSING PLANTS

CWS processing plants in pilot scale has been designed, built and operated in the past. Key examples are:

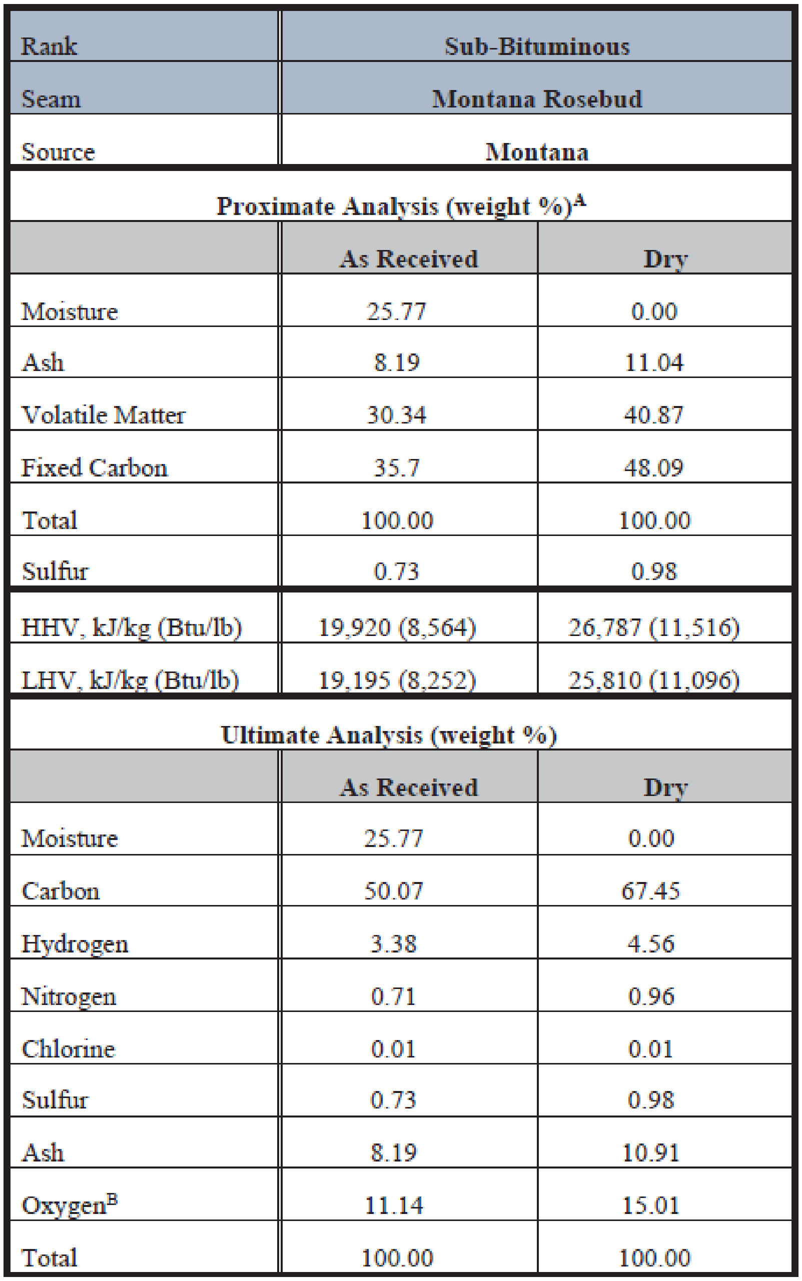
- University of North Dakota's Energy & Environmental Research Center (EERC) CWS production process with hot water drying (using Kentucky and Usibelli coals) [5,6]
- Jameson Flotation Cell (Glencore Technology) in Australia [7]

A comprehensive review can be found in Nicol [1]. However, so far, no commercial-scale CWS production facility which is commensurate with the stringent requirements of DICE application has been built. In order to have an idea about the "commercial scale", the DICE considered in this project (about 16 MWe generator output) consumes CWS at a rate of **18,750 lb/hr** (about **8.5 metric tons** per hour). The proposed power plant is based on five DICE units.

In order to design the appropriate CWS processing plant, properties of the coal feedstock should be analyzed in great depth. The first step is to obtain a small sample of the coal feedstock to determine if grinding to finer particle sizes liberates the ash. If grinding does not liberate the ash, some cleaning technologies may not be able to produce a low ash coal. Additional lab work would be required to determine the best approach to clean the coal. As discussed in detail, *this is not an easy task*:

The design basis coal for the present project is low-sulfur, subbituminous Power River Basin (PRB) coal (a low rank coal) with proximate and ultimate analysis summarized in Table 3-4. In his 1993 Master's Thesis, Kong identified a total of 25 mineral phases in the samples from the Big Sky and Absaloka mines in the Rosebud subbituminous coal seam [8]. (The Big Sky samples were taken from different layers of the seam.) Mineral concentrations ranged between 5 wt% and 15 wt% on a whole coal basis (see Table 3-5). Pyrite (FeS_2) was the only important sulfide mineral identified. In the B-I sample in Table 3-5, pyrite was 8.5 wt% on coal basis; in B-III sample, it accounted for 2.5 wt%. In the others, pyrite content changed between 0.15 wt% and 1.29 wt%. The data and information clearly illustrates the difficulty of predicting de-ashing effectiveness and MRC product quality from proximate or ultimate analysis.

Table 3-4
Design Basis Coal Analysis



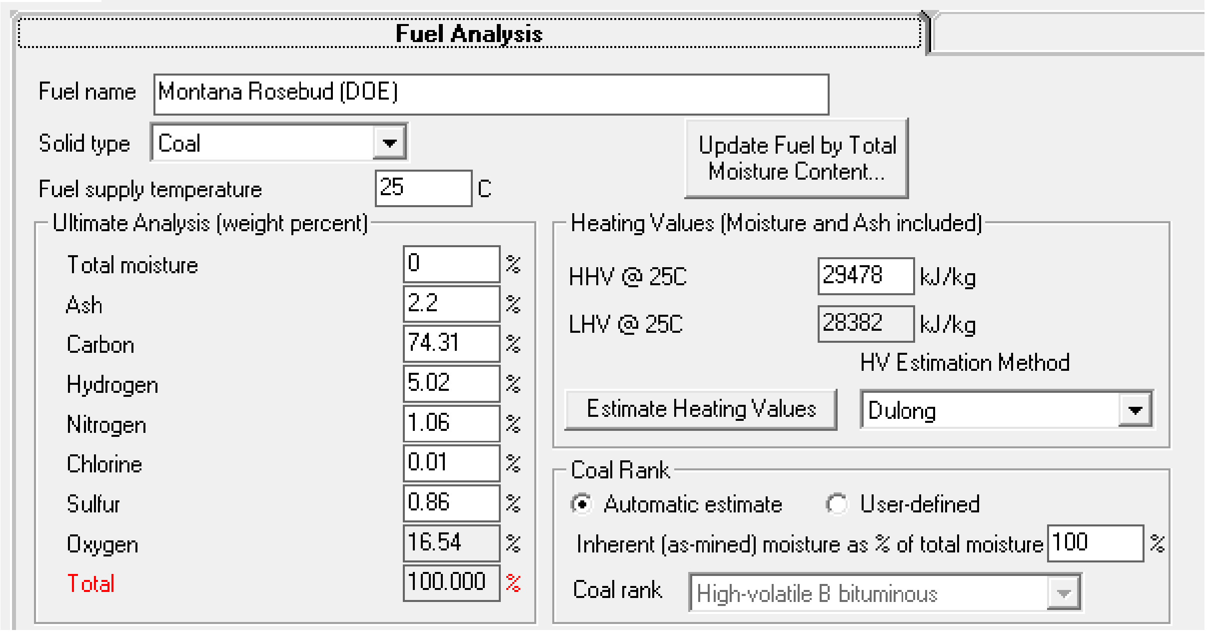
Rank	Sub-Bituminous	
Seam	Montana Rosebud	
Source	Montana	
Proximate Analysis (weight %)[A]		
	As Received	Dry
Moisture	25.77	0.00
Ash	8.19	11.04
Volatile Matter	30.34	40.87
Fixed Carbon	35.7	48.09
Total	100.00	100.00
Sulfur	0.73	0.98
HHV, kJ/kg (Btu/lb)	19,920 (8,564)	26,787 (11,516)
LHV, kJ/kg (Btu/lb)	19,195 (8,252)	25,810 (11,096)
Ultimate Analysis (weight %)		
	As Received	Dry
Moisture	25.77	0.00
Carbon	50.07	67.45
Hydrogen	3.38	4.56
Nitrogen	0.71	0.96
Chlorine	0.01	0.01
Sulfur	0.73	0.98
Ash	8.19	10.91
Oxygen[B]	11.14	15.01
Total	100.00	100.00

The average total mineral content of the five Big Sky mine samples (B-I through B-V) in Table 3-5 is 7.35 wt%. Ignoring the outlier B-I, the average is 5.84 wt%. Accounting for the sulfur in pyrite, non-sulfur mineral content average is 6.17 wt%; without the outlier B-I, the average is 5.33 wt%. At the risk of being somewhat optimistic, we have assumed that non-sulfur mineral content of the design basis coal is 6.7 wt% so that the cleaned coal ash content can be reduced to 1.5 wt%. As far as the sulfur is concerned, we decided to be less optimistic and have assumed that 20% of the sulfur in the "as-received" coal is inorganic and can be removed during beneficiation.

Beneficiated “clean” coal properties (dry basis) are shown in Figure 3-2. The improvement in heat content on a higher heating value (HHV) basis is 29,748 / 26,787 = 1.11 or 11 percent.

Table 3-5
Mineral Content of Rosebud Coal Seam Samples (percent by weight)

Mine	B-I	B-II	B-III	B-IV	B-V	A06	Average
Total Mineral	14.91	4.98	8.88	4.76	5.33	5.23	7.35
Pyrite	8.45	0.46	2.5	0.34	0.15	1.29	2.20
S (Pyrite)	4.52	0.25	1.34	0.18	0.08	0.69	1.18
Total - S	10.39	4.73	7.54	4.58	5.25	4.54	6.17



Fuel Analysis

Fuel name: Montana Rosebud (DOE)
Solid type: Coal
Fuel supply temperature: 25 C

Ultimate Analysis (weight percent)

Total moisture	0	%
Ash	2.2	%
Carbon	74.31	%
Hydrogen	5.02	%
Nitrogen	1.06	%
Chlorine	0.01	%
Sulfur	0.86	%
Oxygen	16.54	%
Total	100.000	%

Heating Values (Moisture and Ash included)

HHV @ 25C: 29478 kJ/kg
LHV @ 25C: 28382 kJ/kg
HV Estimation Method: Dulong

Coal Rank
● Automatic estimate ○ User-defined
Inherent (as-mined) moisture as % of total moisture: 100 %
Coal rank: High-volatile B bituminous

Figure 3-2
Beneficiated “Clean” Feedstock Properties

This study assumes that the MRC composition is 45 wt% water and 55 wt% beneficiated and micronized coal. The resulting MRC fuel composition is listed in Table 3-6. The LHV of this fuel is 14,513 kJ/kg (HHV is 16,214 kJ/kg). It should be emphasized that, for an accurate determination of MRC composition, more detailed information about the feedstock (i.e., petrography data) is requisite. Depending on the actual coal microstructure, final MRC ash content can be 2 wt% or higher.

Table 3-6
Study MRC Composition

	As Is (wt%)	Washed	Dry	Dry (wt%)	Slurry	MRC (wt%)
Moisture	25.77	25.77	0.00	0.00	81.82	45.00
Carbon	50.07	50.07	50.07	74.31	74.31	40.87
Hydrogen	3.38	3.38	3.38	5.02	5.02	2.76
Nitrogen	0.71	0.71	0.71	1.05	1.05	0.58
Chlorine	0.01	0.01	0.01	0.01	0.01	0.01
Sulfur	0.73	0.58	0.58	0.87	0.87	0.48
Ash	8.19	1.49	1.49	2.21	2.21	1.21
Oxygen	11.14	11.14	11.14	16.53	16.53	9.09
Total	100.00	93.15	67.38	100.00	181.82	100

It is noted that this MRC composition based on PRB coal as feedstock differs from that listed in the coal beneficiation study in Appendix B. The MRC composition for this pre-FEED study assumes 45 percent total moisture and 55 percent dry coal solids by weight. In the coal beneficiation study performed by Sedgman, the coal beneficiation process OEM, it is assumed that the MRC has a free moisture content of 45 percent by weight and that the 55 percent solids by weight in the product still contains the inherent moisture of the PRB coal.

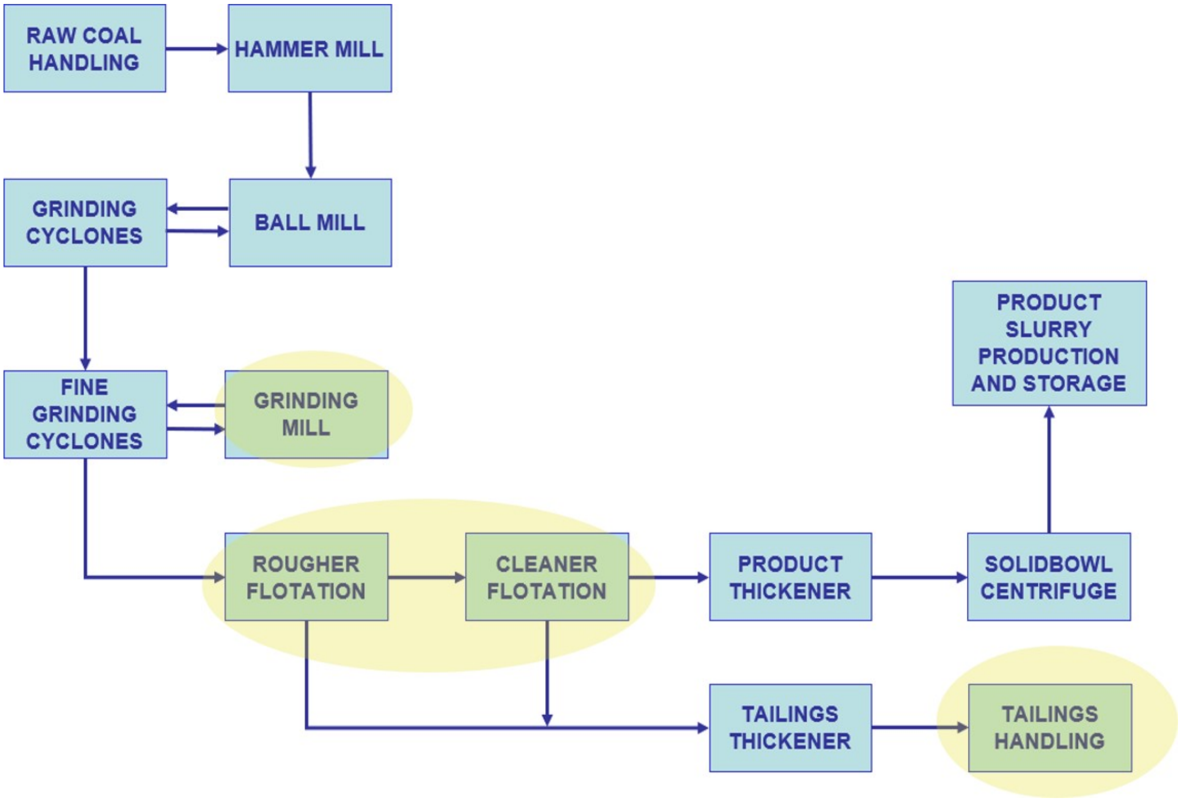
Due to the lower total moisture content of the MRC assumed in this study's design, the performance may be optimistic. The actual total moisture content of the MRC needs to be studied further and verified via testing on actual coals. These tests should establish the moisture content of the micronized coal and the minimum moisture content required for the slurried MRC to meet DICE rheology requirements.

3.3 TECHNOLOGY GAPS, RISKS, AND DEVELOPMENT PATHWAYS

3.3.1 Potential R&D Needs

For the typical commercial beneficiation process, there are *currently no specific components, equipment, or systems which require undertaking traditional R&D nor having any technology gaps*. However, as part of the overall beneficiation process, there are key commercially available plant unit operations whose end-use application is novel - ***when beneficiation is based on coal***. As shown in Figure 3-3, these unit operations include fine grinding mill, ash removal (via rougher flotation and cleaner flotation), and tailings handling.

Figure 3-3
Key Coal Beneficiation Unit Operations



Based on the findings from the Performance Results and Cost Results reports, while the various components for a conventional flotation-based coal beneficiation plant, as shown in Figure 3-3, are all commercially available, the low overall product yield and tailings handling are areas that need to be addressed in order for the process to be economically feasible.

In the DICE CRCC pre-FEED study that uses PRB coal as the feedstock to the beneficiation plant, the overall product recovery yield was about 50 percent on both a mass and combustible value basis. A consequence of this low product yield is the large quantity of reject tailings that, while still containing significant heating value, is in slurry form, and has no commercial value. The unsaleable tailings thus has to be disposed of in ash ponds, which constitute an environmental risk.

While it is possible to process the reject slurry (via dewatering, briquetting, etc.) to a more functional form, this requires additional energy and cost input. It is therefore key to address the likely technology gap associated with disposing the otherwise unsaleable reject slurry tailings from coal beneficiation.

It is of utmost importance to increase the product recovery yield to way beyond the current 50 percent. Doing so would not only decrease the coal feed required by the beneficiation plant, but also minimize the quantity of reject tailings. It is understood that the hydrophilic nature of the subbituminous coal as-is makes it difficult to achieve a high recovery via the conventional flotation process for ash separation. Tests on various coal samples should therefore be undertaken to identify coal types that can achieve maximum product recovery.

Virginia Tech has developed a process that can increase combustible recoveries of typically hydrophilic materials such as PRB coals, which involves using an additive to increase their hydrophobicity. Virginia Tech plans to investigate and develop this technology further under the USDOE CoalFIRST Critical Components development program. Besides performing tests on a variety of high- and low-rank coals, this technology can also be used to recover MRCs from waste coals that are currently being discarded in the eastern US coal fields. If it can be demonstrated that these waste coal fines can be successfully beneficiated to produce suitable CWF fuels for firing in DICE, this substantially reduce the coal cost and produce MRC-based CWFs at cost below $1.50/MMBtu. Supply of low-cost CWF fuels should expedite the commercialization of DICE technology and ensure a success of the CoalFirst program.

Additionally, Virginia Tech's process is understood to be able to reduce the inherent moisture of the coal particles in the MRC via a mechanism known as dewatering by displacement (DbD), described in US Patent 9,518,241. In this process, a hydrophobic liquid is introduced to displace the water trapped within the coal's pore structure and reduce its moisture. The resulting hydrophobic liquid phase contains coal particles free of surface moisture and entrained droplets of water stabilized by the coal particles, while the aqueous phase contains the mineral matter. By separating the entrained water droplets from the coal particles mechanically, a clean coal product of substantially reduced mineral matter and moisture contents is obtained. The spent hydrophobic liquid is separated from the clean coal product and recycled.

Another advantage of Virginia Tech's technology is that it processes the coal at a relatively coarse size, which allows the rejects to be easily disposed of without the need for expensive dewatering or environmentally hazardous ponds. Furthermore, the coarse product coal is dry yet does not catch fire spontaneously during shipping, which allows for the beneficiated product to be shipped to the DICE CRCC plant dry, where it is micronized and slurried on-site. This ability to ship a relatively coarse, dry product that avoids spontaneous combustion is believed to be able to reduce the overall fuel costs substantially.

3.3.2 Development Pathway via Testing

Since there is no requirement for undertaking traditional R&D, there is however a need for a commercial development pathway to definitively verify, validate, and confirm the key assumptions, design/concept impact, and end-use application of the highlighted beneficiation unit operations based on coal. Testing (e.g. combinations and permutations of laboratory based, independent/third-party, or any performance testing) is highly recommended and required to be undertaken. Currently, the beneficiation testing opportunities based on coal are limited since such applications are primarily market-driven. For commercial end-use application, further testing and development is required on specific coal types for optimal yield and efficiency for each of the key unit operations covering:

- **Fine Grinding Mill**: Available proven technologies include impact and attrition mills. Selection of most suitable grinding technology depends on various factors which include product size, feed size, and energy consumption
- **Ash Removal (via rougher/cleaner flotation)**: Different proven flotation technologies available with different energy and reagent input requirements. The low ash concentration in product coal (2 wt% db) is a potential challenge which need to be proven-out via testing
- **Tailings Disposal/Utilization**: There is no market value in slurry form. There is additional energy/cost to process (dewatering, briquetting). Disposal and utilization is a function of product yield (< 50% for PRB coal)

3.3.3 Testing Regime - Future Work Plan

From this study, items in proposed order of testing as discussed below, should be included in an ongoing work plan to further progress the development pathway of MRC as fuel for the DICE CRCC. As shown in Table 3-7, these tests will verify, validate, and confirm the key assumptions, design/concept impact, component and equipment selection and sizing.

The specific detailed testing regime will be dependent on the final coal type(s) selected, availability of sample, and the testing work budget and schedule.

Table 3-7
Testing Required to Confirm Key Assumptions, Design/Concept Impact

Key Assumptions	Design/Concept Impact	Testing Required to Confirm
Feed quality size independent – all feed processed	▪ Pre-sizing requirements ▪ Screening requirements ▪ Feed handling system (conveyors)	▪ Size/ash analysis of feed ▪ Coal Grain Analysis
Liberation of carbon requires grinding to 100% passing 50 micron	▪ Grinding technology and power requirement ▪ Downstream processing technology and size (flotation thickening, dewatering)	▪ Size/ash analysis ▪ Coal Grain Analysis ▪ Grinding characteristics testing
Deep froth and high wash water required for low ash product	▪ Flotation technology	▪ Flotation testing (tree flotation)
2 stage flotation required to reach required product ash	▪ Flotation plant layout and size ▪ Power and consumables requirement	▪ Flotation testing (tree flotation)
24 hour product storage	▪ Product slurry storage tank size and number	▪ Based on DICE CRCC pilot plant

Feed Coal Analysis: One of the main drivers for the success of DICE CRCC is the feed coal selection. The PRB coal is shown to be not ideal based on the current pre-FEED study. The low product yield results in a large quantity of as-received feed requirement, while generating similarly large quantities of tailings for disposal. Thus, bench-scale tests needed on various coals to establish and select feed with the best available yield. As part of the testing regime, analysis on a selection of possible feed coals should be carried out. A shortlist of possible feed coals with suitable properties (ash, sulfur content, and energy levels) could be selected based on known existing coal quality from different mine sites. The selection of the preferred coal type is a critical component of any ongoing work as this will drive the downstream test work, the results of which will determine equipment sizing and final project costs (e.g. capital and operating).

Coal Grain Analysis: Once a preferred coal source, or sources, are identified, the development team shall carry-out detailed coal grain analysis on this coal to determine liberation requirements to reach the required product ash level. The results of this analysis is critical to both the grinding and flotation equipment selection.

Crushing and Grinding Test Work: Laboratory scale comminution tests (comminution is particle size reduction by breaking, crushing, or grinding of ore, rock, coal, or other materials) should be carried out on the selected coal to determine the energy inputs required for crushing and grinding. These tests can be performed by a metallurgical testing laboratory or by sending samples to equipment suppliers. The following tests are recommended:

- Drop shatter
- Hargrove grindability

- Abrasion index testing
- Bond crushing work index or JK drop weight test
- Bond rod mill index
- Bond ball mill work index
- Signature plot and/or jar test

Flotation Tests: Flotation tests should be performed on freshly ground coal samples to avoid oxidation of the particle surfaces which will adversely impact flotation performance. These can be performed as part of a metallurgical laboratory suite of testing or samples can be sent to different suppliers/technology providers. These tests will assist in determining:

- Flotation behavior of ultrafine feed material
- Suitable flotation technology
- Suitable flotation circuit configuration to achieve required performance (ash and yield) - e.g. rougher-cleaner, rougher-scavenger, and rougher-cleaner-scavenger
- Reagent dosage required
- Froth carrying capacity
- Wash water requirements
- Froth depth requirements

The results of the flotation test work may require an iteration of the grinding work to be done.

The coal grain analysis will provide a target value for liberation size, however, the variability of coal feed and inefficiencies of the flotation process may necessitate a finer grind to be performed to realize the target ash. If this is the case then iterative tests may need to be performed.

Thickening and Dewatering Tests: Both the product (concentrate) and tailings material from the flotation test work would need to be collected to perform thickening and dewatering testing.

Thickener testing will help to determine thickener size, flocculant type and dosage rates. Dewatering test work will help to size the dewatering equipment and assist in selection of the final dewatering technology to use.

Rheology Characterization: To support the sizing and selection of agitators, pumps and piping a range of range of rheology characterization should be undertaken on the key intermediate and final product and tailings slurry streams. This testing will provide information on the deformation and flow behavior of the slurry compositions expected in the plant.

Pilot Plant Operation: The proposed flowsheet utilizes commercially available equipment however for most major equipment, as highlighted the commercial application to coal is novel. It is therefore recommended that following the completion of the above initial laboratory scale analysis, a pilot plant be constructed and operated to provide an indication of the expected continuous performance. A nominal throughput of 1 ton per hour should be considered as basis however the throughput will likely be based upon the size of the equipment commercially available. Often equipment can be leased from one or more laboratory testing companies or equipment suppliers. Evaluation of a suitable location for undertaking the test work should consider the proximity to the feed coal, the disposal method for the tailings/waste, and if the product will be tested/utilized in the same location, i.e. a DICE CRCC pilot plant included with the coal beneficiation pilot plant.

.

Section 4 Development Coordination

4.1 OBJECTIVES

There is a need to work in close coordination with the DICE and coal beneficiation process developers. For example, the ash content, sulfur content, rheology, among other beneficiated MRC properties, need to be established between the DICE and coal beneficiation developers.

There must be an objective to develop this coordination under DOE CoalFIRST Critical Components development program. Accordingly, there are two competing “chicken or egg” factors that make a coordinated DICE development approach very difficult:

1. As clearly indicated by the findings of the pre-FEED study, a dedicated “fuel block” with each DICE is clearly not an economically viable proposition

2. Without a readily available fuel supply, DICE technology is a dead end

While the obvious solution to widespread DICE deployment is a centralized “coal-water slurry fuel factory” similar to a refinery producing gasoline or diesel fuel (after all, DICE CRCC is best suited to distributed generation), the question that remains is also obvious:

> *Who would make the investment into such a fuel factory without a readily available market for its product?*

The second obvious question is a corollary of the first:

> *Who would make the investment into DICE technology without a readily available fuel supply?*

Evidently, the two questions can be formed into a single one:

> *What is the market for DICE (or another technology for that matter) firing coal?*

The key problem to this is that unless there is a coordinated effort akin to a “Manhattan Project” to “impose” widespread deployment of a modular, flexible and efficient coal-burning technology such as DICE CRCC for distributed generation applications in a future generating portfolio with heavy contribution from solar and wind energy (and other non-fossil fuel technologies).

Addressing this problem is certainly out of the scope of the pre-FEED study. However, it is still necessary to come up with a coherent approach to develop the technology in a feasible manner to TRL 8 or 9. The key obstacle in this endeavor is still the same, i.e., cost, and ultimately a question of financing.

4.2 DICE DEVELOPMENT PATHWAY

A development pathway is proposed in the context of a revised positioning of the DICE fuel cycle, including:

- Energy security
- High thermal efficiency and lower CO_2/MWh at small unit size
- A new coal replacement for oil, coal and natural gas
- Nimble generation to support variable electricity demand
- Underpinning a high penetration of intermittent renewables (it is the CO_2 intensity of the overall system that is key – not that of the individual technologies)
- A first commercial DICE plant by 2030

Also, the program considers several development imperatives, de-risking by staged development and scale-up risk, discussed per the following:

4.2.1 Development Imperatives

Recent R&D has highlighted development imperatives, which have shaped the proposed development pathway:

1. Securing the commitment of an engine OEM and component manufacturer (e.g., fuel systems).
2. Development of a suitable large engine test facility (i.e. small-scale demonstration engine), which is capable of firing MRC at near commercial scale conditions; for example, an inline 6-cylinder variant of a larger V18 cylinder engine suitable for commercial generation.
3. Small demonstration-scale engine tests to obtain key performance data on combustion, using tonnage lots of consistent and high-quality MRC produced from larger fuel plants.
4. Detailed techno-economic assessment of DICE for different markets to assist with developing engine and fuel targets, and to increase the case for industry commitment.
5. Detailed risk and hazard review to further de-risk the new fuel cycle, identify key technology gaps/showstoppers, and to broaden stakeholder engagement.
6. Duration engine tests to investigate fouling. These tests could be performed using smaller engine tests and a range of adapted boiler test methods, to avoid the need for producing a larger tonnage amount of MRC and the costs of duration operation of the larger test engine.
7. R&D to obtain data for optimizing fuel handling logistics, and to enable engineered systems to be developed for a range of scenarios (local generation, distributed generation, export).
8. Developments in MRC standards, in particular, to account for the wide differences and trade-off in MRC properties between different coals.
9. Developing an outreach program to ensure correct positioning and avoid negativities from coal's past image.

4.2.2 De-risking with Staged Development

While the previous R&D has provided promising findings for a range of technical issues around coal-engine interactions, this work can only provide a *technology readiness level* (TRL) of 4 for most technical aspects. De-risking by increasing the TRL from 4 to 8 in order to justify (e.g. a 50 MWe) commercial demonstration project requires that appropriate small-scale demonstration tests are undertaken – taking full benefit of the many technical improvements over the last 25 years. DICE needs considerable development and demonstration to match the technical development of current power generation technologies. However, this can be cost-effectively fast-tracked. Compared to the incumbent technologies, DICE has strong technical merit because of the ability to carry out a near-commercial scale demonstration at a relatively small size (e.g. 5 MW).

The 5 MW capacity engine-generator can be obtained in skid form, in a straight 6 configuration, giving a cylinder of approximately 400 mm bore and operating at 500 rpm. The simple in-line configuration and fewer cylinders ensure easier and faster incorporation of new components for testing - *essential to shortening development time*. This includes the option of only needing to make changes to one cylinder – which can also be swapped out as a complete power unit in a few hours to facilitate testing.

The data, information, and experience gained from this engine would be directly applicable to a larger semi-commercial demonstration (e.g. a V18 configuration producing 15 MW at 500 rpm). It is envisaged that successful demonstration at this scale would lead to larger commercial installations comprising multiple 15-20 MW engines, as is practiced for gas engine installations. This would not entail any scale-up of DICE. Standard approach to reduce capital cost and to improve overall efficiency is a conventional combined cycle. For higher efficiency, DICE CRCC is the ideal solution.

4.2.3 Scale-Up Risk

The cylinder size, rating and power output from a single engine unit for the proposed development steps to a full-size commercial engine are shown in Table 4-1).

Table 4-1
Scale-Up Factors from Demonstration through to Large Comercial Installation

Development stage	Bore (cm)	Cylinder rating (kWe/cyl)	Cylinders Units	Plant output (MWe)	Scale up
Small scale demonstration	46	1000	6	5-6	1
Demonstration plant	46	1000	18	20	1
First commercial	46	1000	18 5 units	100	1
Large commercial 4-stroke	63	2000	18 5 units	200	2x
Large commercial 2-stroke	94	5000	12 6 units	360	5x

The scale-up factor (based on cylinder area) between the development stages is at most 2-5x, which are relatively small scale-up steps that have low technical risk:

- The scale-ups are considered very conservative by the engine manufacturers – especially if a National Test Facility is available to test the latest developments before deployment
- In contrast to many technologies, DICE has the advantage of being able to undertake near full-scale demonstration at small-scale.
- As cylinder size increases, many of the technical issues associated with firing MRC decrease (e.g., more time and space for combustion allows reduced atomization, and wear effects also decrease).

Overall, it is envisaged that a staged development program could be established with an engine manufacturer and OEMs (e.g. suppliers of injection and turbocharging components) to quickly undertake the demonstration program, to enable commercial deployment by 2030.

4.2.4 Staged Development Program

The recommended program involves 3 stages, which allows sequential de-risking and the development necessary to provide the experience and data required to develop the components to adapt an engine for a demonstration plant. In contrast to other new technologies, DICE has the advantage of being based entirely on relatively small adaptations of existing commercial technology, and at a small scale to drastically shorten the time required to progress from single-cylinder tests through to commercial deployment. The stages and timings are as follows:

Stage 1 (2020-22)	Single-cylinder engine tests - component development, single-cylinder engine tests, logistics and business cases
Stage 2 (2023-26)	DICE test facility and fuel plant (5 MW)
Stage 3 (2027-30)	Semi-commercial DICE plant (20 MW units)

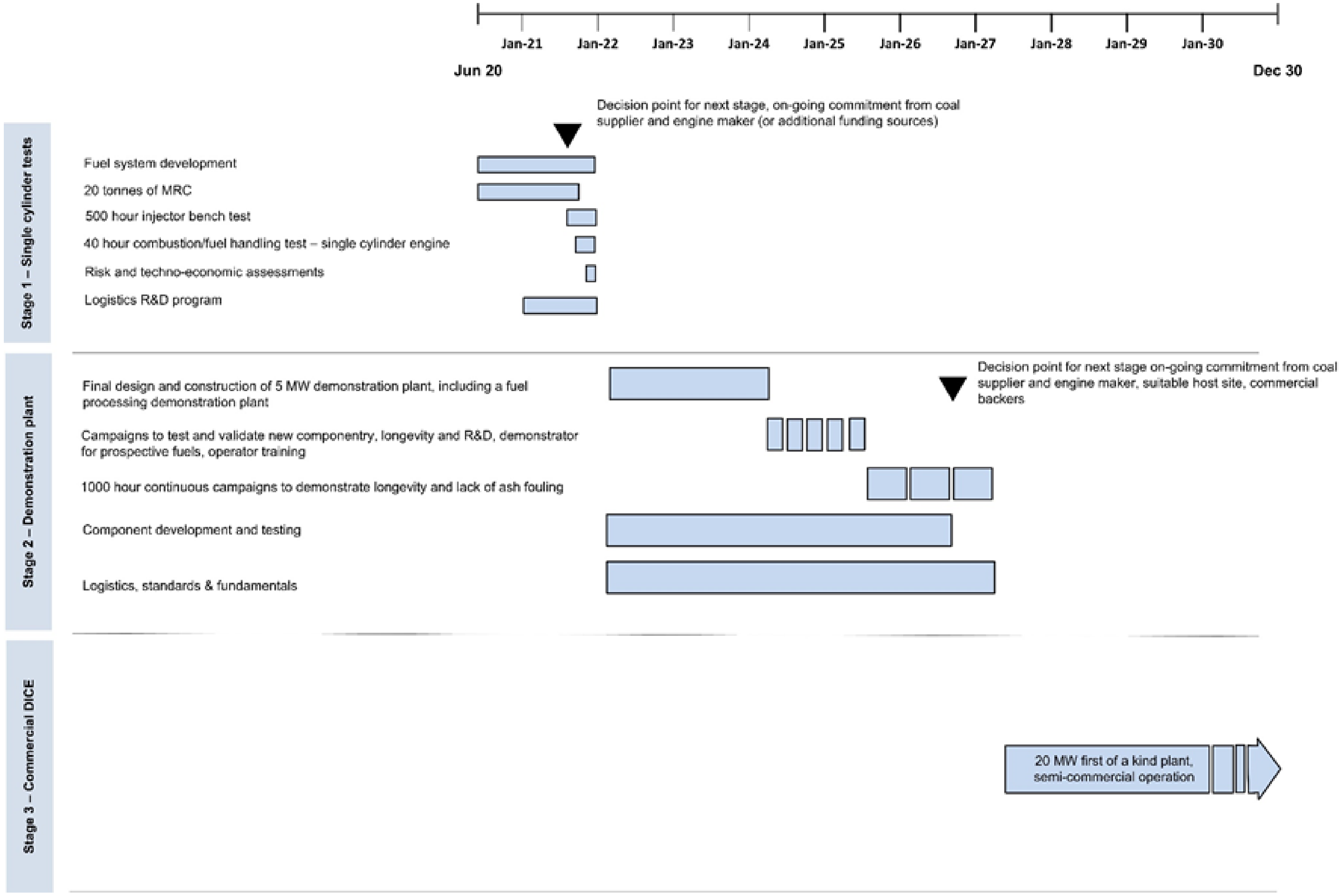
The program timeline is also shown in Figure 4-1, with additional details on the individual activities given below.

4.2.4.1 Stage 1 - Single-cylinder engine tests

These tests will provide both a focus and a framework for the entire fuel cycle, including:

- Processes and experience in the production of (say) 20 mt of suitable fuel
- Negotiation of a trade-off between fuel quality and engine modifications – both for short-term tests and future commercial operations.
- Hands-on experience with producing, handling and storage of bulk MRC fuel
- Fuel quality testing
- On-engine fuel handling experience, including both the low-pressure fuel supply system and the high-pressure injection system
- DICE operating strategy, including startup, operation at various load settings, and shut down with or without system flushing
- Optimizing pilot fueling
- Exhaust emissions
- Duration testing of a new injector
- Preliminary data on ash fouling
- Preliminary techno-economics and risk assessment
- Business case for DICE facility – a shared national facility or consortia owned
- Broadening stakeholder engagement with real data

Figure 4-1
Proposed 3-Stage Development Program



4.2.4.2 Stage 2 – DICE demonstration plant (5 MW)

Development of a suitable engine test facility (i.e., demonstration engine), capable of firing MRC under near commercial scale conditions is essential to development – of both the engine and fuel production.

While all manufacturers are capable of undertaking engine tests in dedicated test cells, to avoid competition for test cell access, it is recommended that either a dedicated test cell is obtained, or a new host site is used close to supporting engineers. Also, while a brake dynamometer is normally used for engine testing, a standard alternator load (i.e., as a genset) can be used with sufficiently accurate information of combustion and engine performance being obtained from cylinder indicator readings. The use of a generator also allows power exports to offset test costs (important for the longer duration tests).

An engine-generator producing around 5-6 MWe is recommended to increase the validity of the test results by demonstrating the technology with a cylinder size suitable for commercial operation – for example, a 6-cylinder variant of the 18V 48/60 engine by MAN.

An engine of this size will require around 6000 liters of fuel per day, equivalent to about 2 t/h of processed coal - which would also ensure MRC production at a reasonable scale.

Engine tests could determine the effects of the following on combustion/heat release, performance, thermal efficiency, lubricant contamination, wear, etc.:

- Engine load
- Cylinder air inlet temperature (by changing coolant flow to the aftercooler)
- MRC coal loading and rheology
- Pilot fuel timing and rate
- Development of operating strategies for starting, warmup, load changing, and shut down (short and long)
- Component durability tests – which could include using different materials and component designs for individual cylinders to provide a quicker and more cost-effective comparison of component performance than using individual test campaigns.
- Emissions as a function of load and fuel properties
- Engine ash fouling
- Turbine abrasion

Additional fuel supply tanks should be available to enable fuel batching to ensure consistent fuel quality for each series of tests.

It is also recommended that a parallel R&D and logistics program be undertaken, including:

- Detailed risk and hazard assessment, to further de-risk the new fuel cycle, identify key technology gaps/showstoppers, and to broaden stakeholder engagement. MRC slurry fuels and new coal combustion equipment will be required to demonstrate no surprises. For example, MRC is finely divided coal, but it is not classified as flammable. Spills can be readily cleaned up with a shovel once the fuel loses a few percent moisture. While MRC looks like oil, spills are less detrimental (see Figure 4-2), and different handling and storage procedures are required.

Figure 4-2
MRC Spill 24 Hours Later (From Hydrothermally Treated Lignite)

- Detailed techno-economic assessment of DICE for different markets to assist with developing engine and fuel targets, and to increase the case for industry commitment. This assessment should include using DICE as both incremental and old replacement capacity at existing coal-fired power plants, as well as for greenfield development.
- R&D to obtain data for optimizing fuel handling logistics, and to enable engineered systems to be developed for a range of scenarios (captive or mine-mouth generation, decentralized generation, centralized generation, export).
- Developing standards and certification to account for the very different properties of MRC compared to fuel oil.
- Developing a detailed business case for commercialization.
- Broadening engagement/outreach. DICE is a potential new (and large) market for both coal suppliers and engine manufacturers and their componentry. However, recent experience has shown that engine manufacturers are generally reluctant to consider DICE due to coal's high CO_2 intensity (at the burner tip) – on top of their business-as-usual competing commercial priorities. It is therefore essential at the outset to establish and clearly articulate both the economic and environmental benefits of DICE to all stakeholders, for example:
    - Nomination as clean coal is no longer enough.

  - DICE allows the novel use of coal to provide the backbone for a nimble, secure, ultra-low emissions power system by underpinning a high penetration of renewables - including the direct use of biomass and renewable ammonia. **It is the performance of the overall system that is key, <u>not</u> the individual technologies, as neither would likely exist without the other.**
  - Also, once DICE is installed it can utilize a wide range of alternative fuels including crude bio-oils, chars and other niche fuels etc – giving many other advantages (increased utilization, reduced processing costs and losses, and the use of bioenergy wastes). These should be quantified using life cycle analysis. Only a streamlined LCA will be required to show the overall benefits. The LCA should be supported by a corresponding techno-economic assessment of the integrated energy cycle.

4.2.4.3 Stage 3 First-of-a-Kind DICE plant – 20 MW

The smallest representative, first of a kind DICE power plant, is likely to be that of a single large 4-stroke engine (say) 20 MWe.

- An engine of this size can be broken down into manageable sections, to enable road transport to most locations.
- Although essentially a commercial operation, it is expected that only limited performance warranties would be provided by the engine manufacturer, but this would be offset via the initial pricing and by close supervision of operation and maintenance by the engine manufacturer (and other equipment suppliers).
- Suitable locations or host sites for the first of a kind DICE plant are envisaged as:
  - Alongside existing pf steam plants to enable sharing of coal supply, logistics, and transmission infrastructure – possibly with the long-term aim of progressively replacing older pf units. This could have an additional benefit of training future operators and maintenance personnel. The MRC plant could also be used to supply light up and low load fuel to the pf plant.
  - A mine-mouth power plant. This location would provide additional economic benefits for the coal miner and allow any lower quality MRC feed coals to be diverted to conventional markets.
  - Alongside a natural gas fired power plant with limited gas supply – with the possibility of switching out/retrofitting existing engines for MRC.

4.2.4.4 Commercialization Approach beyond Stage 3

Following the successful demonstration, rapid commercialization is possible, and likely to be driven by a strong need for incremental coal generation capacity for:

- Replacing old, inefficient and uneconomic PC power plants (say units smaller than 300 MW and/or older than 30 years in plant economic life)
- New load-following capacity to secure a higher penetration of renewables, and in direct competition with gas open cycle plants with gas prices over $5/GJ

- Remote generation, especially for supplying large mines and surrounding regions
- New capacity with CO_2 capture and storage, as DICE has the potential for a 30 percent reduction in the cost of capture over PC coal plants. The cost reduction is due to a combination of higher thermal efficiency (fewer kg CO_2/MWh) and the ability to use 130°C coolant and exhaust heat for stripping
- Once an engine is adapted for DICE it will be capable of handling a wide range of other alternative fuels (i.e. difficult) fuels (for example coal-biochar or coal-ammonia blends, crude bio-oils) which would extend the facilities value past the proposed demonstration, and provide additional environmental incentives for the facility and commercialization of DICE.
- MRC, including higher ash products, could be used to replace fuel oil for boiler light-up and low load operation.

Section 5 Emissions Control Technology

DICE CRCC is a fossil-fuel power plant burning two different types of fossil fuels: coal (in the form of a slurry) and natural gas. Let us address the second fuel first.

In DICE CRCC, natural gas is burned in the reheat combustor upstream of the hot gas expander and/or in the HRSG duct burners. In the introductory variant considered in the pre-FEED study, the reheat combustor is eliminated. Natural gas is the cleanest fossil fuel and is not a significant source of PM, VOC and SOx emissions. In the duct burners, flame temperatures are quite low so that no significant NOx emissions are expected either. Nevertheless, during the field operation, CO production due to flow and combustion instabilities can be a source of CO. In any event, minute amounts NOx and CO generated in the HRSG duct burner are going to be managed by the SCR (downstream in the HRSG). In conclusion, there is no technology gap associated with this fuel, from the perspective of equipment for NOx and CO removal.

5.1 SOX AND HG REMOVAL

PRB is a low-sulfur coal and the elemental sulfur is removed during the beneficiation process. SOx removal is accomplished in the direct contact cooler (DCC) with caustic injection (to cool the flue gas and remove the bulk of the SOx in the flue gas).

PRB coal typically contains less than 1 percent (wt) sulfur and less than 50 ppm chlorine, and the mercury (Hg) is primarily in the elemental form. Due to this reason, it is expected that the coal beneficiation process will remove some or most of the Hg in the coal feedstock. A feedstock sample analysis is requisite in order to provide a concrete estimate. For Hg remaining in micronized refined coal, post-combustion removal from the flue the gas is necessary to meet MATS requirements.

Activated carbon injection (ACI) is the standard method used for removal of Hg from the flue gas in coal-fired power plants. Activated carbon sorbents and high surface area unburned (loss on ignition, or LOI) carbon should be very effective for mercury capture when sufficient halogens (e.g., fluorine (F), chlorine (Cl) or bromine (Br)) or halides such as HCl are present in the flue gas[3].

Activated carbon catalyzes SO_2 to H_2SO_4 in flue gas. The overall mercury adsorption capacity is dependent on the formation of H_2SO_4 on the surface of the carbon. Thus, the capacity of activated carbon for mercury is higher in low SO_2 flue gas such as in DICE CRCC. However low content of chlorine or bromine in the flue gas can render ACI infeasible for application in DICE CRCC. Once again, sample analysis and combustion tests with flue gas chromatography are requisite to provide a concrete answer.

---

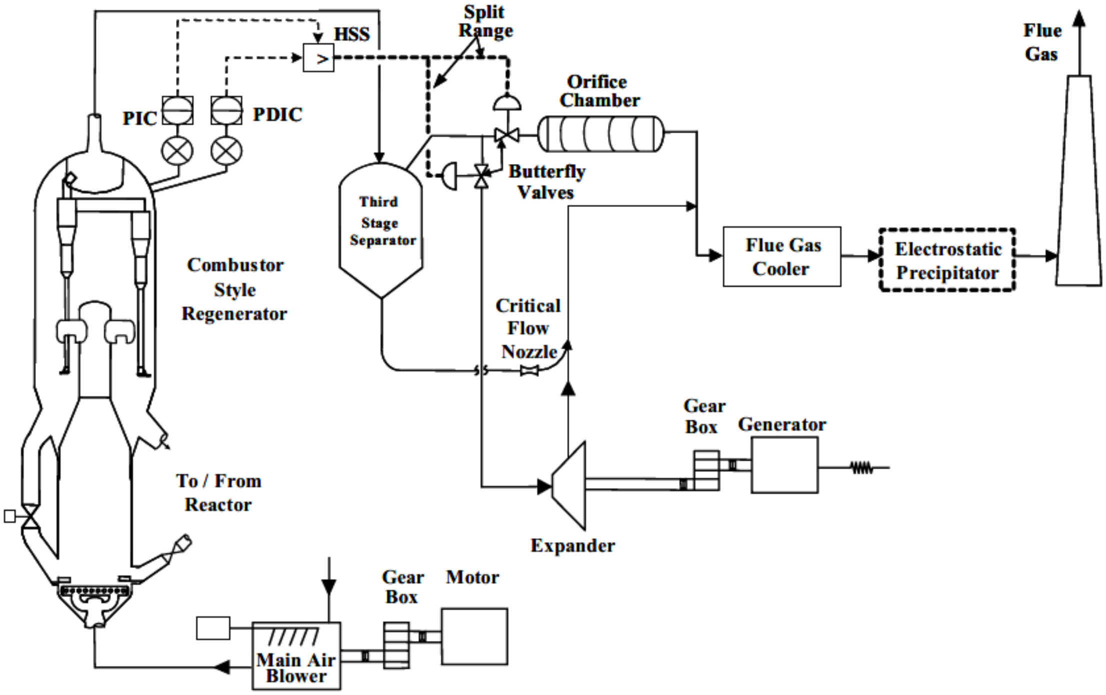
[3] HCl increases the mercury removal effectiveness of activated carbon and fly ash for mercury, particularly as the flue gas HCl concentration increases from 1 ppm to nominally 10 ppm.

In any event, the vanadium-based SCR catalyst used for NOx-control promotes the oxidation of elemental mercury Hg to Hg^{2+} in the flue gas. Hg^{2+} is water soluble and can effectively be captured in a wet scrubber or, in this case, in the DCC.

5.2 PARTICULATE MATTER REMOVAL

Coal burned in the DICE is "cleaned" during the fuel production process to contain low ash and sulfur, sources of PM and SOx emissions, respectively. DICE exhaust gas is scrubbed in a cyclone-type device to reduce PM content for protection of the downstream equipment, in particular, the hot gas expander. Similar devices have been widely used in fluidized catalytic cracking (FCC) of heavy hydrocarbon feeds for separating fine solids from vapor streams exactly for the same purpose, i.e., protection of the hot gas expander downstream (used for power recovery). A typical system is shown in Figure 5-1.

Figure 5-1
FCC Power Recovery System (UOP Honeywell)



It is worth noting that the hot gas expander shown in Figure 5-1 is the same piece of equipment used in DICE CRCC. The equipment used to clean up the particulate matter in the gas coming from the FCC reactor is the "third stage separator" (TSS). In order to understand the use of TSS and its suitability to application in DICE CRCC, an overview of the FCC process is provided.

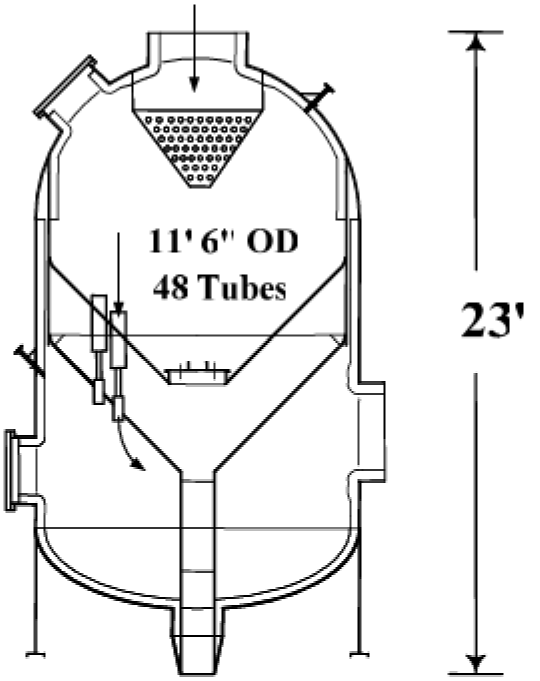
In the FCC process, catalyst particles circulate between a cracking reactor and a catalyst regenerator. The cracking reaction deposits coke on the catalyst, thereby deactivating the catalyst. The catalyst regenerator burns coke from the catalyst with oxygen containing gas, usually air. Flue gas formed by burning coke in the regenerator is treated for removal of particulates (by the regenerator cyclones) and for conversion of carbon monoxide. Even so, the amount of solid particles in most FCC flue gas streams exiting the regenerator is enough to cause severe erosion of the power recovery turbine (i.e., the hot gas expander) blades. Unfortunately, the PM remaining at this point are exceedingly difficult to recover, having successfully avoided capture despite passing through (typically) two stages of highly efficient cyclones. These particles (“fines”) are very small, essentially all of them are below 20 microns, and including significant amounts of submicron to under 5-micron sized material. Thus, a third stage of separation, which can capture these fines is necessary, i.e., the “third stage separator”.

The TSS uses a large number of small diameter cyclones because they give much better fines collection than larger cyclones, for the same gas velocity and pressure drop[4]. A schematic diagram of UOP Honeywell TSS is shown in Figure 5-2. FCC regenerator flue gas enters the TSS at the top and passes through a number of small-diameter, high efficiency, cyclonic elements arranged in parallel and contained within the separator vessel. After the catalyst particulates are separated from the flue gas in the cyclones, the clean flue gas leaves the separator. A small stream of gas, called the underflow, exits the separator through the bottom of the separator vessel. In some applications with stringent emission limits, the underflow is directed to an additional separation (i.e., the “fourth stage separator”) and collection stage before combining with the clean flue gas.

---

[4] For example, for a 5 to 20-micron dust mixture, dust collection improves significantly as cyclone diameter decreases, i.e., with collection efficiencies for 6, 9 and 24-inch cyclones being 90%, 83% and 70% respectively.

Figure 5-2
UOP Honeywell TSS



As highlighted earlier, the hot gas expander used in DICE CRCC (by Baker Hughes) is the same equipment used in FCC applications. Equipment specification by Baker Hughes regarding PM is shown below (the term "catalyst" refers to the catalyst fines discussed above):

"The warranty is valid subject to the following conditions, to be fulfilled by Purchaser during the four (4) years of continuous operation:

- The catalyst concentration in the flue gas to the expander shall be maintained at less than 100 ppm (by weight)
- The catalyst particle size distribution shall not exceed the values listed below:
  - 99.9 percent less than 12 microns
  - 98.5 percent less than 10 microns
  - 92.0 percent less than 5 microns
  - 75.0 percent less than 2 microns

Typical coal (MRC) water slurry used in DICE has the following ash characteristics:

- 0.2 to 1 percent (w) mineral
- 1.5 to 3 percent (w) total
- With P50 of 10-15 microns and P95 of 70 microns

DICE exhaust gas conditions are around 1,000 °F and 60 psia, which are well within the range typical of FCC applications. For the particular fuel used in pre-FEED performance calculations, particulate loading at the inlet of the TSS would be around 750 to 800 ppm (by weight). Consequently, in order to satisfy the expander requirements, the TSS should be capable of 90 percent reduction.

UOP Honeywell confirmed that the service is similar to the typical FCC application for protecting a hot gas expander. They also confirmed that the temperature and pressure is within our experience range. UOP Honeywell is confident that, even without doing any calculations, they typically can meet the expander PM requirements of 100 ppm and the removal of large particles (<10 micron). However, they also stated that they would need more detailed particle size distribution (PSD) and particle density in order to perform requisite calculations. UOP Honeywell also recommended a more detailed feasibility study to further optimize the TSS design, the turndown strategy, and to further refine the cost estimates. Depending on the scope and what other information is required, a high-level estimate for this study is estimated to be approximately $150,000.

In conclusion, equipment necessary for removal of PM from the DICE exhaust stream does not present itself as a technology gap as such. While the application of the existing equipment in DICE CRCC would be a first, it is clear that what is needed is requisite FEED to pinpoint the final design for the selected feedstock. This may require some testing as is the case with the design of the coal beneficiation system. Remaining fines (100 pm and P90 5 micron or less) will be washed away in the direct contact cooler upstream of the carbon capture block.

Section 6 References

1. Nicol, K., 2014, The Direct Injection Carbon Engine. London, UK: IEA Clean Coal Centre. Retrieved from www.iea-coal.org

2. Hägglund, T., *Comparative advantages of Orimulsion®, LNG and Petcoke*, Private Power in Central America, Miami, June 13-14, 2002

3. Rao, A.K., *Coal-diesel technology looks good for Clean Coal 5*, 1994.

4. Wibberley, L.J., *DICE – the best option for coal?*, www.dice-net.org, 18 May 2014.

5. DOE/NETL-2007/1287, *Clean Coal Diesel Demonstration Project – A DOE Assessment*, July 2007, U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory.

6. TIAX, *Clean Coal Diesel Demonstration Project – Final Report*, March 2007, Principal Author Dr. R.P. Wilson, TIAX LLC, Cambridge, MA, TIAX Ref. D0195.

7. Wibberley, L.J., 2013, *Development of the Direct Injection Carbon Engine (DICE)*, Presented at the 38th Clearwater Clean Coal Conference, 2-6 June 2013.

8. Kong, L., 1993, *Petrography and inorganic geochemistry of the Rosebud coal seam at the Absaloka, Big Sky and Rosebud mines, Powder River Basin, Montana*, MS Thesis (164), University of North Dakota.

Appendix A Turbocompounding

Turbocompounding has a long history going back to 1930s and 1940s for locomotive and aircraft propulsion. MAN Diesel & Turbo installed several turbocompound electric power generation systems about 20 years ago. MAN Diesel & Turbo also developed a turbocompound system for ship propulsion(e.g., see Figure A-1 for the system flow diagram). As shown in the diagram, the hot gas expander (the power turbine) is driven by part of the exhaust gas flow which bypasses the turbochargers. The power turbine produces extra output power for electric power production, which depends on the bypassed exhaust gas flow amount.

Figure A-1
Schematic Diagram of MAN D&T Turbocompound Ship Propulsion System

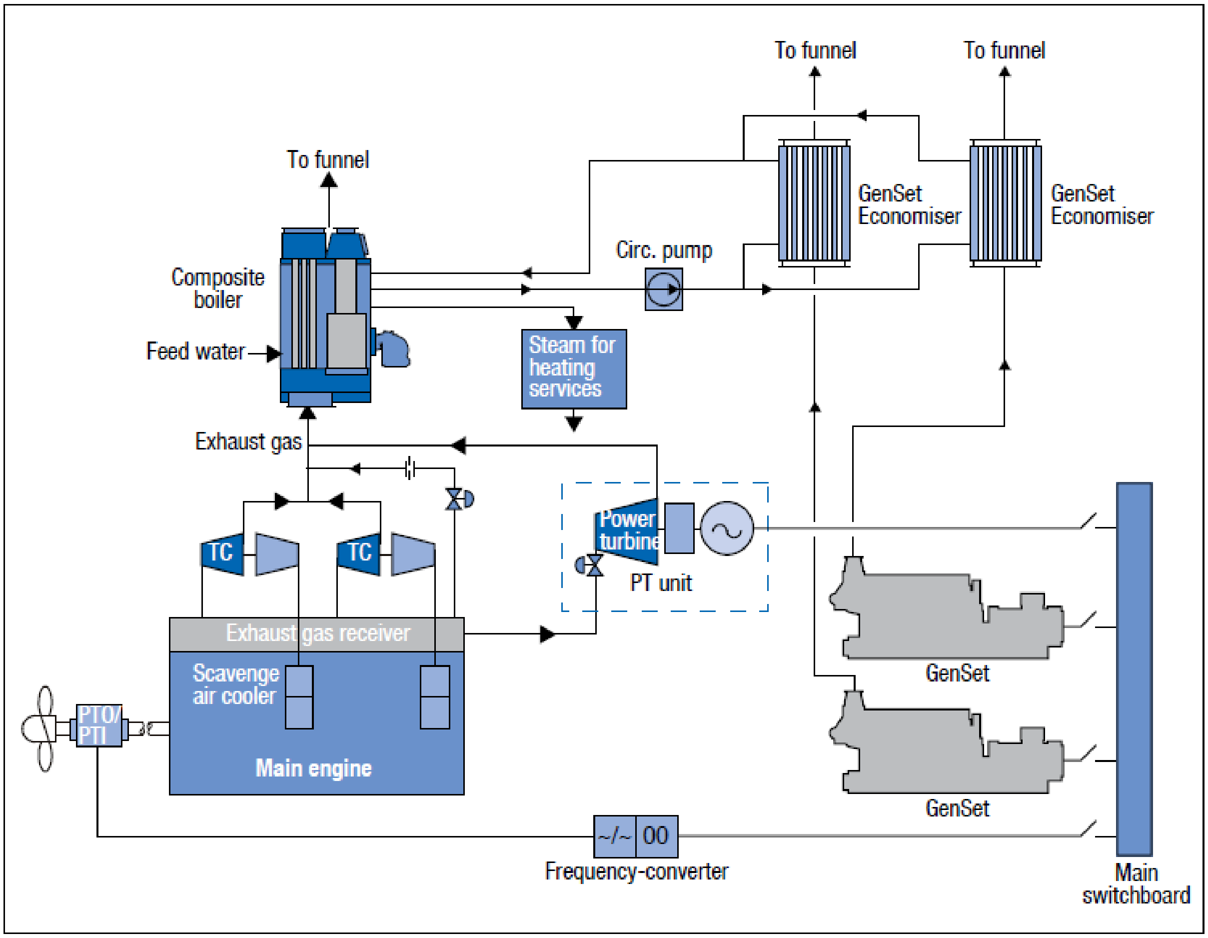


Table B-1 contains the detailed descriptions of the USDOE's TRLs.

Table B-1
Detailed Descriptions of USDOE's TRLs

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected mission conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning (1). Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.

Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants (1). Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
Technology Development	**TRL 5**	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants (1) and actual waste (2). Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
Technology Development	**TRL 4**	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste (2). Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants (1). Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Basic Technology Research	**TRL 2**	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.

[1] Simulants should match relevant chemical and physical properties.

[2] Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, ALARA, cost and project risk is highly desirable.

Source: U.S. Department of Energy, "Technology Readiness Assessment Guide". Office of Management. 2011.