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

VOLUME IV: PERFORMANCE RESULTS REPORT

U. S. Department of Energy (DOE)

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

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Section 1 Technology Overview

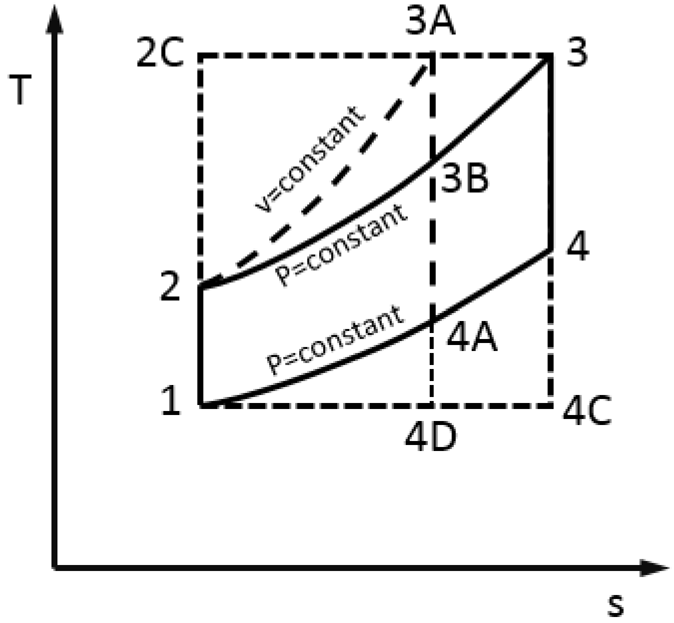
1.1 BASIC OPERATING PRINCIPLE

The fundamental thermodynamic basis behind the Direct Injection Carbon Engine (DICE) Gas Turbine Compound Reheat Combined Cycle (GT CRCC) plant concept is described in detail in the papers and articles by Gülen earlier, e.g., Refs.[1,2]. The thermodynamic cycle of the power plant is a seamless integration and mesh of Atkinson (internal combustion engine) and Brayton (gas turbine) cycles, which combines the two most effective heat engine cycle performance enhancers: constant volume heat addition and reheat. As illustrated in the temperature-entropy diagram in Figure 1-1, the resulting new cycle has six processes (instead of the typical four processes in Carnot, Brayton and Atkinson cycles):

1. Isentropic compression (1 to 2)
2. Constant volume heat addition (2 to 3A)
3. First isentropic expansion (3A to 3B)
4. Constant pressure heat addition (3B to 3)
5. Second isentropic expansion (3 to 4)
6. Constant pressure heat rejection (4 to 1)

This new ideal cycle {1-2-3A-3B-3-4-1} is the thermodynamic basis of the turbocompound-reheat gas turbine cycle. By adding a "bottoming cycle" into the lower triangular area {1-4-4C-1}, cycle waste heat, i.e., heat rejection from 4 to 1, can be utilized for additional work. Thus, one arrives at the *turbocompound-reheat gas turbine combined cycle*.

Figure 1-1
Comparison of CPC {1-2-3-4-1} and CVC {1-2-3A-4A-1} cycles



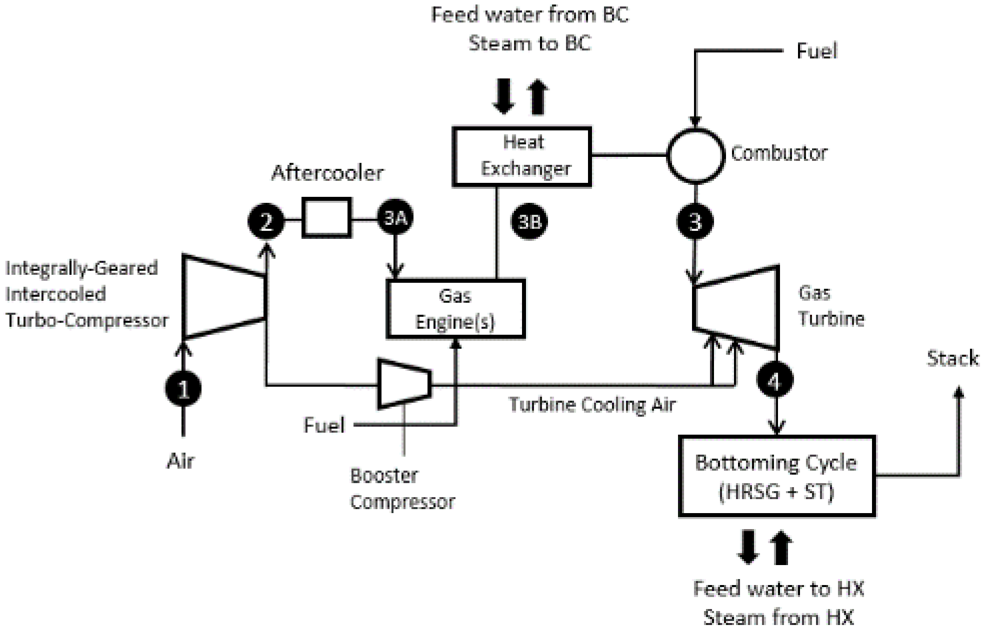
1.2 OVERVIEW OF DICE CRCC SYSTEM

1.2.1 Original Gas-Fired Turbocompound Reheat Embodiment

The original embodiment of the natural gas-fired turbocompound reheat (TC-RHT) gas turbine combined cycle (GTCC) is disclosed in the US Patent 9,249,723 (Gülen, February 2, 2016). It comprises three pieces of major equipment (a simplified system diagram is shown in Figure 1-2):

1. An intercooled, integrally geared centrifugal turbocompressor with an aftercooler
2. Advanced gas engine with the turbocharger removed
3. An industrial (heavy duty) gas turbine with the compressor section removed

Figure 1-2
Simplified Schematic Diagram of Original Embodiment of Turbocompound-Reheat GTCC



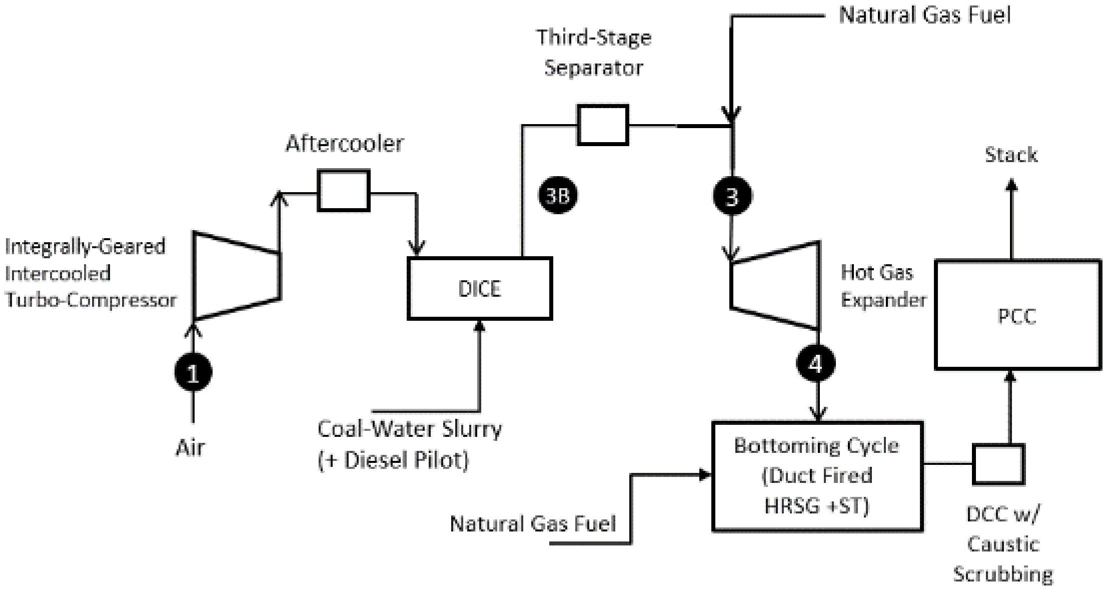
1.2.2 Current Coal-Fired Embodiment

For the pre-FEED design of the coal-water slurry-fired DICE-CRCC, a simplified version is considered for the following reasons:

- Minimum amount of equipment modification
- Shortest possible timeframe from concept to front-end engineering design (FEED) to pilot plant

A simplified system diagram is shown in Figure 1-3.

Figure 1-3
Simplified Schematic Diagram of Coal-Fired DICE CRCC with Hot Gas Expander and Duct-Fired HRSG



Compared to the original embodiment as shown in Figure 1-2, this system has the following differences:

- The heat exchanger between the DICE and the hot gas expander is eliminated
- The reheat combustor and gas turbine are replaced with a hot gas expander due to the following constraints:
  - Limited availability of oxygen in DICE exhaust gas (roughly 10 percent by volume)
  - Necessity for supplementary firing in the HRSG to generate sufficient steam to meet the demand of the stripper reboiler in the post-combustion capture (PCC) block, which required supplementary air to make up for oxygen spent in the reheat combustor
  - The cap put on non-coal fuel consumption (maximum 30 percent)
- Duct-firing heat recovery steam generator (HRSG) is utilized to meet steam demand of PCC system
  - In the presence of diesel pilot fuel in DICE (roughly 5 percent of DICE heat consumption), no supplementary air is supplied to the HRSG duct burner. This would otherwise have made satisfaction of less than 30 percent non-coal fuel consumption requirement impossible to meet with the reheat combustor. The resulting system is simpler and cheaper with very low impact on plant efficiency.
- Particulate matter (PM) removal is achieved with the presence of the “third-stage separator” (TSS) downstream of the DICE exhaust
- SOx scrubbing is achieved in a *direct contact caustic scrubber* with sodium hydroxide Na(OH) injection along with flue gas cooling to meet the CO_2 capture absorber requirements
- 90 percent of the CO_2 in the HRSG exhaust is captured using a standard 30 wt% MEA-based chemical absorption-desorption process

As shown in Figure 1-3, air compressed in the turbocompressor is sent to the DICE engine intake after being cooled in an aftercooler to a suitable temperature (~120 °F). Since the charge air is already compressed at the engine air intake, there is no need for the engine turbocharger.

Multiple DICEs, operating in parallel, burn MRC slurry to generate power. The DICE exhaust gas temperature, expected to be between 575 and 600 °C, is sent to the hot gas expander for power generation.

The bottoming cycle is a Rankine steam cycle comprising an HRSG and a steam turbine generator with the balance of plant (BOP) including a backpressure steam turbine, myriad pipes, valves, pumps and heat exchangers. The HRSG is a waste heat recovery boiler utilizing hot gas turbine exhaust gas to make steam. Duct firing of natural gas in the HRSG is required in order to generate enough steam to meet the demand of the PCC system.

Superheated steam generated in the duct-fired HRSG is first expanded in the backpressure steam turbine for additional power generation. The expanded steam leaves the backpressure turbine at 60 psia and is desuperheated to saturated conditions. This steam is consumed in the PCC stripper reboiler, which uses the latent heat of the steam to generate the vapor needed to strip CO_2 from the MEA solution. The reboiler returns hot condensate to the HRSG, where it is heated to generate steam to complete the cycle.

The flue gas leaving the HRSG contains about 300 ppm of SOx. If left untreated, this high level of SOx in the flue gas will cause unacceptable levels of amine degradation in the PCC unit. The flue gas therefore is desulfurized in a direct contact caustic scrubber, a packed bed column that uses caustic to reduce the SOx content in the flue gas to less than 10 ppm and reduce amine losses in the downstream PCC unit, while also cooling and condensing water from the flue gas.

The desulfurized flue gas is then sent to the PCC plant for CO_2 removal. This is a standard amine-based chemical absorption-desorption process where 90 percent of the CO_2 in the flue gas is absorbed by lean amine in an absorber column. The treated, CO_2-depleted flue gas leaves at the overhead of the absorber column to the stack for release into the atmosphere. The rich amine containing the absorbed CO_2 is sent to the MEA stripper column where it is stripped of CO_2 with heat supplied by LP steam from the backpressure turbine. The regenerated lean amine is then pumped, cooled, and routed to the absorber column for CO_2 absorption again.

Section 2 Coal Beneficiation

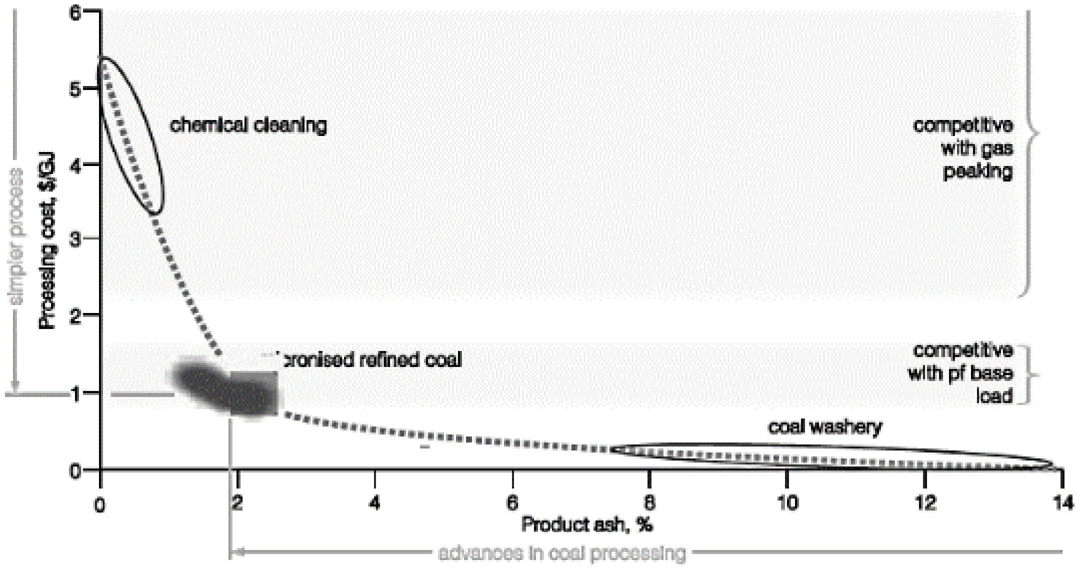
2.1 INTRODUCTION

The fundamental technical and operational challenge in modifying a standard reciprocating internal combustion engine (RICE) – designed for liquid fuel (e.g., heavy fuel oil, HFO) – for coal-fired operation is to protect the mechanical moving parts of the engine that are exposed to either the coal-water fuel (which is abrasive) or the solid particulate products of combustion, which contain both ash and traces of unburned coal. The objective is to ensure acceptable engine life as well as reliability, availability, and maintainability (RAM) without excessive operating and maintenance (O&M) costs.

Coal cleaning/washing, commonly referred to as "beneficiation", can be "physical" (e.g., froth flotation, selective agglomeration and dense medium separation) or "chemical" (i.e., using solvents). The purpose of beneficiation is to reduce the ash content of the coal fuel to a level acceptable to the engine.

Earlier US DOE work (Clean Coal Diesel Demonstration Project) concluded that coal with 1 to 3 percent (by weight on a dry basis) ash was suitable for DICE [3]. Wibberley reports that, after collaborating with MAN in DICE development R&D in Australia (under the auspices of CSIRO), 1 to 2 percent was deemed acceptable as long as one could live with the trade-off between processing cost and engine and maintenance costs [4]. This is dramatically illustrated by the chart in Figure 2-1 (from [5], original work done by Wibberley in 2013).

Figure 2-1
Product Ash (Dry Basis) of Coal Beneficiation Techniques with Cost



Micronized Refined Coal (MRC) in Figure 2-1 refers to finely ground low ash carbons in a slurry, which is similar in consistency to acrylic paint. For effective atomization when injected into the DICE cylinder, MRC should have a maximum size of around 50 microns and a beneficiated coal solids concentration of at least 55 percent (i.e. 45 percent water). The average (P50) size is less than 20 microns.

There are a variety of MRC production processes, which are described in some detail in other reports [5]. In generic terms, for high rank coals, the process comprises (in the order listed) [6]:

- Washing
- Micronizing (fine grinding/milling)
- Froth floatation (deashing)
- Partial dewatering to 55 wt% coal MRC

(Micronizing before deashing instead of before injection avoids fuel contamination by the grinding media)

In order to fully understand the coal beneficiation process, as well as the associated technology gaps and risks involved in building a commercial-scale coal-water slurry (CWS) processing plant to serve the needs of the DICE CRCC, the project team has contracted a company with past experience in DICE technology, **Sedgman** (www.sedgman.com). Sedgman has been involved with the **DICEnet**[1] (www.dice-net.org) for a number of years and has previously investigated this process for the coal beneficiation facility in Australia.

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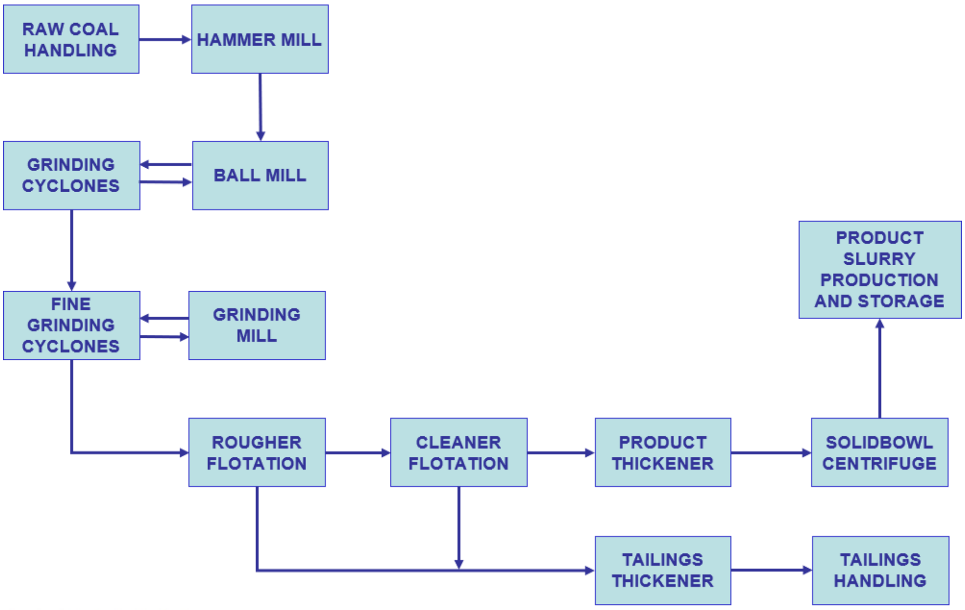
[1] DICEnet was established in March 2013 to support DICE development internationally, including pilot and demonstration projects with Generation 3 technology, and R&D for Generation 4

2.2 PROCESS DESCRIPTION

Sedgman utilized its experience in coal and mineral processing technology to investigate various options for design of the MRC plant. A simplified process block diagram of the coal preparation plant is shown in Figure 2-2.

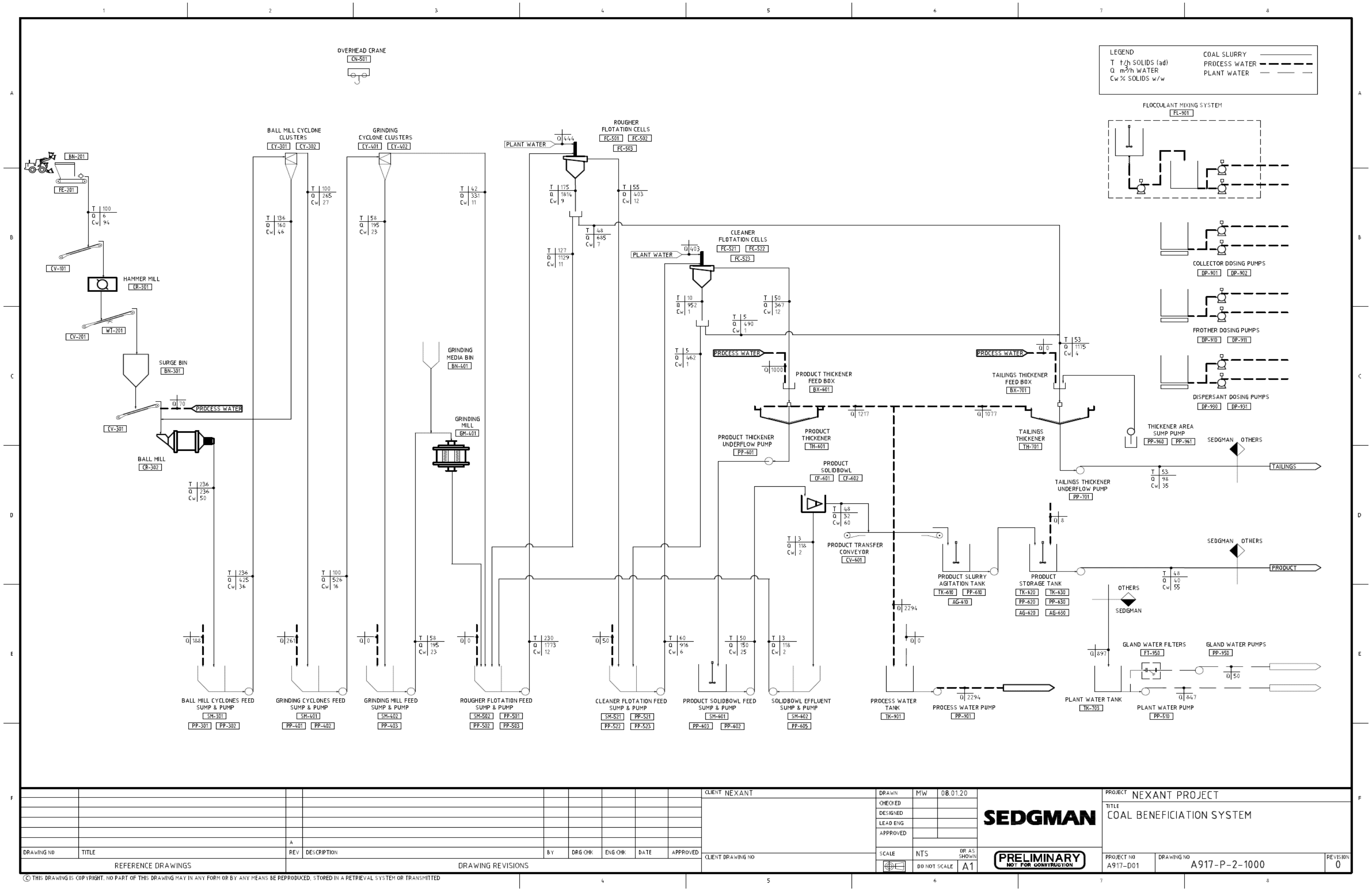
Figure 2-2
Coal Preparation Plant Simplified Block Flow Diagram



A more detailed process flowsheet is shown in Figure 2-3. This scheme was selected for the study as it was considered the most robust, given that it allows for full grinding of the plant feed and is suitable for processing a broad range of feed quality. It consists of the following processes:

- Feed coal receiving and handling
- Hammer mill first stage size reduction
- Ball mill second stage size reduction
  Vertimill (tower mill) fine grinding
- Two-stage (rougher/ cleaner) flotation
- High-rate thickeners for both product and tailings
- Solid bowl centrifuge dewatering of product
- Baffled and agitated tanks for product slurry storage

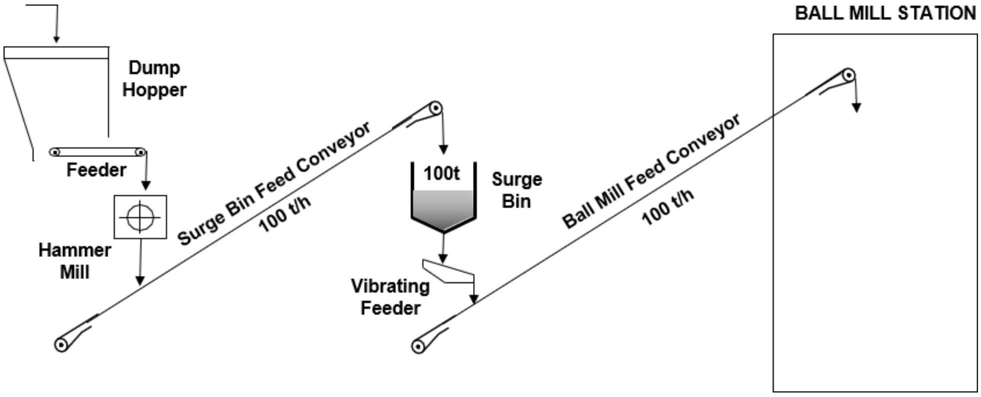
Figure 2-3
Coal Beneficiation Plant Process Flowsheet



2.2.1 Feed Coal Receiving and Handling

The feed coal receiving and handling arrangement is presented in Figure 2-4. The feed coal is loaded from the feed coal stockpile into the dump hopper by a front-end loader. Material in the hopper is drawn out of the hopper by a belt feeder and transferred to the hammer mill.

Figure 2-4
Raw Coal Handling Diagram



2.2.2 First Stage Size Reduction

Based on the feed coal size distribution and the possible reduction ratios of conventional size reduction equipment, two stage size reduction was deemed necessary. The recommended equipment for this application is to use a hammer mill as primary size reduction, followed by a ball mill to reduce the top size of the grinding mill feed material to a P80 of 93 µm. Hammer mills are proven technology which can produce the required primary size reduction down to a P80 of 13 mm at the required throughput with suppliers confirming that capability. A typical hammer mill is shown in Figure 2-5. Fines generation which is typically of concern in a coal washing plant are not an issue here and are encouraged to assist the grinding circuit.

Figure 2-5
Typical Hammer Mill Installation

2.2.3 Secondary Size Reduction

The hammer mill product top size is suited to a ball mill for secondary size reduction. Ball mills are a common method of impact grinding and have proven capability of producing the required discharge particle size distribution. A typical ball mill is show in Figure 2-6.

Figure 2-6
Typical Ball Mill Installation

2.2.4 Primary Grinding Classification

The ball mill will be required to operate in closed circuit with classifying cyclones. The cyclones are used for size separation and to ensure no oversize material is fed through to the regrind mill.

Ball mill product is pumped to the ball mill grinding cyclones. The cyclones will separate the coal slurry based on particle size at a cut-point of 93µm (P80). Undersize material will continue on to the regrind mill, while oversize material will be directed back to the ball mill feed for further size reduction.

2.2.5 Fine Grinding

The regrind mill will provide the final stage of size reduction, to the desired P100 of 50µm for ash flotation. Stirred mills are a method of wet grinding that are proven to be highly efficient when very fine grinds are required. For this application, a VXPmill will be suitable for achieving the desired level of grinding at the specified throughput. This mill is a medium intensity mill running at higher speed than a Vertimill but lower speeds than and IsaMill. A typical VXPmill is shown in Figure 2-7.

Figure 2-7
Typical VXPmill Installation

The selection of the most suitable fine grinding technology will depend on a number of factors/requirements including:

Required product size (P_{80})

For a given feed size, as the required product sizing gets finer, the energy requirements increase, with some technologies being more suited to ultrafine grinding than others. For the 50 µm product size requirement for this project, rod mills will not be suitable as they have difficulty generating product less than 1mm (1000 µm). Further, rod mills require in excess of 30 percent more power than ball mills performing the same duty. Suitable technologies for this product size include tube mills, stirred mills and tower mills.

Feed sizing (F_{80})

Different milling technologies have different maximum feed sizes that they can handle, depending on the required product size. Some tower mills require very fine feed size (1 mm or less) which typically would require multiple additional crushing and grinding stages to prepare the feed, adding to circuit complexity and maintenance requirements and capital cost.

Grinding efficiency

The amount of energy required to reduce particle size increases as the particle size decreases. The energy requirement to attain the desired PSD can vary depending on the method of grinding employed and ultimately the grinding efficiency. Two common methods are impact (e.g. Ball mill, Tube mill, SAG mill) and attrition (tower or stirred mills). Typically, impact mills are less efficient for very fine grinding as energy is lost through media impact, noise and the energy required to rotate the shell to lift the media compared to slower moving attrition mills.

Other factors that impact on grinding efficiency include: slurry flow rate, slurry density, and slurry rheology all of which can be controlled to a certain extent.

Operating Costs

Energy is by far the most significant operating cost of any mill, however, other items also contribute to the ongoing operating costs, including wear liners and grinding media. Typically, attrition mills will have reduced wear on liners as they do not operate by impact of media on the ore. The mill operating speed will impact the liner and media wear rate as well as its grinding efficiency and is dependent on the technology selected. Additional testing is recommended to show which technology provides the optimal balance for this application.

2.2.6 Fine Grinding Classification

For this application, the VXPmill will operate in an open circuit with classifying cyclones. Classifying cyclones are used for size separation to ensure limited oversize material is fed through to the flotation circuit. While this is not catastrophic, it will likely impact the final ash content.

Ball mill cyclone cluster overflow is pumped to the fine grinding cyclones. These cyclones separate the material based on particle size at a cut-point of 32µm (D95). Undersize material continues to the flotation circuit, while oversize material is recycled to the VXPmill for a final stage of grinding.

Whether the fine grinding cyclone must operate in closed or open circuit with the fine grinding mill is dependent on the technology selected and must be considered in any further technology trade-off.

2.2.7 Ash Removal

The most efficient method for ash removal from the feed material will be dependent on the optimal size requirement. For the purposes of this study, it is assumed that the feed material will need to be reduced to a liberation size that would require flotation as the only feasible conventional processing method.

Operation of the flotation cells have a number of variables that can be adjusted to obtain the required product quality. These include; reagent dosage, froth depth and wash water rate.

There are a number of different flotation technologies available which have different energy and reagent input requirements. Regardless of the technology chosen, flotation of such fine coal to such a low concentrate ash will have the following issues which must be addressed/determined:

Froth carrying capacity

Carrying capacity is the rate at which material can be removed from the cell (t/h/m^2 cell area). Ultrafine coal typically has a very low carrying capacity compared to ‘standard’ coal flotation (at most half the value). This will invariably lead to a larger number of cells required to process the material.

Froth washing

To achieve the low concentrate ash, froth washing will be required. High ash slimes will invariably be present in the concentrate with such a fine feed after being liberated in the grinding circuit as it is carried with water into the froth. The best method of removing this material is to wash the froth with clean water. This involves running the cell with a relatively deep froth at depth of 1 to 1.5 m (3 to 5 ft).

Multiple stages

Even with froth washing, it will be necessary to have multiple stages of flotation to achieve the desired ultra-low ash content in the product coal. This will be a cleaner stage which would re-float the concentrate from the first stage (roughers) to allow additional ash removal. The requirement for this would depend on the quality of the feed. A low ash fines feed may not require a second cleaning stage.

Note that if a relatively coarse sizing (e.g. 250-500 micron) is possible to achieve the required ash content, then cheaper processing technologies e.g. spirals, reflux classifiers, could be employed. These technologies do not require any additional reagents and typically require less circulating water volumes and pumping requirements, resulting in operating cost savings.

2.2.8 **Dewatering**

The use of flotation as the main processing technology for this material results in a slurry product of relatively low solids concentration (approximately 12 wt%) whereas the solids concentration in the final coal water slurry product is 55 wt%. Dewatering of the flotation product is therefore required to reach the desired final slurry concentration.

The philosophy to dewater the MRC product to a higher solids concentration than required in the final slurry to allow a controlled addition of water (and dispersant) to be added back in so that the target solids concentration can be obtained.

Fortunately, due to the low ash content of the product (and given the relatively good quality feed to the system, medium level ash of the tailings), dewatering behavior of the material is not expected to be impacted by excessive slimes or clays, which are detrimental to dewatering performance. However, given the ultrafine size of the material in the plant, dewatering is still a relatively high intensity process to achieve the required moisture.

At this size, the most common dewatering methods are plate and frame filters, belt press filters, screen bowl centrifuges and solid bowl centrifuges. Sedgman evaluated each of these ultrafine dewatering systems on a qualitative basis and provided a high-level comparison of these technologies as shown in Table 2-1.

Table 2-1
Dewatering Technology Comparison

	Assessment Criteria*							
Technology	Product Moisture	Fines Loss	Flocculant Dosage	Continuous Production	Footprint	Maintenance	Circuit Complexity	Total
Solid bowl Centrifuge	3	3	3	1	1	1	1	**13**
Screen bowl Centrifuge	2	4	2	1	1	2	2	**14**
Plate and Frame	1	1	1	4	1	4	4	**16**
Belt Press Filter	4	2	4	1	4	3	3	**21**

*1 = best, 4 = worst

From the comparison table, the solid bowl centrifuge technology, as depicted in Figure 2-8, was deemed the most favorable. It should be noted that this evaluation was conducted in the absence of any test data, and that test work on the various dewatering processes, including items such as flocculant dosage and equipment footprint would need be carried out with the slurry product in order to verify this finding and indicate the specific capacity of the equipment.

Figure 2-8
Typical Solid Bowl Centrifuge Installation

All these technologies will require some form of pre-thickening of the feed to help improve dewatering efficiency and minimize the size of equipment required. Therefore, a high rate thickener needs to be installed upstream of the selected dewatering equipment. A typical thickener installation is shown in Figure 2-9.

Figure 2-9
Typical Thickener Installation

2.2.9 **Slurry Preparation**

Product material is discharged from the solid bowl centrifuges to a product transfer conveyor, which in turn deposits the material into the product slurry agitation tank. It is likely that a dispersant will be added to the slurry to keep the solids in suspension for extended periods before usage. Product slurry is then pumped into one of two product storage tanks.

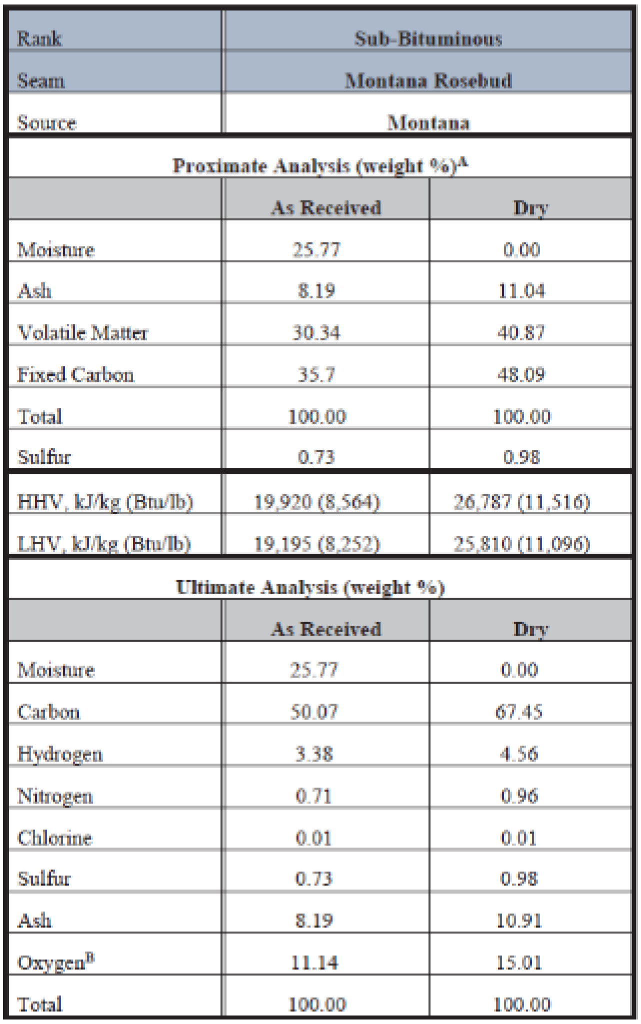
Once the slurry mixture has been created, moving this material to long term storage will require pumping, however, the high solids concentration of this material make the use of conventional centrifugal pumps unlikely to be viable. A progressive cavity or positive displacement pumping technology will likely be required. Viscosity testing of the final slurry material will be required to determine the best pumping technology for this material.

2.3 COAL BENEFICIATION PROCESS PERFORMANCE

2.3.1 Beneficiated Product Yield

The study coal is low-sulfur, subbituminous PRB coal (a low rank coal) with proximate and ultimate analysis as summarized in Table 2-2.

Table 2-2
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

Sedgman made the following assumptions in estimating the composition of the beneficiated coal product and reject tailings based on the process described in Section 0. The estimation effort was based on Sedgman's work done during the DICEnet collaboration and from its overall experience in coal and mineral processing technology.

- The coal feed is sub-bituminous Montana Rosebud, as shown in Table 2-2
- The beneficiated coal product is upgraded to 2% ash on a dry basis (db) and its sulfur content is reduced by 20 percent
- For mass balance purposes, the remaining components related to the organic part of the coal including C, H, N, O and Moisture retain the same proportions in both the product and reject material as in the original feed

- Mass balance calculations from an open circuit mill show a 47.5 percent beneficiated product yield on an *as received* (ar) basis, or 45.8 percent yield on a dry basis
- Final MRC slurry composition is 55 percent dry coal solids and 45 percent moisture
- The calculation methodology entails the following steps:
  - Feed ultimate = Feed (ar) from Table 4-1
  - Feed adjusted to dry basis
  - Product ash set to 2 percent (db) and S set to 80 percent of Feed S percent (db)
  - Product adjusted to (ar) basis after feed moisture is adjusted for ash and S changes
  - Reject (ar) calculated for each component according to yield percent (ar)
  - Reject (db) calculated for each component according to yield percent (db)
  - Check calculation for Reject (db) from Reject (ar).

Table 2-3 shows the calculated Ultimate Analyses for the Feed, Product and Reject streams.

Table 2-3
Ultimate Analysis Calculations for Feed, Product, and Reject Streams

Component	Feed ar (%)	Feed Dry (%)	Prod Dry (%)	Prod ar (%)	Reject ar (%)	Reject Dry (%)
C	50.07	67.45	74.53	53.31	47.14	61.48
H	3.38	4.55	5.03	3.60	3.18	4.15
N	0.71	0.96	1.06	0.76	0.67	0.87
S	0.73	0.98	0.79	0.56	0.88	1.15
Cl	0.01	0.01	0.01	0.01	0.01	0.01
Ash	8.19	11.03	2.00	1.43	14.31	18.66
Moisture	25.77	0.00	0.00	28.47	23.32	0.00
Oxygen	11.14	15.01	16.58	11.86	10.49	13.68
Total	100	100	100	100	100	100

Table 2-4 shows the estimates of the beneficiated coal product and tailings reject energies on both a dry and an-as received basis. The combustible recovery rate is about 50.5 percent on an HHV basis. The beneficiated coal product in final slurry form consists of 55 wt% coal solids and 45 wt% moisture. The resulting MRC fuel composition is listed in Table 2-5.

Table 2-4
Energy Estimates of Beneficiated Coal Product and Reject

			Product	Reject
Dry basis	HHV	kJ/kg	29535	24409
		Btu/lb	12715	10509
Ar basis	HHV	kJ/kg	21125	18719
		Btu/lb	9094	8058
	LHV	kJ/kg	19673	17640
		Btu/lb	8470	7594

Table 2-5
Study MRC Composition

	Dry (wt%)	Slurry (wt%)
Moisture	0.00	45.00
Carbon	74.53	40.99
Hydrogen	5.03	2.77
Nitrogen	1.06	0.58
Chlorine	0.01	0.01
Sulfur	0.79	0.43
Ash	2.00	1.10
Oxygen	16.58	9.12
Total	100.00	100.00

For the 100 MWe DICE CRCC power plant, 642 MMBtu/hr (HHV) of MRC feed is required. This translates to about 92,000 lb/hr of MRC slurry at 55 wt% solids/45 wt% moisture. On a dry basis, this is about 50,600 lb/hr of beneficiated coal product. At the stated recovery rate of 45.8 percent (dry) or 47.5 percent (as-received), the coal beneficiation plant therefore has to process about 149,000 lb/hr of as-received PRB coal.

2.3.2 Beneficiation Plant Power Consumption

The estimated power demand for the coal beneficiation plant is shown in Table 2-6 and totals about 5.5 MWe. The power to the plant will be supplied by the DICE CRCC plant, thus reducing the net output of the plant.

Table 2-6
Coal Beneficiation Auxiliary Load Breakdown

COAL BENEFICIATION PLANT AUXILIARY LOADS	**kWe**
Hammer Mill	240
Ball Mill	800
Grinding Mill	2,800
Grinding Cyclones Feed Pumps	44
Flotation	288
Dewatering	529
Slurry Transfer and Storage	333
Miscellaneous	438
TOTAL AUX LOAD	**5,472**

Section 3 DICE System Design

3.1 CONCEPTUAL DICE PLANT BACKGROUND

The following section details the conceptual DICE power plant based on the current understanding of the technology, and how large 4-stroke medium speed diesel engines could be adapted for DICE.

3.1.1 Base Engine Choice

Although a wide range of engines has been used for MRC coal slurry fuels, including up to 1,900 rpm in the earlier US DOE program, it is generally accepted that the lower speed engines are most suitable:

- Low-speed two-stroke marine type engines (10-100 MW at 90-120 rpm), as depicted in Figure 3-1. Note that the latest super long-stroke versions of these engines (~60 rpm) are considered less likely to economic for land-based generation due to the cost of the alternator, extra weight and foundations required
- Large four-stroke medium-speed engines (20 MW at 400-500 rpm), as depicted in Figure 3-2

Figure 3-1
Low Speed Engine with Generator by MAN (55 MW, 120 rpm)

Figure 3-2
MAN Gas Engine Generators (20 MW, 500 rpm)

Low engine speed is recommended because this increases the time for ignition and combustion which reduces the requirement for fine atomization of the fuel (requiring lower viscosity fuel and higher nozzle velocity). While fine atomization of slurry fuels is technically possible, this comes at the cost of increased atomizer wear.

Low speed engines also have larger cylinder bores which have two important advantages for MRC fuels:

- Allows for longer fuel jets - important for difficult fuels as fuel jets must not impinge on the liner
- Larger cylinder heads/covers provide more space for a dual injection system

An additional benefit of the large, low-speed engines is their longevity and tolerance to lower quality fuels – for conventional diesel engines, this includes the use of residual fuel oils, which contain up to 0.2 wt% of highly abrasive corundum-like catalyst fines. For MRC, this includes increased tolerance to mineral ash content, coarser coal top size and, higher viscosity.

The choice of engine will also be site- and application-dependent. While the low-speed engine has slightly higher efficiency and lower maintenance costs, the cost of these engines is higher at nominally $1,300 k/MW compared to $750 k/MW for medium-speed engines. Overall, installed costs will be location, site, and project-specific.

3.1.2 Recent Developments on Coal-Slurry Fuels Adaptability

Despite being an extremely mature technology, reciprocating engines continue to undergo development that improves suitability for DICE. These developments should result in higher thermal efficiency, higher flexibility, and lower capital cost than for conventional coal-based generation plants. Developments include higher firing pressures (up to 300 bar), electronic control, more efficient turbochargers, new materials for highly stressed components (valve seats, cylinder liner coatings, ring coatings, valve seats/sealing for high-speed gas valves). To some extent, this has been driven by the use of alternative fuels such as biofuels (corrosive), LNG, and bitumen water fuels. For example, electronically controlled (eg MAN ME type) engines are implemented as "intelligent engines" with auto-tune ability for individual cylinders – highly beneficial for maximizing combustion efficiency for MRC.

3.1.3 Manufacturers

A range of manufacturers produce lower speed 4-stroke engines (say 500 rpm), which could include derating of 600 and 720 rpm engines.

For large marine-type 2-stroke engines, there are only 3 suppliers – MAN, WING&D and MHI. All of these 2-stroke engines are produced in SE Asia (China, Korea, and Japan) under license. Although MAN is presently the only supplier offering large 2-stroke engines for land-based power generation, other suppliers have expressed interest in producing large low-speed 2-stroke engines optimized for (constant speed) power generation given sufficient need.

While most manufacturers have had some previous negative experiences with coal fulling of engines, all acknowledge that the previous work was undertaken without a high level of commitment, and none of the programs were completed because the expected scenario of oil shortages did not materialize or funding ceased.

Future developments will benefit from recent experience with Orimulsion and MSAR (multiphase superfine atomized residue), previous experiences from the USDOE program for black coals, and more recently by CSIRO's R&D for both black and brown coals and chars.

3.1.4 Bitumen-Water Fuels as Analogs for MRC

The use of bitumen water emulsions and slurries in diesel engines provides a good analog for MRC.

Over the last 25 years, there have been several initiatives to produce bitumen water fuels to replace HFO in boilers, and these fuels have also been used in diesel engines. Fuels include Orimulsion produced from natural bitumen and MSAR produced from refinery residue (an extremely heavy tar) - developed as an Orimulsion replacement for diesel engines. While it is a problematic fuel, giving both poor ignition and highly abrasive catalyst fines, it is used as a marine fuel in adapted engines. Also, as the bitumen component of MSAR has a very high viscosity of >106 mPa.s at ambient temperature, it is essentially a slurry of solid bitumen in water and thus is analogous with MRC (especially from bituminous coals).

Wärtsilä has extensive experience with firing Orimulsion into medium-speed 4-stroke engines (including a 40 MW demonstration power plant at Vaasa, and a 150 MW power plant in Guatemala).

Suitable adaptations have been considered by two large engine manufacturers, and examples are shown below, noting that several of these have already been developed for bio-oils. A fuel testing program is underway between CSIRO and Chinese engine manufacturer Zibo Zichai New Energy Co., Ltd to develop fuel specifications and identify a suitable engine for a demonstration plant.

3.1.5 Humidified Diesel Engines

A summary of humidified diesel engines is given, as water in fuel is associated with poor thermal efficiency in steam plants, and is not normally associated with diesel engines.

Combustion of fuel-water emulsions is the oldest and easiest method of reducing NOx emissions in diesel engines. In this technology, water is added to the fuel and passed through an emulsifier immediately before injection into the combustion chamber as an effective way of reducing the flame temperature - thereby suppressing the formation of NOx. An efficiency penalty of ~2% (ie an increase of 4% in fuel consumption) is incurred for a water/fuel volume ratio of 0.87 (equivalent to ~50% water in fuel on a mass basis) – which is considerably less than if used in a steam plant.

3.1.6 Direct Water Injection (DWI)

Several direct water injection technologies have also been used: Wärtsilä has used this in medium-speed engines, and involves injecting water into the cylinder just before injection of the fuel. Injection rates of 0.4-0.7 kg water/kg of fuel are typically used. Special injectors, comprising separate water and fuel nozzles, are used. The advantage of this system is that the water penalty is substantially avoided as the water spray cools the compressed air charge, thereby reducing compression work.

Mitsubishi Heavy Industries has developed a more complicated version of water in fuel for NOx control. This system is called stratified fuel-water injection (SFWI), and it uses a single injector to inject slugs of fuel-water-fuel sequentially into the combustion chamber to maintain more extended control of peak combustion temperatures.

DWI and SFWI systems generally give a 70% reduction in NOx for a thermal efficiency penalty of 1 1.5% points (around 2-3% on a heat rate basis).

Scavenge air moisturization (SAM) is the most favored system for reducing NOx for the larger low-speed engines and involves humidifying the scavenge air immediately before entering the cylinder with warm seawater or freshwater injected and evaporated into the hot air from the turbocharger compressor to saturate the air to the cylinder (around 7-9 vol% water). Wärtsilä has a variant of this for large 4-stroke engines, with fogging nozzles introducing freshwater directly into the charge air stream after the turbocharger, resulting in combustion air with a humidity of around 60 g water/kg of air (10 vol %). This technique reduces NOx levels by over 70%.

MAN has achieved similar NOx reduction levels by increasing the humidity of the charge air with seawater. Compressed hot air from the turbocharger is passed through a humidification tower (a packed bed) that is fed with hot seawater heated by the engine's cooling system.

Overall developments in humidification have demonstrated that diesel engines can tolerate high levels of water ingestion (including seawater mist) without a significant impact on fuel consumption, thermal efficiency, or engine longevity. MDT claims an efficiency of 59% (LHV, flywheel) for a 12K98 engine with waste heat recovery using SAM (Jensen, 2009). For stationary power generation, this is equivalent to around 56% sent out basis.

3.2 ENGINE MODIFICATIONS NEEDED FOR MRC

3.2.1 Overall Modifications

Table 3-1 provides nominal engine component modifications for both 2- and 4-stroke engines. The most significant modifications are for the fuel supply (i.e. the low-pressure fuel supply from the service tank) and the high-pressure injection system.

Table 3-1
Nominal Engine Component Modifications for DICE

Component	4-stroke	2-stroke
Engine foundations	No change	
Engine frame, bed plate, crankcase	No change	
Crank shaft	No change	
Cylinder liners	Hard coating, optional provision of oil scrapper grooves to allow increased bore lubrication and flushing of solids to reduce filtration load on crankcase lubrication	Hard coating, optional provision of oil scrapper grooves to allow increased bore lubrication and flushing of solids above the scavenge ports
Piston	No change in short term, optimization of bowl shape for MRC rather than low NOx as required for fuel oil	
Rings	Hard coating, improved design to improve down scrape of contaminated bore oil	
Exhaust valves	No change	
Stuffing box	-	Seal oil protection to eliminate the ingress of contaminated cylinder oil
Scavenge box drainage	-	No change if scrapper grooves are used in the cylinder walls otherwise improved drainage
Crankcase oil filtration	200 percent increased filtration capacity; dual systems to allow on-line maintenance, separate centrifuge for cylinder scrape.	No change, but with separate centrifuge for reconditioning cylinder scrape
Fuel supply system	A dual system is required: One for MRC and one for a diesel/fuel oil used for starting, idling and optional pilot injection (1 5% of heat rate, as is currently used for some gas engines). The MRC system should provide a small, controlled circulation flow around the fuel rail and 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/cut off valve and should 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 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.	
Injection system	Seal oil protected sliding surfaces, including the pump plunger and	

Component	4-stroke	2-stroke
	needle valve. For typical hydrocarbon seal oils, the seal oil should be maintained at around 120% of the fuel supply pressure at all times (critical during engine off), and to 120% of the high-pressure fuel pressure during injection. This strategy minimizes seal oil consumption and oil contamination of the fuel return flow (which, if excessive, can cause coal particles to agglomerate). A single high-pressure seal oil system can be used if a water-soluble seal fluid is used (eg a polyglycol such as UCON).	
Pilot injection	Pilot injection is essential for engine conditions where ignition is less reliable - starting, idle, and shutdown. The amount will depend on the MRC properties, engine speed, cylinder size, and whether Miller cycle is used (lowers compression temperatures). Pilot injection is recommended for engine speeds above 400 rpm, and at low load. The electronically controlled pilot injection is essential to allow fine-tuning of MRC combustion.	
Exhaust manifold (low speed 2-strokes)	While the fly ash produced from MRC combustion is likely to be very fine <10µm and to remain in suspension, the 20-40x increase in solids passing through the engine will inevitably cause ash deposits that will shed periodically as larger grit. A grit dropout before turbocharger is therefore recommended (as is sometimes used with residual fuels). Large horizontal exhaust gas ducting should be provided with a positive grit removal system (eg bottom auger, chain conveyer, blowers) – especially for the large main exhaust collector across the top of the engine.	
Exhaust turbine	No change for ash with aerodynamic diameter <10um. Possible use of coated metal for inlet guide vanes.	
Waste heat recovery	Conventional solid fuel boiler rather than finned heat exchangers common for cleaner fuels. A vertical fire tube or horizontal water tube is preferred to reduce ash clogging. Until experience is gained to prove otherwise (given the different fuel chemistry and combustion conditions) access is required for manual soot blowing with compressed air or steam.	
Exhaust gas cleanup	The same as used for large land mounted 2-stroke engines using heavy fuel oils – ESP or fabric filtration, SCR and FGD	
Lubrication	Adjustment of crankcase oil base number to match sulfur content of the MRC and with increased detergency to keep char and ash in suspension. Base number should take into account any sulfur reporting to the ash.	Adjustment of cylinder lubricant base number to match sulfur content of the MRC. Base number should take into account any sulfur reporting to the ash.

3.2.2 **Fuel Supply System**

There have been several fuel supply systems proposed for DICE, which all involve some method of agitating the fuel in storage, plus a valving system to enable system flushing of the pump and lines to the injectors. A better system includes a screening system before the main fuel supply pump and controllable return flow. This system is shown schematically in Figure 3-3 and operates as follows:

- Fuel is stored in a 12,000 m^3 service tank sufficient for ten days supply for a 100 MWe plant. This tank is equipped with either a live bottom or a very slow speed rake-type agitator (say 1 revolution per hour). Note, that, conventional high-speed tank mixers are ineffective, giving localised agitation only due to the shear thinning behavior of MRC, and are energy intensive.

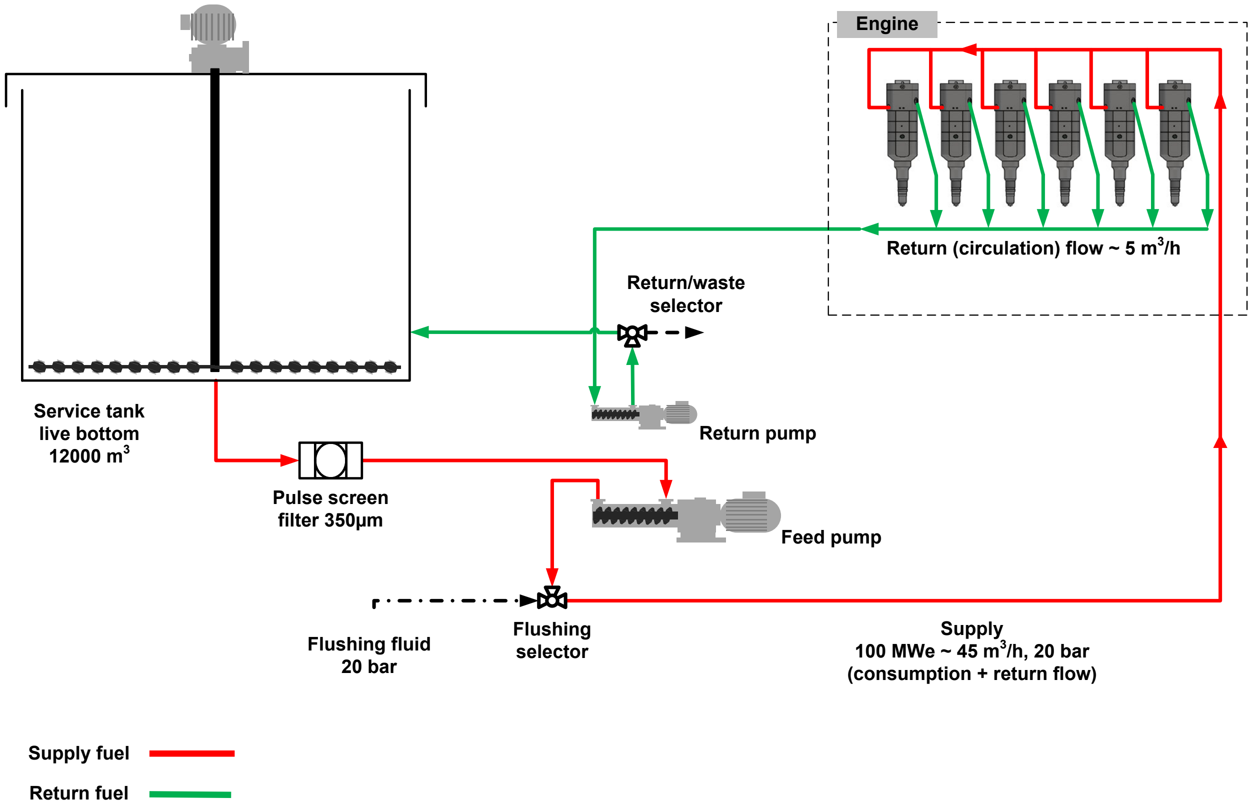
- Fuel passes through a pulse screen filtration device before a positive displacement supply pump. The speed of the supply pump is controlled to maintain the supply rail pressure. A screen aperture of 350µm would be suitable for an engine with injector orifices of 600-800µm. Various screening devices can be used. However, MRC rapidly clogs filters with apertures finer than 10-15x the maximum particle size unless pulsed. The purpose of screening is to allow the bulk of the fuel to pass but trap major oversize particles and contamination such as flakes of rust, paint etc.

- The fuel supply pump is a positive displacement pump (progressive cavity type) which supplies the fuel supply rail. The speed of the supply pump is controlled to maintain the supply rail pressure.

- Electronically controlled unit injectors are preferred for the MRC (eg HEUI or MEUI type) to allow closer control of injection timing. The injectors should preferably incorporate fuel circulation valves, which allow controlled flow of fuel down through the injector's pump and preferably down the body of the injector to the needle/cut off valve seat, and back out to a return rail.

- A positive displacement (progressive cavity type) return pump operating in reverse is advantageous to control the total return flow to the service tank, or in the case of flushing, to a dump tank. The letdown pump need only be ~10% of the capacity of the supply pump – which would enable complete flushing of the system within (say) 30 seconds. The speed of the return pump is controllable to set the return flow. Operating the return pump in reverse reduces shaft seal wear. Controllers should be tuned to allow dead-heading without damaging the pumps.

Figure 3-3
Suggested Fuel Supply System



3.2.3 Fuel Injection System

A range of high-pressure injection systems have been used for MRC, including:

1. Conventional jerk pump (200 bar) - line - media separator (shuttle piston or diaphragm) – nozzle (GE and Cooper Bessemer during the earlier USDOE programs).
2. Hydraulic actuated pump (600 bar) – media separator (diaphragm) – nozzle (CSIRO)
3. Unit injector: Common rail hydraulics (700 bar) – seal oil protected media separator – nozzle (WING&D/Maersk)
4. Unit injector: Hydraulic ram (150-300 bar) – seal oil protected plunger – nozzle (CSIRO/MAN)

Although all options have been made to work with MRC, the unit injector-types 3 & 4 have the advantage of compactness and controllability. Desirable features include:

1) Modular body construction (to facilitate maintenance and component development), comprising a:

    - servo oil valve module containing a high-speed solenoid valve
    - hydraulic actuator module
    - pump module,
    - fuel ring module containing a non-return valve for the fuel inlet
    - lower flanged body which contains the usual spring, push rod, nozzle body and cut-off needle valve.

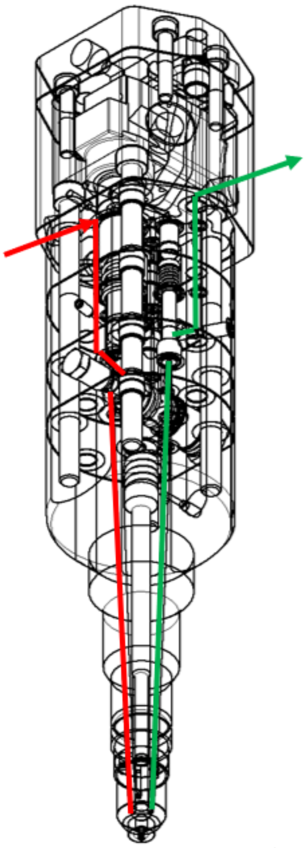
2) An automatically (this could also be electronically actuated) operated return valve to provide positive fuel flushing around the injector between injection events and whilst the engine is standing. This ensures continuous movement of the fuel, which dramatically reduces the chance of clogging, enables rapid fuel switching, or system flushing – either during engine operation or when stopped. Figure 3-4 shows the circulating flow around the injector required to ensure high reliability. This injector shown is an enlarged version of an injector for a 4L single-cylinder laboratory engine at CSIRO.

3) All fuel wetted surfaces are provided with seal oil continuously (this can be hydraulic or motor oil) at a slightly higher pressure than the fuel (say 25 bar).

4) The fuel pump and needle spindle are provided with high-pressure seal oil during the actual injection event. The seal oil pressure can be provided by an integral intensifier pump within the injector's hydraulic ring, or from an external supply. In the case of the latter, a two pressure system should be used to reduce seal oil pressure when the engine is standing, to avoid unnecessary seal oil contamination of the return fuel.

5) Although MRC has a much higher viscosity than diesel fuel, CSIRO has found that only a slightly larger orifice size is required (say 10% larger diameter) due to the strongly shear-thinning behavior of MRC fuels (if correctly prepared). Shear-thinning results in marked wall slip, which increases the volumetric flow of a nozzle. Experience has shown that a nozzle size of 500-750µm will provide a balance between atomization and jet penetration for cylinder bores up to (say) 50 cm.

Figure 3-4
CSIRO Injector Showing Fuel Return Circulating Flow through the Injector



3.3 DICE FUEL SPECIFICATIONS

This section discusses the specifications of MRC required for combustion in DICE. An overall summary of fuel specifications is followed by additional discussion for each of the critical properties.

Fuel for DICE has significantly different quality requirements than for conventional coal slurry fuels used in boilers. This difference is because engines have short combustion times (say 30 ms in engines, versus 1-2 s in boilers), which requires more intense atomisation than for a boiler. Also, in engines, unburnt char and ash particles will cause chronic engine wear, piston ring jamming, and even turbocharger erosion. Also, the exhaust system of engines is not designed to pass significant ash – which for DICE could be 30x that of even the lowest quality residual fuel oil.

In DICE, it is paramount that the fuel 1) gives a high degree of atomization during injection (which ensures rapid ignition, combustion, and complete burnout), 2) forms minimal abrasive ash particles, 3) has the highest coal solids loading. These requirements will be strongly interdependent, and also be strongly influenced by the size of the cylinders, engine speed, and the extent of engine armoring. Overall properties include:

- Low abrasive mineral content – to minimize injector nozzle and cylinder/ring wear especially
- Coal particle size distribution with a d50 of <15µm and a d90 <60µm to ensure burnout
- High coal content to minimize latent heat losses in the engine – subject to meeting the viscosity specifications
- High stability of formulated fuel to prevent settling in the fuel handling equipment, as well as ease of transportation and storage
- Strongly shear thinning behavior to allow injection and effective atomization – essential for controlled heat release and to minimize unburnt char
- Resistance to microbial action – some slurry fuels degrade rapidly, which can affect both stability and shear thinning behavior – in addition to increasing occupational, health, and safety (OH&S) concerns

Nominal target specifications, based on both literature and recent engine experiences are as follows (formulated MRC slurry basis):

- Ash content < 2% (dry basis)
- Residual mineral size <15µm and preferably <5µm
- Coal particle distribution giving a d50 of < 15µm and d98 < 50µm
- Coal content of the fuel should be as high as attainable, while still meeting the following nominal rheology targets:
  - >10,000 mPa-s @ 0.1/s
  - <400 mPa-s @ 100/s
  - <100 mPa-s @ 10,000/s and be shear thinning at higher shear rates
- Heating value > 18 MJ/liter
- pH of 3.5-8.5

- Stable – say exhibiting no settling (coherent cake on the bottom surface) over 90 days when stored in a sealed 500 mL measuring cylinder at (constant) ambient temperature. After 90 days, all MRC should drain from the upturned measuring cylinder

Experience has shown that, while individual properties can be readily met, achieving a balance between all properties is more difficult. For example, a high SE fuel can be produced by increasing the solids content, which will have the advantage of also increasing fuel stability. However, this will also increase the viscosity and may cause shear thickening behavior, which will make the fuel very difficult (even impossible) to inject, resulting in poor atomization. The resulting large fuel droplets (containing many smaller coal particles) will likely dry to form a single large coal agglomerate, resulting in slower ignition and incomplete combustion. This will invariably lead to chronic ring jamming by char. The resulting flash from poor atomization is also likely to be larger due to the interaction and fusing of fine mineral grains and organically bound ash forming components within the coal. These interactions are discussed in more detail below.

3.3.1 Coal Loading

Coal loading has two main effects, 1) strongly affects fuel viscosity – especially at higher coal loadings (say >55 wt%), and 2) water reduces the calorific value of the fuel and increases the latent heat penalty.

It is important to note that while the effect of coal loading on calorific value is linear, the effect on viscosity is exponential at higher coal loadings (say 57wt% for bituminous coals, and above 53% for sub-bituminous coals – depending on the shape of the size distribution). This rapid increase in viscosity means that the maximum coal loading is usually dictated by the highest viscosity - which ensures satisfactory atomization..

3.3.2 Coal Particle Size

As a guide, at 500 rpm, around 30 ms is available for combustion, and practical experience suggests that a coal top size of 50-60μm will give satisfactory combustion with minimal unburnt char in the exhaust – providing atomization is sufficient. Sub-bituminous coals (higher oxygen content, more reactive chars) and lower speed engines are likely to allow a coarser tail in the size distribution.

However, there are several other factors that need to be considered, as the particle size distribution of the coal in the MRC strongly affects the fuel's rheology for a given coal loading, and therefore its atomization, ignition, and combustion. The particle size distribution also affects the degree of mineral liberation during fuel preparation and the size distribution of liberated minerals in the final fuel. In general:

- A wide size distribution allows a higher particle packing efficiency, and therefore coal loading (this can be calculated), which improves thermal efficiency and fuel stability, and reduces fuel transport costs.
- An optimum coal loading and wide particle size distribution should give a high low shear viscosity (essential for fuel stability in storage) and shear thinning behavior, which enables injection and atomization. Coal loadings above the optimum rapidly cause shear-thickening fuel, which causes fuel system clogging and poor atomization.
- Both the quality of atomization and the coal top size affect the effective size of the coal at the time of ignition - which in turn determines the time for combustion. Finer grinds may not be better: For example, overly fine grinds can increase fuel viscosity and result in poor

atomization. Subsequent agglomeration of the coal during heating, and before combustion, results in a coarser effective coal particle size distribution than that of dispersed particles.

In general, the slower the engine, the larger the allowable top size; however, this also depends on the devolatilization behavior of the coal under the extremely rapid heating and intense combustion intensity in an engine. Combustion intensity can exceed 5 GW/m3 – around two orders greater than for pf combustion –some coals are likely to exhibit a large enhancement in volatiles yield, which gives faster ignition and combustion. Overall, combustion data for coal in engines is lacking, and existing data for pulverized coal firing is likely to be misleading for DICE.

3.3.3 Coal Volatiles

Although there is no literature information on the effect of coal volatile content, with previous engine experience using only medium to high volatile coals (28-40%), higher volatile coals are expected to give improved ignition and combustion. However, the standard method of determination of coal volatiles (the Proximate analysis) will underestimate the effective volatiles content under the extremely rapid heating rates of atomized MRC and the high pressures in diesel engines (which can exceed 150 bar at the start of injection). The morphology of the resulting char is also likely to be very different than that for conventional pulverized coal combustion in boilers, and more akin to that in slurry fed gasification.

The effects of volatiles on ignition and combustion are also affected by the oxygen content of the coal. For example, CSIRO has found that low volatile chars (carbonized at 850°C and containing around 5% volatiles) require 40°C higher charge temperature to achieve the same ignition performance as a 30% VM bituminous coal, and hydrothermally treated Victorian brown coal (45% VM and with 25-27% O) giving an ignition temperature 60°C lower. Note that with these low rank coals, a significant proportion of the volatiles content is CO_2 and H_2O).

3.3.4 Ash content

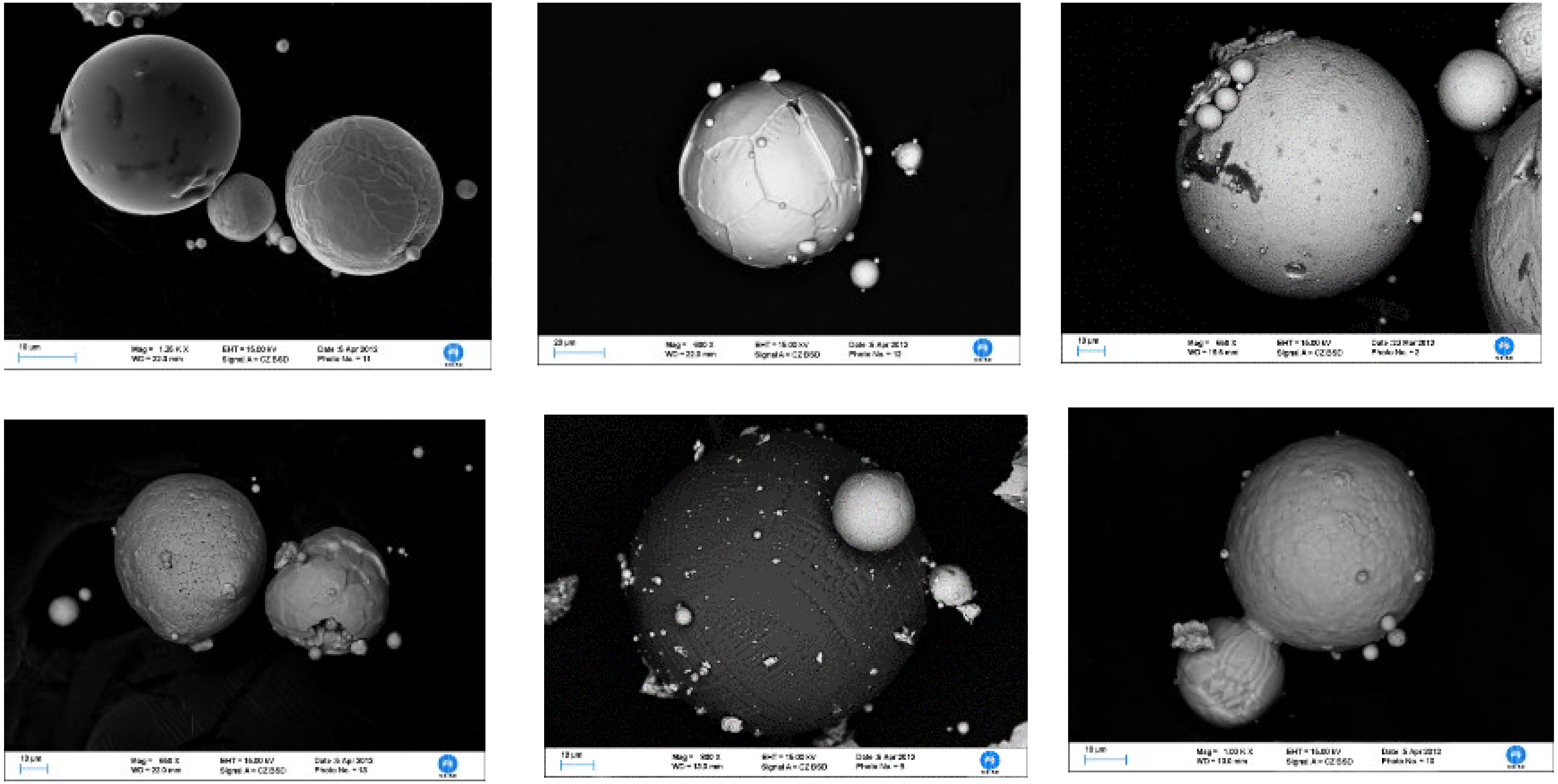
Ash is the residue after complete combustion, and comprises altered mineral particles from the extraneous ash components, plus finer particles from condensed, oxidized and sulfated compounds formed from the fine, organically bound and mineral particles contained within the coal particles. As the latter interact during burnout of the char, these particles are usually a complex mixture of aluminosilicates and sulfates depending on the coal.

After combustion in a diesel engine, all mineral particles below 10µm size are spheroidized, including quartz. However, even highly fused ash particles have the potential to cause cylinder wear unless the diameter is less than the minimum oil film thickness (1-2µm). Larger sand particles will be most problematic.

For low rank coals and wood chars, the ash also comprises ultra-fine micron size particles formed from the volatilized ash components. Cenospheres have also been observed (see Figure 3-5). Neither the submicron fume nor the cenospheres are likely to cause abrasive wear.

The wear implications of ash require that a detailed investigation of the occurrence of the ash forming constituents of the target coal is undertaken to understand the ramifications for engine wear. This also requires collecting fly ash from either an engine or an appropriate high-pressure spray combustion chamber.

Figure 3-5
SEM Images of Cenospheres from DICE using a Hydrothermally Treated Victorian Coal



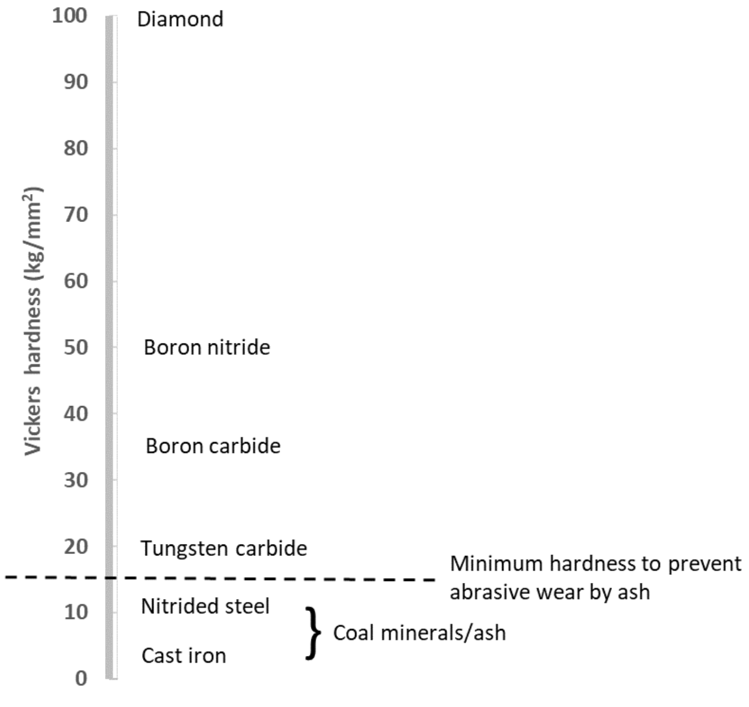
The present understanding of ash-engine interactions is that:

- Coarse (say, >5µm) and hard minerals (quartz, pyrites, rutile) in the fuel will increase abrasive wear of the atomizer nozzles, rings, cylinder wear, exhaust valve seat, and the turbocharger turbine inlet vanes and rotor.
- Ash residues can also deposit in the oil film on the cylinder wall and be scrapped by ring action to pack in the piston ring grooves behind the ring – a potentially serious condition leading to catastrophic scuffing.

Although these issues could theoretically be eliminated by using harder material and changing the design of engine componentry, all previous DICE projects have been on the basis that DICE requires cost-effective production of ultra-low ash coals - the cleaner, the better.

However, coal specifications for commercial deployment of large diesel engines remain to be established, and in particular, there is a lack of data linking engine wear to ash content and the morphology of the mineral content. Also, there is no information on the trade-off between processing cost, fuel ash, and engine component and maintenance costs. For example, abrasive wear can only occur if the abrading particle is 30% (approximately) harder than the underlying material. For coal ash, the dominant hard material is usually quartz with a hardness (Vickers) of around 11 kgf/mm^2, showing that a wide range of commercially available ceramics could be used to prevent abrasive wear (Figure 3-6) – provided that they can be incorporated into an engine.

Figure 3-6
Hardness of Materials Relative to Coal Ash



The earlier USDOE work generally concluded that coal with 2-3% ash would likely be suitable, thereby enabling the use of physically cleaned coals (as distinct from more costly chemical cleaning). In recent studies with MAN and WING&D/Maersk, the target ash was <1.5% with a maximum of 2%, noting that this limit was set by available fuel quality and the use of unarmored engines, rather than based on a sound techno-economic basis. Also, these targets were set with little consideration of the type and morphology of the starting mineral matter – mostly due to limited capacity to produce tonnage fuel required for the large engine tests involved. The morphology is very significant, as recent wear tests (using a modified HFRR test) by CSIRO has shown that oils contaminated with fine ash from lower rank coals decreases wear of hardened steel by up to 30%. For tungsten carbide HFRR components, there was a negligible difference between clean and contaminated oils regardless of the mineral type.

Overall, the lack of data has caused a divergence of philosophies between the engine manufactures and the coal industry, which has hampered DICE development. To generalize, the engine manufactures have required that the fuel should be made to match the (current) engine componentry, whilst the coal suppliers have pressed for armored engine componentry to allow higher ash MRC. This dilemma requires that a full-size DICE facility (including fuel preparation plant) are established to allow longer-duration engine trials with armored engine componentry, and for a range of MRC quality. Quantifying the effect of ash on engine componentry costs, durability, and other R&M issues would result in a scientifically based coal quality value model needed to progress the technology.

3.3.5 **Sulfur**

Large diesel engines designed to operate with heavy fuel oil can tolerate relatively high sulfur fuels (2 percent) providing cylinder lubrication uses the appropriate lubricant (i.e. base number) to avoid acid attack of the cylinder walls. As MRC will require deep cleaning of coal, sulfur levels of PRB coals will not be a problem – even if S containing dispersants are used for fuel formulation (e.g., NaPSS – sodium polystyrene sulfonate).

3.3.6 **Alkalis**

While alkalis are a significant issue for coal-fired boilers (nominally, for $Na_2O:SiO_2$ ratios >0.04, or in the presence of high S and Cl), to date, there is no evidence that alkalis are an issue for DICE. Recent CSIRO experience with a chemically cleaned coal (a caustic ash removal process) with a high $Na:SiO_2$ ratio showed negligible ash deposits after 40 hours at full load of a 4-liter single-cylinder test engine – see Figure 3-7. Other indirect evidence is from marine engines, which show no cylinder fouling despite ingesting salt spray (from humidification or aftercooler leaks).

It is surmised that the lack of ash fouling is a result of the large pressure swings (> 100 bar) for each engine cycle, which regularly mechanically sheds the porous particulate ash deposits (ie deposit panting).

Figure 3-7
Head Valves after 40 hours of Full-Load Operation Using MRC Produced from Yancoal UCC

3.3.7 Viscosity/Rheology

Fuel rheology has been largely overlooked in previous RD&D programs to use coal for diesel engines, other than to ensure the fuel's viscosity was sufficiently low to enable injection without nozzle clogging. However, in the recent CSIRO studies, fuel rheology was a major focus due to other important interrelated effects - ignition, burnout, and both injector and cylinder wear.

In general, the coal content must be maximized (at least 50%, and preferably >55%) to reduce latent heat penalty - but also while meeting the following rheological targets:

- High viscosity at low shear rates (say 10,000 mPa.s @ 0.1/s) is essential for good stability
- Rheology that is strongly shear thinning
- Viscosity of <400 mPa.s @ 500/s to ensure good injectibility and atomization.

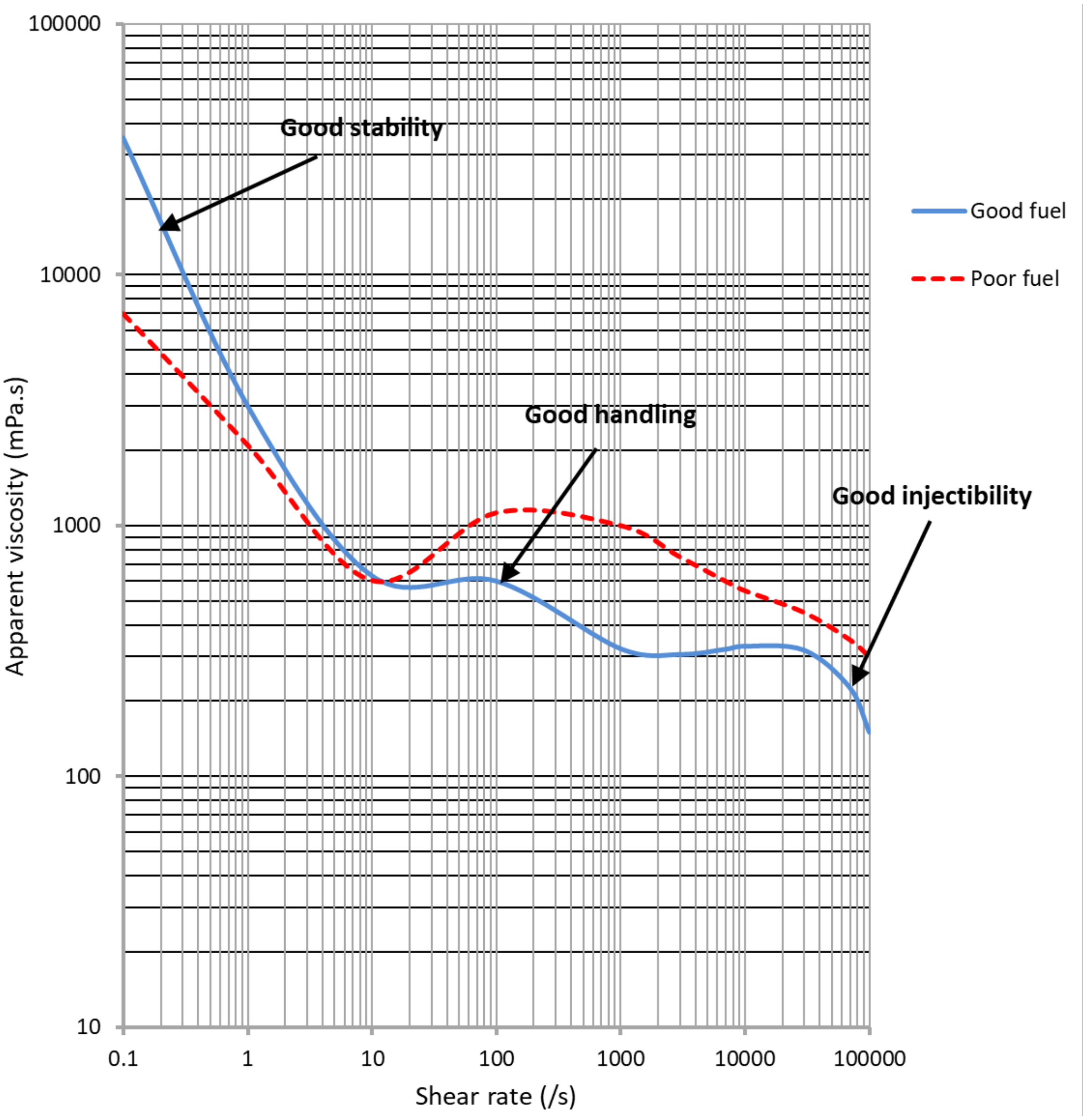
These specifications are very different to that of coal water slurries for boilers, which have a higher coal loading and much higher viscosity at higher shear rates (including being shear-thickening rather than thinning). This difference in rheology is clearly apparent when the different fuels are poured from a beaker, as shown in Figure 3-8.

The first two requirements above – stability and shear thinnng - are the most important attributes, as fuel stability is essential to producing a fuel with the correct rheological properties for DICE: Stable and shear thinning fuel (providing the calific value is high enough) will always makes a good engine fuel – which can be thinned if necessary prior to injection with trim water additions. However, the reverse is not always the case: Highly injectable fuels will not automatically exhibit good stability. Strongly shear thinning fuel (correlates with good stability, handling, injectability, atomization - and ultimately good combustion and reduced wear issues from unburnt char packing behind piston rings.

Figure 3-8
Fuel Rheology: Left, Coal Water Fuel for a boiler by JGC; right, MRC for DICE

Unstable fuel is particularly problematic, regardless of how well it injects, due to the formation of deposits in fuel handling equipment, which, at worse will clog fuel injector nozzles, or at least increase the effective particle size of the fuel entering the combustion chamber leading to poor combustion and char issues. Once MRC forms a hard pack deposit due to poor stability, mechanical means are required for its removal. Figure 3-9 shows nominal rheology plots for good, and poor MRC fuels.

Figure 3-9
Nominal MRC Rheology for a Good and Poor Fuel



3.3.8 Stability

Fuel stability, or lack of build-up of sediment in fuel containers with storage, is essential to avoid serious operational issues from blockages, plus secondary effects described in the rheology section above. An unstable fuel is unacceptable for DICE.

Most established stability tests only require stability over relatively short periods (say) 1 week – this is too short. CSIRO work is aimed at 100% stability for >1 month, and preferably >6 months. This testing period is much longer than specified by most stability tests for coal water fuels for boilers. It is noted that some bulk slurries produced to this specification have been completely stable with negligible sediment for more than 2 years. In general, lower rank coals will provide more stable fuels.

3.3.9 **Control of Microbial Activity**

Microbial activity in the fuel has the potential to destabilise the slurry, in addition to causing safety concerns. However, CSIRO experience with MRC fuels from 48 coals from Australia, Venezuela, Indonesia, and Germany have shown no evidence of microbial activity – except for a single NSW coal slurry prepared by others. Microbial activity has however, been observed with MRC produced from low-temperature chars – see Figure 3-10.

Figure 3-10
Microbial Activity on Pine Char Slurry after 205 Days

3.4 DICE PERFORMANCE

3.4.1 DICE Performance Modeling

Engine:

- Stock engine is based on Wärtsila 18V46, but with estimation of many key parameters
- Thermal efficiency loss using MRC slurry is estimated approximately 1.8 percentage points
- Output reduction is estimated as 9 percent (based on Orimulsion experience)

Fuel:

- PRB coal, analysis as supplied, normalized to 2 percent ash dry basis, as specified by the coal beneficiation process
- MRC slurry assumes 55 wt% coal.
- Temperature on injection 90 °C.
- Pilot fuel is diesel at 5 percent of the total heat rate

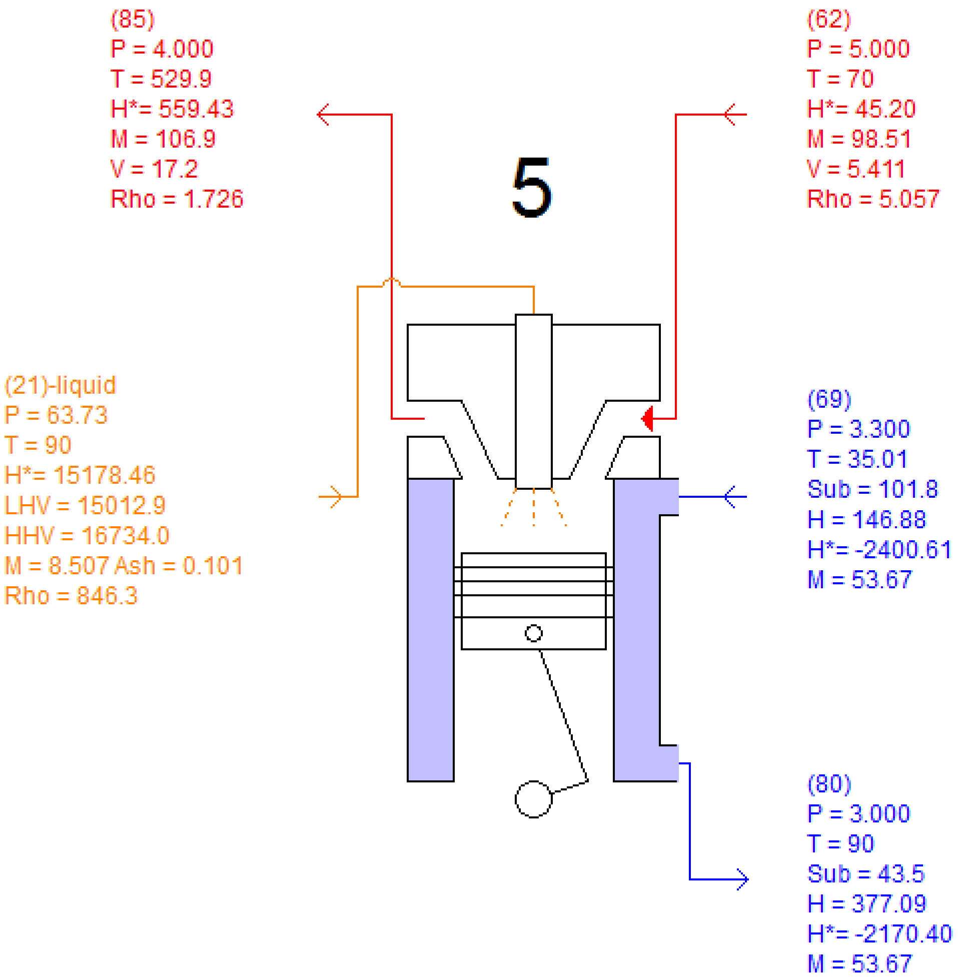
Stock engine heat and mass balance data fired with HFO and MRC slurry is presented in Table 3-2.

Table 3-2
Stock Engine Heat and Mass Balance

		Stock Engine (HFO Fuel)	MRC Slurry	MRC Slurry (Fuel preheat)
Heat Consumption	kWth	37,480	36,578	35,491
Fuel Heating	kWth			389
Charge Air Cooler Heat Rejection	kWth	5,082	5,082	5,082
Lube Oil	kWth	2,294	2,294	2,294
Jacket Water	kWth	1,694	1,694	1,694
Surface heat	kWth	519	519	519
Exhaust	kWth	10,289	10,740	10,042
Mechanical Losses	kW		231	231
Shaft Output	kW	17,602	16,018	16,018
		47.0%	43.8%	45.1%
Heat Balance Error	kW	0	0	0
HB Error / Heat Consumption		0.00%	0.00%	0.00%
Generator Output	kWe	17,303	15,746	15,746
Generator Efficiency		98.30%	98.30%	98.30%
Overall Efficiency		46.17%	43.05%	44.37%
Exhaust Flow	kg/h	106,920	106,920	106,920
	kg/s	29.70	29.70	29.70
Exhaust Temp	ºC	342.0	369.0	327.2

With the turbocharger removed, engine charge air is supplied at 5 bar and 70 ºC by the MAC with the aftercooler. Exhaust gas is at 4 bar and 530°C. Engine heat and mass balance in the Thermoflex model is shown in Figure 3-11.

Figure 3-11
Thermoflex "User-Defined" Reciprocating Engine DICE Model



3.4.2 Performance Validation

The DICE performance model development was described in great detail in Section 2.2.3 of the Conceptual Design Final Report (submitted on August 13, 2019) and will not be repeated herein. In brief, it was an amalgamation of several sources of data and information, including

- OEM's specs (tested for heat and mass balance consistency)
- Detailed engine simulation by Czero, Inc (including combustion modeling)
- Published DICE performance reports
- Field experience with Orimulsion

At this point, there is no opportunity to validate the predicted performance in the field or in the laboratory. The only available option was to ask a third party to conduct a rigorous engine simulation study and compare the results with what we have. Consequently, CSIRO, who has done extensive studies on DICE, was contracted to undertake this study as part of their contract.

Due to their unique position of being the most experienced organization in DICE (and their extensive past collaboration with MAN in fuel injector development and testing), CSIRO is in the best position to provide valuable feedback on DICE performance predictions.

Nevertheless, it is important to realize that this type of simulation can only provide a guide to engine performance until detailed information is available on the combustion characteristics of the chosen PRB coal, and engine adaptations are proven with full-scale operational experience. For example, the engine maker may require the derating of the peak firing pressure due to ring wear concerns or may reduce the allowable pressure limit to account for the increase in power (and therefore stresses on other parts of the engine) that is possible with MRC firing.

The CSIRO DICE engine modeling/simulation study is described in detail below and in Appendix C of the overall pre-FEED study package.

An engine model was used to predict the thermal efficiency and exhaust gas of a MAN 18V48/60TS engine using MRC from a Powder River Basin coal (2wt% ash, but otherwise using an as-mined coal composition). This data is required for the assessment of heat recovery/integration options by others.

The engine model used is a 1-dimensional thermodynamic model, using thermodynamic data from the NASA thermo-build system, and free energy minimization from the NASA CEA program. In-cylinder processes assume a homogeneous mixture of air and combustion products, ideal gas behavior and that the system is at thermodynamic equilibrium.

3.4.2.1 Cylinder heat loss

The heat transfer co-efficient is calculated using the Woschini equation[2]. With this equation three stages in an engine cycle considered:

- gas exchange period (between exhaust valve open and inlet valve close)
- compression
- combustion and expansion period

$$h_c = \frac{3.26}{1000} D^{-0.2} P^{0.8} T^{-0.53} w^{0.8}$$

where:

h_c = heat transfer coefficient (kW/m^2.K)

D = cylinder bore (m)

P = cylinder pressure (kPa)

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[2] Woschni, G., "A Universally Applicable Equation for the Instantaneous Heat Transfer Coefficient in the Internal Combustion Engine," SAE Transactions, Vol. 76, p. 3065, 1967

T = cylinder temperature (K)

w = average cylinder gas velocity (m/s)

$$w = C_1 S_{\text{MeanPiston}} + C_2 \frac{V_{displacement} T_0}{p_0 V_0} (p - p_m)$$

where:

C_1 = constant (6.18 for period 1; 2.28 for periods 2 and 3)

$S_{\text{MeanPiston}}$ = mean piston speed (m/s)

C_2 = constant (0 for periods 1 and 2; 3.24×10^{-3} for period 3)

$V_{displacement}$ = cylinder displaced volume (m^3)

T_0, p_0, V_0 = temperature, pressure and volume

3.4.2.2 Equilibrium Products

Additionally, during combustion, the equilibrium composition is calculated using free energy minimization. A limited number of species are modeled, Ar, CO, CO_2, H, H_2, H_2O, N, N_2, NO, NO_2, N_2O, O, O_2, OH, SO_2. These species are the only ones that will occur at any significant concentrations and were included mostly to account for dissociation at higher temperatures, rather than the amounts of minor species. SO_2 levels in the exhaust gas assumed that there is no partitioning of S to fly ash components. While the latter does occur in boiler off-gases (especially for coals with high alkali/alkaline ash), the extent is unknown for DICE with much shorter residence times below 1000°C.

3.4.2.3 Friction Calculations

The model uses the Chen-Flynn friction model[3] which has the form:

$$\text{FMEP} = C_{\text{FMEP}} + (C_{\text{PCP}} * P_{\text{Peak}}) + (C_{\text{MPS}} * S_{\text{MeanPision}}) + (C_{\text{MPSS}} * V_{\text{MeanPistion}}^2)$$

where:

FMEP = friction mean effective pressure (bar)

C_{FMEP} = constant for FMEP

C_{PCP} = constant factor for peak cylinder pressure

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[3] Chen, S.K., and Flynn, P.F., "Development of a Single Cylinder Compression Ignition Research Engine," SAE Paper 650733

P_{Peak} = peak Cylinder Pressure (bar)

C_{MPS} = constant factor for mean cylinder velocity

$S_{MeanPiston}$ = mean piston velocity (m/s)

C_{MPSS} = constant factor for mean cylinder velocity squared

3.4.2.4 Heat Release Rate

The most important aspect of the combustion phase is the calculation of the rate at which the fuel will combust, generally referred to as the heat release rate (HRR). The model using a three term Weibe heat release model[4] fitted with actual heat release rate data from a hydrothermally treated Victorian lignite, which imposes a non-predictive burn rate based on crank angle.

Its single term form is

$$C_A = \left(\frac{D_A}{2.302^{-(1+E_A)} - 0.105^{-(1+E_A)}}\right)^{-(1+E_A)}$$

where:

C_A = Weibe constant for part of the combustion

D_A = duration of that part of the combustion (°)

E_A = exponent for that part of the combustion

In the three-term form used in the model, the combustion profile is separated into three section, a premix phase, a main diffusive phase and a tail diffusive phase. With these three phases an overall expression for the fraction of fuel consumed is as follows:

$$F_t = 1 - (F_P + F_d)$$

$$\begin{aligned}\mathcal{F}_{Fuel}(\theta) = {} & F_P(1 - e^{-C_p(\theta - \mathcal{T}_{SOI} - \mathcal{T}_{IgnD})^{(E_p+1)}} + \\ & F_d(1 - e^{-C_d(\theta - \mathcal{T}_{SOI} - \mathcal{T}_{IgnD})^{(E_d+1)}} + \\ & F_t(1 - e^{-C_t(\theta - \mathcal{T}_{SOI} - \mathcal{T}_{IgnD})^{(E_t+1)}}\end{aligned}$$

where:

$\mathcal{F}_{Fuel}(\theta)$ = Fraction of fuel burnt at crank angle θ

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[4] Wiebe I., Halbempirishe Formel dur die Verbrennungsgeschwindigkeit, in Krafstoffaufbereitung und Verbrennung bei Dieselmotoren, ed. G Sitkei, pp. 156-159, Springer-Verlag, Berlin, 1964

F_P = Fraction of fuel burnt in premix phase

F_d = Fraction of fuel burnt in diffusive phase

F_t = Fraction of fuel burnt in tail phase

The values of the constants can be varied to match actual heat release data from experimental data. In the model this has been done with the data for coal, while recommended values have been used for diesel.

During the exhaust phase the cylinder contents discharge to an exhaust chamber, which is assumed to remain at a constant pressure.

To calculate the exhaust mass flow, compressible flow through the exhaust valve in both choked and un-choked conditions must be modeled – based on the criteria of Streeter and Wiley.

The effective area for the exhaust port is calculated as the annular area created between the actual exhaust port and the exhaust valve as it is opened multiplied by a discharge coefficient. The lift profile is modeled initially with a sinusoidal function based on a specified lift rate. The area is then unchanging until the valve closes again based on the same lift rate. The shape of the curve can be varied by changing the value of the lift rate as well as the opening and closing positions.

3.4.2.5 Base Engine Parameters

The model was based on engine parameters obtained from MAN Energy Solutions, and missing parameters (some key information are proprietary) estimated from best available literature data – e.g., valve timing. The procedure was to:

- Obtain a reasonable fit with published data using diesel fuel, and using the same parameters repeat for PRB coal assuming 50 and 55wt% coal in the fuel (Cases PRB-1 and PRB-2 respectively).
- Repeat the calculations for two different firing strategies: PRB-3--fixed heat input rate and PRB 4--fixed peak combustion pressure. These cases were included to simulate likely operating extremes using MRC (because the water content and heat release rate are significantly different from diesel fuel oil, resulting in lower combustion pressure).

The ignition delay for fuel oil was 2.5 ms, and for MRC 5 ms was used (experimentally determined for hydrothermally treated Victorian brown coal).

3.4.2.6 Results

The full set of modeling results are presented in CSIRO DICE Study Report in Appendix C. The modeling results for the four combinations described above show that Cases PRB-1 and PRB-2 (with the same heat input as for diesel fuel oil) give the closest match in engine performance, with:

- Thermal efficiency of 45.1-45.8% LHV.
- A 40 bar (15%) reduction in the peak combustion pressure.
- A decrease in power output of 6-8%.

- An increase in coal loading from 50 to 55%, giving an increase in thermal efficiency of 0.7% points, or a decrease in the heat rate of 1.6%.

These findings fully confirmed the findings from the conceptual design study. **Consequently, it was decided to continue the pre-FEED study with the DICE engine performance used in the conceptual design study.**

The modeling results with the same peak pressure as for diesel fuel oil, Cases PRB-3 and PRB-4, gave a radical change in engine output and exhaust conditions. If practical (at this point not deemed to be likely), this method of firing would

- Increase power output by around 68%.
- Increase exhaust temperature significantly and reduce the oxygen content to 6-7 mol% (and thereby increase CO content).
- Reduce engine thermal efficiency by 4.5% points compared to diesel fuel.
- Overall, this option would be best suited for plants additional heat integration – including with waste heat recovery by turbo compounding and/or steam plant, or post-combustion capture of CO_2.

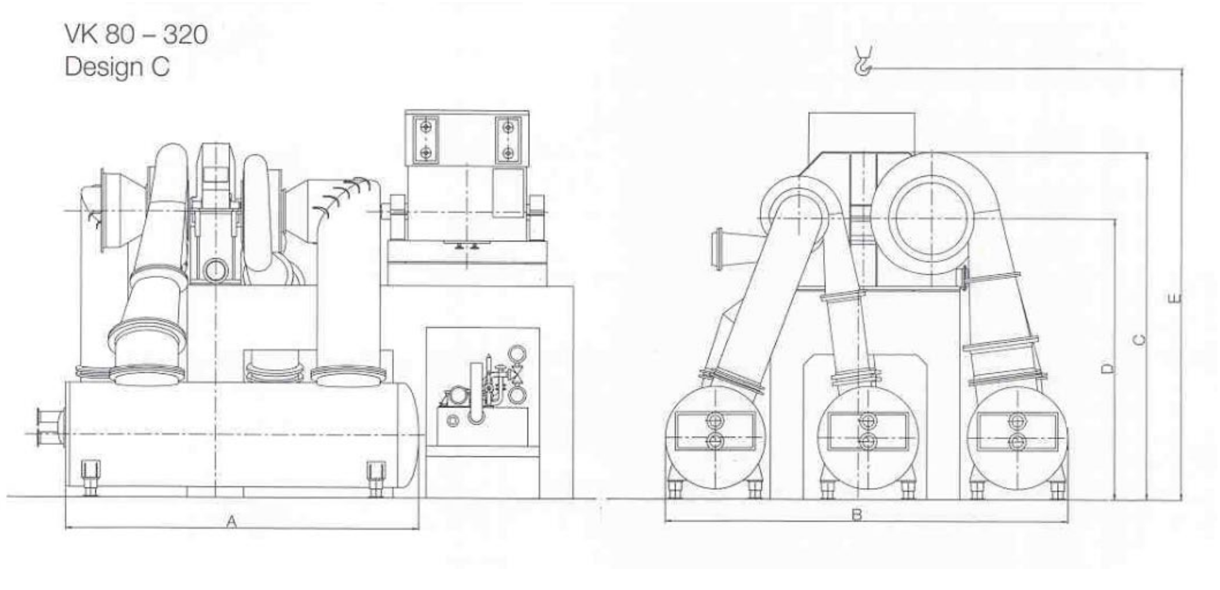
Section 4 DICE CRCC Other Major Plant Components

The remaining major plant system components were previously described in the Phase 1 Conceptual Design Report and reported here for completeness and clarity. These system components are standard off-the-shelf equipment that are commercially available and do not need further development.

4.1 MAIN AIR COMPRESSOR

The main air compressor (MAC) is an integrally-geared, intercooled centrifugal process compressor, which supplies the charge air to the DICE. For the present plant concept, Siemens Turbocompressor STC-GV (200-3) is considered. The compressor package includes the main driver (electric motor), air inlet filter, auxiliary support systems and the control system. The compressor has three stages with a 78 in. first stage impeller. Power consumption is about 110 hp (about 85 kW) per lb/s of airflow. The unit can be turned down to 50 percent flow with cooled bypass.

Figure 4-1
Main Air Compressor (MAC) Plane View (Siemens)



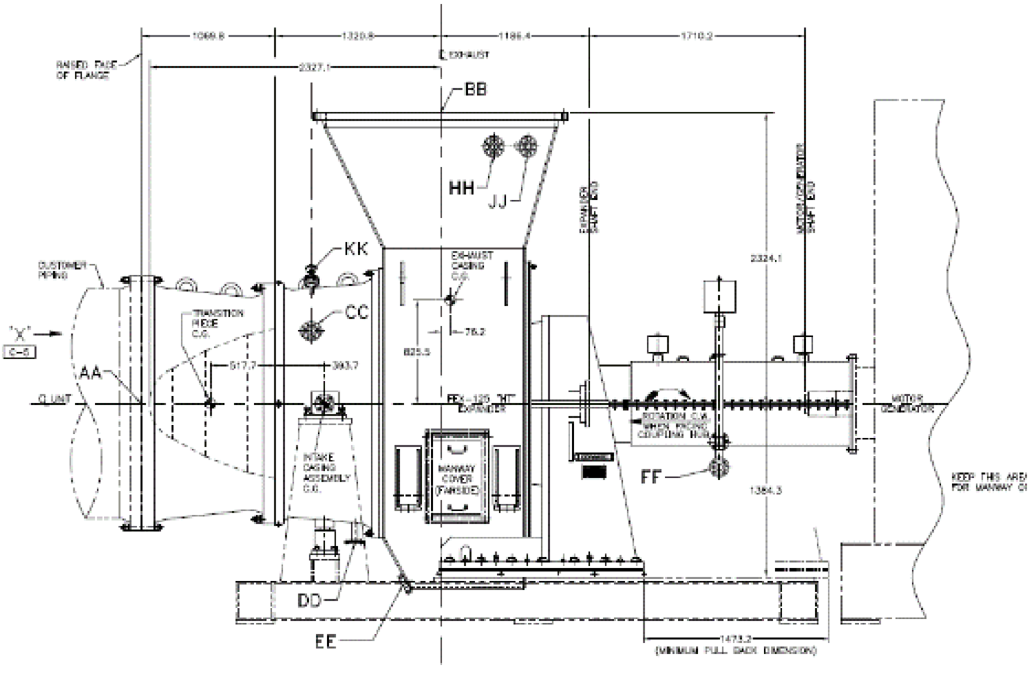
A: 8,490 mm (overall length), B: 10,400 mm (width), C: 8,500 mm (overall height), D: 6,900 mm (shaft centerline height), E: 9,500 mm (crane hook height)

4.2 HOT GAS EXPANDER

The hot gas expander (HGE) is a product of Baker Hughes (BHGE, formerly Nuovo Pignone of General Electric). BHGE had previously designed and commissioned several units of the same frame size proposed for this application (up to a pressure ratio of 4 and inlet temperature of 1,400 °F). An elevation view of the HGE is shown in Figure 4-2. The machine has four major parts: Intake casing and nose cone, rotor assembly, inner exhaust casing and exhaust casing. The rotor assembly comprises the following parts: shaft, rotor disc (from austenitic nickel-based superalloy), seal ring, tie bolt and rotor blades. At 4 bara and 760 °C inlet conditions, the unit can generate about 140 kW per lb/s of gas flow. At the introductory pre-FEED conditions, i.e., pressure ratio of about 3.6 and inlet temperature of about 980°F, the specific power output is about 95 kW per lb/s.

Hot gas turbo-expanders are widely employed in *Fluid Catalytic Cracking* (FCC) industry for conversion of flue gas pressure into useful shaft power. For reliable operation and long blade life (up to four years before replacement), catalytic fines in the flue gas must be removed prior to entry into the expander[5]. Otherwise, extremely abrasive particles can catastrophically damage the blades and casing walls within a few hundreds of hours of operation.

Figure 4-2
Baker Hughes Hot Gas Expander (HGE) Elevation View



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[5] Catalytic (or catalyst) fines, cat fines in short, are hard aluminum and silicon oxide particles that are normally present in heavy fuel oil. For refineries relying on catalytic cracking, cat fines are added to the crude oil to enhance low temperature fuel cracking.

4.3 THIRD-STAGE SEPARATOR

For the hot gas expander, BHGE requires that the abrasive particle concentration in the flue gas to the expander shall be maintained at less than 100 ppm. Furthermore, abrasive particle size distribution should not exceed 12 microns with D75 of two microns. In FCC applications, cat fines are removed in large-diameter primary/secondary cyclones in the FCC regenerator and in the "third-stage separator" (TSS) prior to entry into the HGE.

In refineries, typically, 2 to 8 primary and 2 to 8 secondary cyclones are utilized in FCC regenerators because of mechanical constraints and pressure drop concerns. These cyclones have a fairly large diameter, which restricts the amount of centrifugal acceleration which can be achieved. These cyclones let particles below 15 to 20 micron range pass through. Thus, a Third-Stage Separator (TSS) is installed upstream of the turbo-expander to reduce the catalyst fine loading and protect the blades. In essence, TSS is a containment vessel with a multitude of small-diameter cyclones inside. They are designed to withstand very abrasive service at a temperature of 1,450 °F. As such, TSS is the ideal choice for particle removal equipment in DICE CRCC.

4.4 HRSG

The HRSG is single-pressure with no-reheat and includes the SCR and CO catalyst sections. It is equipped with a duct burner upstream of the HP superheater section. The scope of supply of the HRSG vendor is complete from the combustion turbine outlet flange through the exhaust stack including all of the required pressure parts necessary to generate the desired HP steam production, LP system for generation of deaerating steam (either to an integral deaerator supplied by the vendor or a remote deaerator supplied by others), interconnecting ASME Section I Code piping local to the boiler, ASME boiler trim including feedwater control valve stations and water and steam flow measurement devices, recirculation system to elevate the temperature of the incoming condensate to 60 °C (140 °F), exhaust stack with CEMS ports, ladders, platforms and stair-tower.

During the study, several design modifications are adopted:

- The LP section is omitted; condensate return from the PCC stripper reboiler at a high pressure (i.e., above 50 psia), operating the deaerator at a high pressure (say, 45 to 50 psia) and venting steam is sufficient to maintain the dissolved O_2 limit (typically, 7 ppb).
- When the PCC block is off-line, steam extracted from the HP section is utilized to heat the condensate coming from the steam turbine condenser for deaeration.

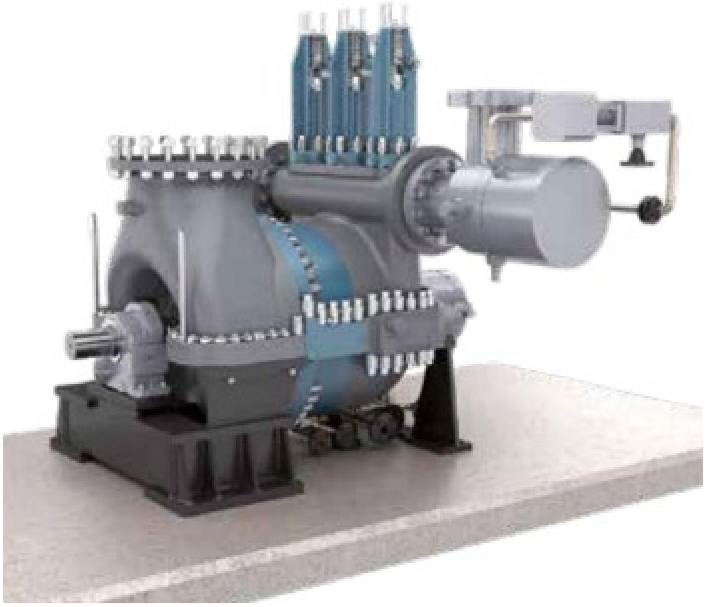
Sulfuric acid dew point is calculated as 291 °F (144 °C). Condensate temperature at the economizer inlet is 283 °F (139 °C) (247 °F [119 °C] when PCC block is offline). In order to ensure minimum tube surface temperature to prevent sulfuric acid condensation on the economizer tubes, the feedwater is recirculated from the economizer discharge to economizer inlet to maintain 150 °C (302 °F) tube temperature.

The HRSG is supplementary (or "duct") fired with natural gas to produce the requisite amount of steam for the MEA stripper reboiler in the PCC plant.

4.5 BACK-PRESSURE STEAM TURBINE (BPST)

The study concept incorporates PCC with amine-based chemical absorption technology. The main purpose of the bottoming cycle is to supply 60 psia nominally saturated steam to the PCC stripper's kettle reboiler. This precludes the utilization of an efficient bottoming cycle design with a condensing steam turbine. The steam turbine in the plant is a backpressure, non-condensing unit, nominally rated at 20,000 hp, which can be supplied off-the-shelf by a multitude of OEMs, e.g., Siemens' Dresser-Rand (D-R) subsidiary. The specific unit that fits the requirements of the application is D-R R/RS standard multi-stage steam turbine, as shown in Figure 4-3. This machine can handle steam inlet conditions up to 915 psia and 900°F. It is designed in compliance with API 611/612 standards with impulse-type blading. The steam turbine rating can be up to 33,500 hp and turbine speed is 15,000 rpm (or less depending on the rating). In this conceptual design, steam conditions are set to 650 psia and 750°F. The turbine is connected to the generator via a gearbox.

Figure 4-3
Dresser-Rand DR R/RS Type Steam Turbine



4.6 LP CONDENSING TURBINE AND SURFACE CONDENSER

Additionally, the DICE CRCC plant is designed for maximum power generation with the addition of a low-pressure (LP) condensing turbine for use exclusively when the PCC is offline. The turbine generates additional power from the steam that is normally routed to the PCC when it is in operation.

The LP turbine is connected to the generator via a SSS ("triple S") clutch. The clutch separates the LP turbine from the generator when the PCC is online. When the PCC is offline, steam from the backpressure is routed to the LP turbine, which starts spinning and the SSS clutch automatically engages for additional power generation. The condenser pressure during LP turbine operation is set to 2.5 in Hg. Condenser cooling water system forms a closed loop with the plant cooling tower.

4.7 DIRECT CONTACT CAUSTIC SCRUBBER/COOLER

For the 100 MWe DICE CRCC plant, a direct contact cooler (DCC) with caustic injection is used to cool the flue gas and remove the bulk of the SOx in the flue gas. This is a packed bed absorber with circulating water to condense out most of the moisture in the flue gas feed. In the DCC, water is directed downward through a packing media to counter the upward flow of the flue gas and to cool it to the required temperature. It also removes acid gases down to around 10 ppm SO_2 equivalent, using caustic injection as determined by pH control.

4.8 POST-COMBUSTION CO_2 CAPTURE (PCC) PLANT

A single-train MEA-based PCC plant treats the flue gas leaving the HRSG to recover 90 percent of the CO_2. The PCC plant consists of two sections: a CO_2 Capture Plant to extract the CO_2 from the flue gas; and a CO_2 Compression Plant to pressurize the CO_2 product for delivery to final sequestration. The CO_2 Capture Plant will be designed with state-of-the-art generic 30 wt% MEA technology. All equipment in the CO_2 Capture Plant is constructed of stainless steel to minimize corrosion effects associated with 30 wt% MEA.

4.8.1 CO_2 Capture Plant

The CO_2 capture plant process scheme consists of flue gas CO_2 absorption and amine solution regeneration.

A flue gas blower located between the scrubber and absorber boosts the pressure of the flue gas in order to overcome the pressure drop associated with the CO_2 absorber. The boosted flue gas with enters the bottom of the absorber column and is scrubbed counter-currently by lean 30 wt% MEA solution to remove 90 percent of its CO_2 content. The CO_2-depleted flue gas continues to travel upwards to the water wash section of the tower, where it is contacted counter-currently with wash water to remove any amine and volatile organic compounds (VOCs) present in the gas, before it is routed to the stack for venting to atmosphere.

The CO_2-rich MEA solvent is collected at the bottom of the absorber and pumped to the stripper column for CO_2 regeneration. Heat is recovered in a rich/lean amine heat exchanger to recover some of the energy in the hot lean amine to minimize steam consumption in the stripper reboiler.

The heated rich solution is then stripped of CO_2 in a reboiled amine stripper to regenerate the lean MEA solution. Overhead vapor from the stripper is cooled with cooling water in an overhead condenser and sent to a reflux drum. The vapor leaving the drum is the recovered CO_2 and needs to be compressed in the CO_2 compression plant before it can be delivered to the battery limit.

The stripper reboiler, a kettle-type heat exchanger, is heated with 60 psia saturated steam leaving the BPST to generate the vapor used to strip the CO_2 from the MEA solution. The steam is condensed in the reboiler and is pumped back to the HRSG to be heated by the hot flue gas again.

4.8.2 **CO_2 Compression Plant**

The CO_2 from the CO_2 capture plant needs to be delivered to the battery limit at 2215 psia. This is accomplished first by compressing the CO_2 vapor to 1,315 psia in a 3-stage centrifugal CO_2 compressor with inter-stage cooling. Each stage has an average compression ratio of approximately 4. The cooled supercritical CO_2 at 1,315 psia is then pumped to the final delivery pressure of 2,215 psia (152 bara).

In order to meet the 50 ppm water specification for the CO_2 product, the CO_2 is dried in a heatless dehydration unit after the second stage of compression at approximately 365 psia. This unit is a pressure swing absorption system that utilizes molecular sieve adsorbents to remove water. It consists of two tanks storing the adsorbents and alternating with each other in drying the inlet gas. About 7 percent of the inlet gas volume is purged in a stream containing the adsorbed moisture. This purge stream is recycled back to the first stage of CO_2 compression where the moisture is removed in the first stage knockout. The net condensate collected from the CO_2 compression section is sent back to the amine stripper for recovery.

Section 5 DICE CRCC Plant Performance

5.1 PROCESS FLOW DIAGRAM

The overall DICE CRCC power plant PFD is shown in Figure 5-1 and comprises the following:

- Coal beneficiation plant
- 5 DICE (nominally 20 MWe each)
- 1 main air compressor (MAC)
- 1 hot gas expander
- Bottoming cycle consisting of HRSG with natural gas duct firing and back pressure steam turbine
- 30 wt% MEA-based PCC unit capturing 90 percent of CO_2 in the flue gas

The overall cycle is described as follows:

- Charge air for the DICE is supplied by the MAC (an integrally geared and intercooled process compressor)
- Exhaust gas from the DICE generates additional power in a hot gas expander
- Gas turbine exhaust is utilized in a natural gas duct fired HRSG to produce enough steam for CO_2 capture
- Superheated steam produced in the HRSG is expanded in a backpressure steam turbine (BPST) to generate additional power
- BPST exhaust steam is desuperheated and sent to the PCC amine stripper reboiler, where its latent heat of condensation is used to regenerate the lean MEA solution
- The hot condensate leaving the stripper reboiler is routed back to the HRSG to be heated and make steam

Additional process flow diagrams depicting in more detail, the CO_2 capture plant, and CO_2 compression plant, are shown in Figure 5-2 and Figure 5-3 respectively. The coal beneficiation plant simplified block flow diagram and detailed process flowsheet have previously been shown in Figure 2-2 and Figure 2-3 respectively.

5.2 HEAT AND MATERIAL BALANCE

The corresponding heat and material balance details of the major streams shown in Figure 5-1 are presented in Table 5-1.

Figure 5-1
100 MWe Nominal DICE CRCC Process Flow Diagram

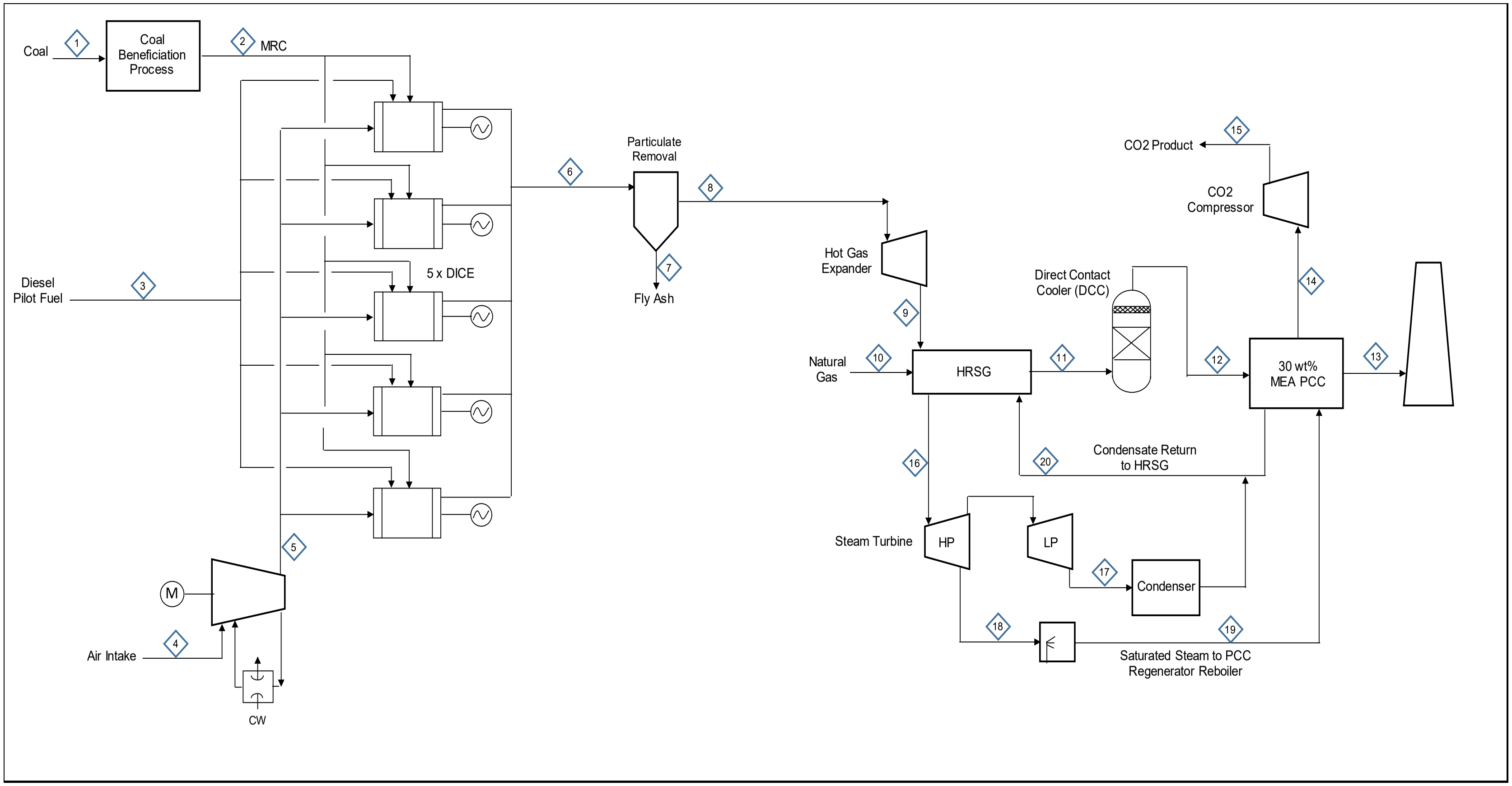


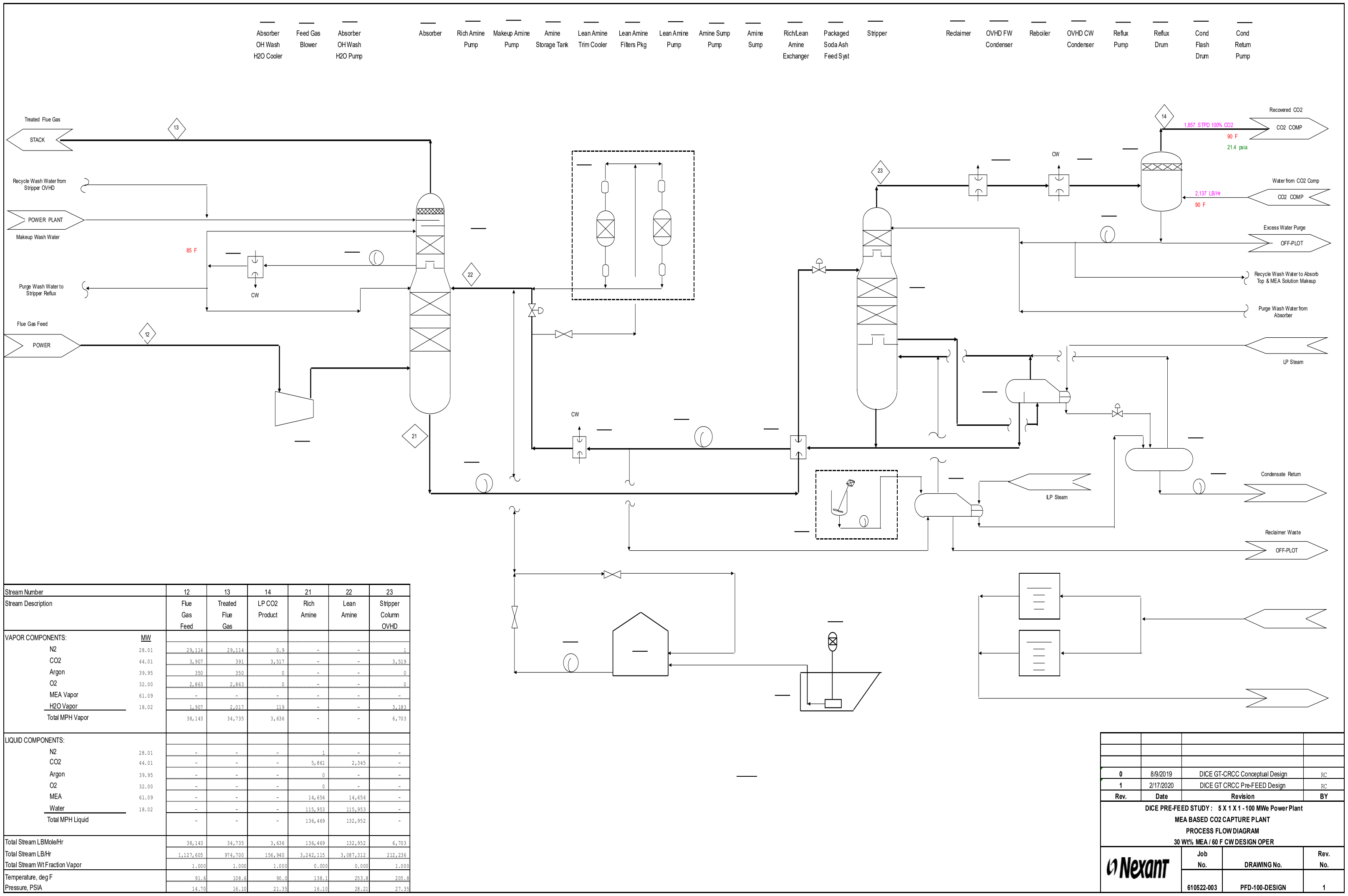
Table 5-1
100 MWe Nominal DICE CRCC Stream Table

V-L Mole Fraction	1	2	3	4	5	6	7	8	9	10
N2	0.0000	0.0000	0.0000	0.7729	0.7729	0.7116	0.0000	0.7116	0.7116	0.0000
O2	0.0000	0.0000	0.0000	0.2074	0.2074	0.1006	0.0000	0.1006	0.1006	0.0000
H2O	0.0000	0.0000	0.0000	0.0101	0.0101	0.0990	0.0000	0.0990	0.0990	0.0000
CO2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0799	0.0000	0.0799	0.0799	0.0000
Ar	0.0000	0.0000	0.0000	0.0093	0.0093	0.0086	0.0000	0.0086	0.0086	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0003	0.0000	0.0003	0.0003	0.0000
SO3 (ppmvd)	0.0000	0.0000	0.0000	0.0000	0.0000	17	0.0000	17	17	0.0000
Total	**0.0000**	**0.0000**	**0.0000**	**1.0000**	**1.0000**	**1.0000**	**0.0000**	**1.0000**	**1.0000**	**0.0000**
Natural Gas Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	10.6
V-L Flowrate, klb/hr	0	0	0	1085.9	1085.9	1178.6	0	1178.6	1178.6	10.6
V-L Flowrate, lbmol/hr	0	0	0	37631	37631	40936	0	40936	40897	614
Coal Flowrate, klb/hr	148.8	0	0	0	0	0	0	0	0	0
Diesel Flowrate, klb/hr	0	0	1.7	0	0	0	0	0	0	0
Slurry Flowrate, klb/hr	0	91.9	0	0	0	0	0	0	0	0
Ash, klb/hr	0	0	0	0	0	1.1	1.1	0	0	0
Pressure, psia	--	--	--	14.7	72.5	56.3	--	56.3	15.3	430
Temperature, °F	--	--	--	59.0	158.0	985.8	--	985.8	642.2	80

Table 5-1 (continued)
100 MWe Nominal DICE CRCC Stream Table

V-L Mole Fraction	11	12	13	14	15	16	17	18	19	20
N2	0.7011	0.7633	0.8382	0.0002	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
O2	0.0689	0.0751	0.0824	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	0.1271	0.0500	0.0581	0.0326	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000
CO2	0.0941	0.1024	0.0112	0.9670	0.9997	0.0000	0.0000	0.0000	0.0000	0.0000
Ar	0.0084	0.0092	0.0101	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO3 (ppmvd)	46	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**
Natural Gas Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	0
V-L Flowrate, klb/hr	1189.2	1127.6	974.7	156.9	154.8	263.5	0	263.4	263.6	263.6
V-L Flowrate, lbmol/hr	41529	38143	34735	3636	3518	14625	0	14620	14632	14632
Coal Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	0
Diesel Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	0
Slurry Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	0
Ash, klb/hr	0	0	0	0	0	0	0	0	0	0
Pressure, psia	14.85	14.70	16.1	21.4	2215	671.4	--	63.0	60.0	54.1
Temperature, °F	345.4	91.6	108.6	90.0	90.0	753.5	--	296.6	293.7	286.1

Figure 5-2
MEA-Based CO_2 Capture Plant Process Flow Diagram



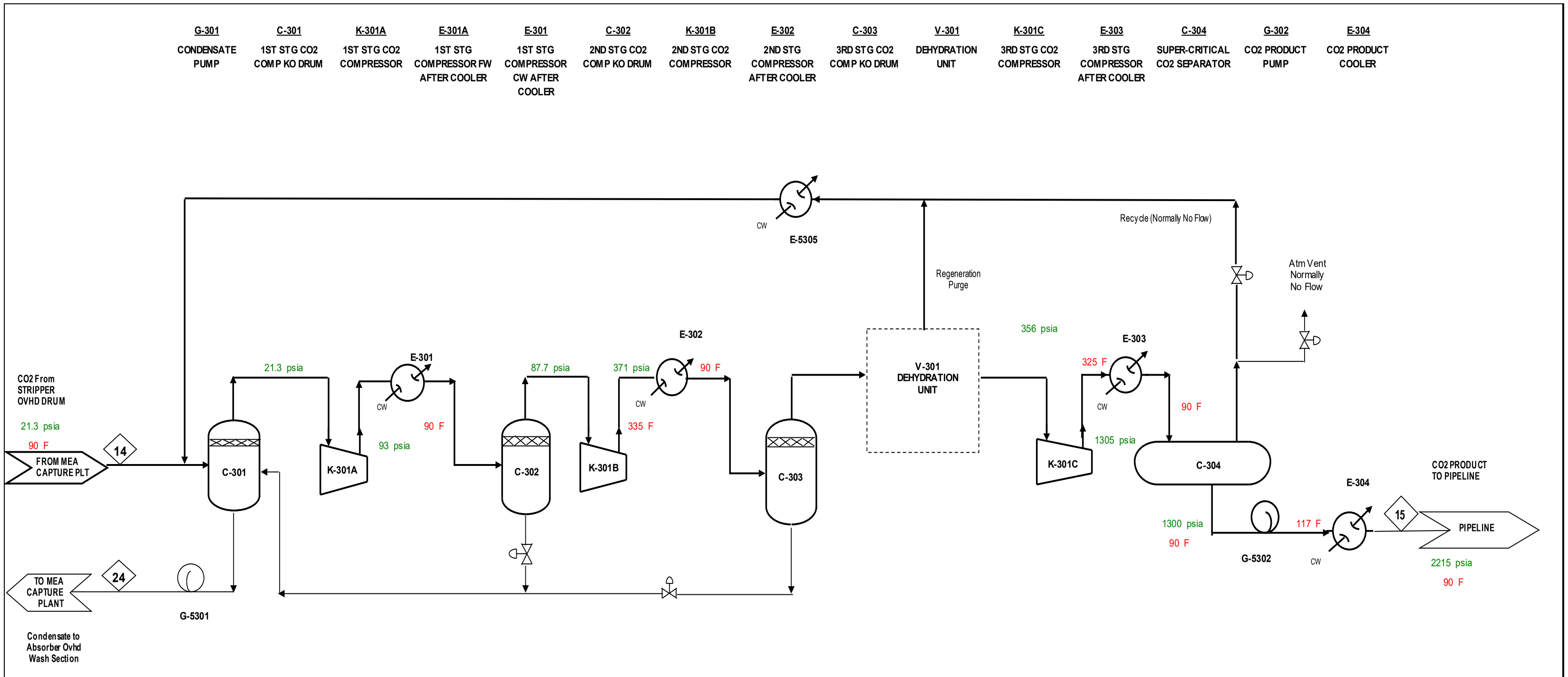
Stream Number		12	13	14	21	22	23
Stream Description		Flue Gas Feed	Treated Flue Gas	LP CO2 Product	Rich Amine	Lean Amine	Stripper Column OVHD
VAPOR COMPONENTS:	MW						
N2	28.01	29,114	29,114	0.9	-	-	1
CO2	44.01	3,907	391	3,517	-	-	3,519
Argon	39.95	350	350	0	-	-	0
O2	32.00	2,863	2,863	0	-	-	0
MEA Vapor	61.09	-	-	-	-	-	-
H2O Vapor	18.02	1,907	2,017	119	-	-	3,183
Total MPH Vapor		38,143	34,735	3,636	-	-	6,703
LIQUID COMPONENTS:							
N2	28.01	-	-	-	1	-	-
CO2	44.01	-	-	-	5,861	2,345	-
Argon	39.95	-	-	-	0	-	-
O2	32.00	-	-	-	0	-	-
MEA	61.09	-	-	-	14,654	14,654	-
Water	18.02	-	-	-	115,953	115,953	-
Total MPH Liquid		-	-	-	136,469	132,952	-
Total Stream LBMole/Hr		38,143	34,735	3,636	136,469	132,952	6,703
Total Stream LB/Hr		1,127,605	974,700	156,940	3,242,115	3,087,312	212,236
Total Stream Wt Fraction Vapor		1.000	1.000	1.000	0.000	0.000	1.000
Temperature, deg F		91.6	108.6	90.0	138.1	253.8	205.8
Pressure, PSIA		14.70	16.10	21.35	16.10	28.21	27.35

Rev.	Date	Revision	BY
0	8/9/2019	DICE GT-CRCC Conceptual Design	RC
1	2/17/2020	DICE GT CRCC Pre-FEED Design	RC

DICE PRE-FEED STUDY : 5 X 1 X 1 - 100 MWe Power Plant
MEA BASED CO2 CAPTURE PLANT
PROCESS FLOW DIAGRAM
30 Wt% MEA / 60 F CW DESIGN OPER

Job No.	DRAWING No.	Rev. No.
610522-003	PFD-100-DESIGN	1

Figure 5-3
CO_2 Compression Plant Process Flow Diagram



Stream No.		14	24	15
Stream Name		LP CO2 Product	Condensate	CO2 Product
Component	MW	lbmol/hr	lbmol/hr	lbmol/hr
N2/Ar	28.15	0.9	0	0.9
O2	32	TRACE	0	TRACE
CO2	44.011	3516.6	0.1	3516.6
H2O	18.016	118.6	118.6	0.0
MEA	61.08	TRACE	TRACE	0
Total	lbmol/hr	3636.2	118.7	3517.5
	lb/hr	156933	2141	154793
Actual Flow	GPM	-	4.3	379
Vapor Flow	MMSCFD	33.1	-	-
Temp	°F	90	88	90
Pressure	psia	21	21	2215

Notes
=========
1) All information show n on this diagram or data sheet represent estimatons for given operations and are provided for pre-feasibility evaluation purposes based on Nexant's in-house data from similar applications. The information show n represent projected best achievable performance for generic inhibited MEA processes. While useful for studies, Nexant does not guarantee the accuracy and completeness of the information show n. Actual performance and design specifications and guarantees are the responsibilities of the selected technology licensors.

2) All rates show n are for 1 train. One identical trains are required for DICE.

3) Normal consumptions for given operation are listed in the utlities summary data sheet. Equipment design sizes are show n under the major equipment listing data sheet.

Rev No.	Date	Revision	Engineer	Checked	Approval
0	8/9/2019	DICE GT CRCC Conceptual Des	RC		
1	2/17/2020	DICE GT CRCC Pre-FEED	RC		

Nexant Inc.
San Francisco, CA

DICE GT-CRCC PRE-FEED DESIGN : 5 X 1 X 1

Process Flow Diagram
CO2 COMPRESSION/ 60 F CW DES OPERATION

Job No.	Drawing No.	Revision No.
610522-003	DS-PFD-1300-DESIGN	1

5.3 DICE CRCC PLANT NET EFFICIENCY

Table 5-2 summarizes the overall performance based on the design of the nominal 100 MWe DICE CRCC power plant. Overall fuel mix to the plant consists of 71.5 percent coal, 3.5 percent diesel fuel and 25.0 percent natural gas, on an LHV basis. The net efficiency of the plant is 30.8 percent on an LHV basis (29.1 percent HHV), not including the heating value associated with the rejects as these do not participate in the combustion reactions. With the heating value of the rejects included i.e. efficiency is calculated based on total heating value from the raw PRB coal, the overall efficiency is 18.0 percent LHV (17.2 percent HHV).

Table 5-2
Power Summary and Net Efficiency

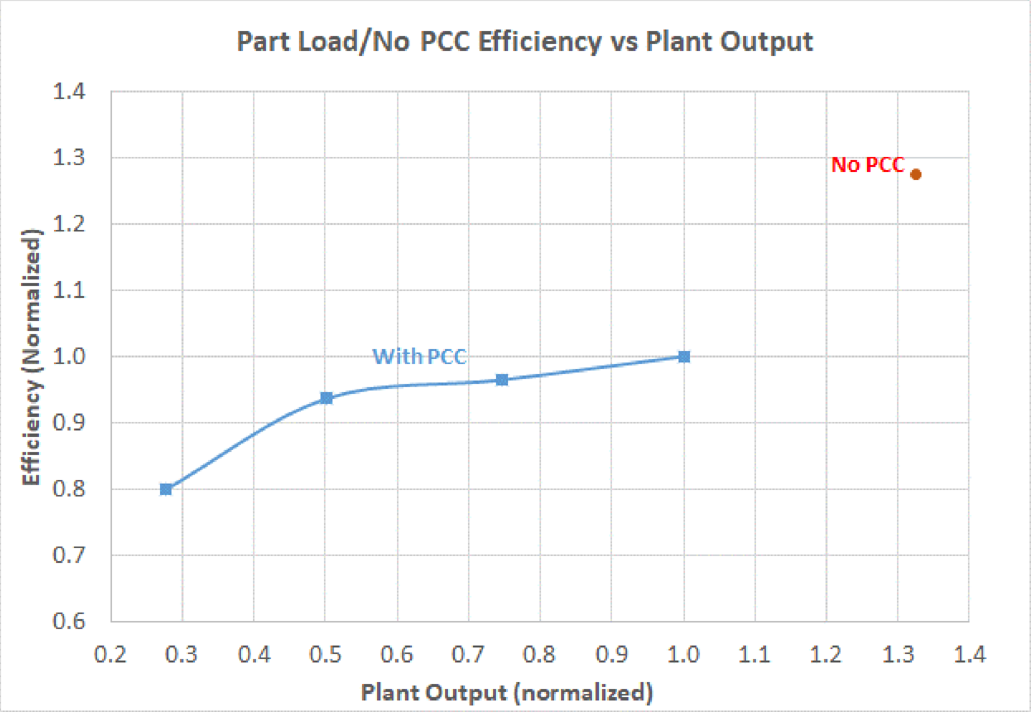
Power Summary	
POWER GENERATION, kWe	
5 x DICE	78,730
Turboexpander	31,787
Steam Turbine	14,676
Total Power Generation	**125,192**
AUXILIARY LOAD SUMMARY, kWe	
MRC Fuel Prep	5,472
Main Air Compressor	26,301
SCR	88
Fabric Filter	69
Boiler Feed Water Pump	261
Economizer Recirculation Pump	5
Steam Turbine Auxiliaries	31
DCC Circulating Pump	400
CO_2 Capture	2,549
CO_2 Compression	7,838
Circulating Water Pumps	2,407
Makeup Water Pumps	70
Cooling Tower Fans	977
Wastewater Pumps	14
Miscellaneous Auxiliaries	135
Transformer Losses	626
Total Auxiliaries, kWe	**47,242**
Net Power, kWe	**77,950**
As-Received PRB Coal Feed, lb/hr	148,818
Beneficiated Coal Slurry Fuel Feed, lb/hr	91,934
Diesel Fuel Feed, lb/hr	1,651
Natural Gas Feed Flow, lb/hr	10,640
Coal LHV Thermal Input, MMBtu/hr	619
Diesel LHV Thermal Input, MMBtu/hr	30
Gas LHV Thermal Input, MMBtu/hr	216
Total LHV Thermal Input, MMBtu/hr	**865**
LHV Efficiency %, based on beneficiated coal feed	**30.8%**
%, based on as-received PRB coal feed	**18.0%**

Coal HHV Thermal Input, MMBtu/hr Diesel HHV Thermal Input, MMBtu/hr Gas HHV Thermal Input, MMBtu/hr	643 32 239
Total HHV Thermal Input, MMBtu/hr	**914**
HHV Efficiency %, based on beneficiated coal feed	**29.1%**
HHV Efficiency %, based on as-received PRB coal feed	**17.2%**

Plant part load performance (normalized) is summarized in Figure 5-4. The horizontal axis indicates the part load net output expressed as a fraction of the full load (5 DICE, with PCC) net output, and is based on an operational range of two DICE through the maximum of all five DICE. The right-most point on the graph shows the net efficiency of the plant when the PCC is not in service and steam is routed to a condensing turbine to generate additional power instead of the PCC reboiler.

The coal beneficiation plant is expected to operate in batch mode and will run intermittently at full capacity to fill up the beneficiated coal slurry buffer tank when its levels are low. The auxiliary load consumed by the coal beneficiation plant is hence not included in the part load performance plot.

Figure 5-4
DICE CRCC Part Load Performance



5.4 OVERALL UTILITIES BALANCE

The overall utilities balance that summarizes the DICE CRCC plant's various utilities consumption and generation, including power, steam, water, water-cooled and air-cooled duties, are shown in Table 5-3.

5.5 DICE CRCC WATER BALANCE

Water demand represents the total amount of water required for a particular process. Some water is recovered within the process and is re-used as internal recycle. The difference between demand and recycle is raw water withdrawal. Raw water withdrawal is defined as the water removed from the ground or diverted from a POTW for use in the plant and was assumed to be provided 50 percent by a POTW and 50 percent from groundwater. Raw water withdrawal can be represented by the water metered from a raw water source and used in the plant processes for all purposes, such as DCC makeup, BFW makeup, and cooling tower makeup. The difference between water withdrawal and process water discharge is defined as water consumption and can be represented by the portion of the raw water withdrawn that is evaporated, transpired, incorporated into products or otherwise not returned to the water source from which it was withdrawn. Water consumption represents the net impact of the plant process on the water source balance.

Table 5-4 summarizes the water balance for the 100 MWe DICE CRCC power plant.

Raw water demand is minimized by reusing the condensate (125 gpm) from the flue gas DCC column in the PCC plant as cooling tower makeup water. Additionally, cooling tower blowdown water (228 gpm) is used for slurrying both the tailings and beneficiated coal to be fed to the DICE, thereby minimizing the raw water needed for the overall operation of the plant.

Table 5-3
100 MWe Nominal DICE CRCC Overall Utilities Balance

Item Name	DICE GT-CRCC Elect. Power	Steam 1000 Lbs/Hr				PCC Condensate	Desuperht Condensate	Demin Makeup	Treated Water	Makeup Water		Internal Recycle	Wastewater			Cooling Water		Air Cooling	
	KW	671 psia/ 754 F	HP Exh: 63 psia/ 318 F	'60 psia / 298 F	Deaerator Vent	54 psia/ 286 F				Ground Water	Municipal Water	Recycle	Internal Recycle	Sewage Water	Process Wastewater	CW, MMbtu/hr	C.W. circ. GPM	MMbtu/hr Absorbed	Remarks
DICE-GT CRCC POWER ISLAND																			
COAL BENEFICIATION																			
COAL HANDLING & CONVEYING:	incl																		
COAL BENEFICIATION & SLURRYING:																			
COAL BENEFICIATION	5,472								0.0				114.3		0.0				
DICE																			
DICE MAIN AIR COMPRESSOR	26,301																		
MAIN AIR COMPRESSOR FIN FAN COOLER																120.0	11,984		
DICE #1	(15,746)																		
DICE #2	(15,746)																		
DICE #3	(15,746)																		
DICE #4	(15,746)																		
DICE #5	(15,746)																		
FABRIC FILTER	69																		
TURBOEXPANDER:																			
HOT GAS TURBOEXPANDER	(31,787)																		
STEAM CYCLE:																			
SCR	88																		
HRSG		263.5			(14.4)	(263)	(0.2)	11.8							2.6				
HP STEAM TURBINE	(14,676)	(263.5)	263.5																
DESUPERHEATER			(263.5)	263			0.2												
BFW PUMPS	261																		
ECONOMIZER RECIRCULATION PUMP	5																		
STEAM TURBINE AUXILIARY LOAD	31																		
PCC ISLAND																			
CO2 CAPTURE:																			
DCC												(62.4)							
DCC CIRC COOLER																133.7	13,357		
DCC CIRC COOLER PUMP	400																		
FLUE GAS BLOWER	1,547																		
MEA ABSORBER												(0.7)			(1.1)				
MEA STORAGE MAKEUP TANK												0.7							
WASH WATER COOLER																16.3	1,625		
WASH WATER PUMP	89																		
RICH AMINE PUMP	464																		
MEA STRIPPER REBOILER				(263.3)		263.3													
CONDENSATE RETURN PUMP	65																		
STRIPPER CONDENSER																64.4	6,435		
STRIPPER OVERHEAD RECEIVER												2.1							
STRIPPER REFLUX PUMP	8																		
LEAN AMINE PUMP	376																		
LEAN AMINE COOLER																167.5	16,734		
CO2 COMPRESSION:																			
1ST STAGE CO2 COMPRESSOR	2,820																		
1ST CO2 COMPRESSOR INTERCOOLER																11	1,093		
1ST STAGE CO2 FEED KO DRUM												(2.1)							
2ND STAGE CO2 COMPRESSOR	2,638																		
2ND CO2 COMPRESSOR INTERCOOLER																10	1,030		
3RD STAGE CO2 COMPRESSOR	2,060																		
3RD CO2 COMPRESSOR INTERCOOLER																19	1,944		
SUPERCRITICAL CO2 PUMP	320																		
SUPERCRITICAL CO2 AFTERCOOLER																3	290		
ELECTRICAL AND MISCELLANEOUS																			
MISCELLANEOUS																			
TRANSFORMER LOSSES	626																		
MISCELLANEOUS AUXILIARIES	135																		
SUBTOTAL DICE/PCC ISLAND	**(81,417)**	**0**	**0**	**0**	**(14)**	**0**	**0**	**12**	**0**	**0**	**0**	**(62)**	**114**	**0**	**1**	**545**	**54,492**		
COOLING WATER , COOLING TOWER AND WATER TREATMENT																			
COOLING TOWER:																			
COOLING WATER PRODUCTION									505.1			62.4	(114.3)		(27.6)	(545)	(54,492)		
CIRCULATING WATER PUMP	2,407																		
COOLING TOWER FANS	977																		
DEMINERALIZER																			
DEMIN SYSTEM								(11.8)			15.4				(3.6)				
MU WATER SUPPLY & TREATMENT																			
MU WATER PUMP	70																		
MU WATER FILTER PACKAGE									(505.1)	297.1	297.1				(89.1)				
POTABLE WATER																			
POTABLE WATER TREATMENT											1.1			(1.1)					
WASTEWATER TREATMENT																			
WASTEWATER PUMPS	14																		
SUBTOTAL CW & CT	**3,467**	**0**	**0**	**0**	**0**	**0**	**0**	**(12)**	**0**	**297**	**314**	**62**	**(114)**	**(1)**	**(120)**	**(545)**	**(54,492)**		
OVERALL DICE-CT CRCC	**(77,950)**	**0**	**0**	**0**	**(14)**	**0**	**0**	**0**	**0**	**297**	**314**	**(0)**	**0**	**(1)**	**(119)**	**0**	**0**		

DICE GT-CRCC PRE-FEED UTILITIES SUMMARY	**JOB NUMBER**	**610522.003.01**	
		Drawing No.	**REV.**
REVISIONS		**DS-UTIL-001**	**A**

Table 5-4
100 MWe DICE CRCC Water Balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	gpm	gpm	gpm	gpm	gpm
MRC Slurrying	228	228	0	--	--
Demin Water Makeup	31	--	31	--	31
Demin System Discharge	--	--	--	7	-7
Steam Cycle Blowdown	--	--	--	5	-5
Deaerator Vent	--	--	--	18	-18
DCC Discharge Water	--	-125	--	--	--
MEA Absorber Discharge		-1	--	2	-2
MEA Storage Tank Makeup	1	1	0	--	0
MEA Regenerator Ovhd Makeup	4	4	0	--	--
CO_2 Compression KO Water	--	-4	--	--	--
Cooling Tower Makeup	1,134	125	1,009	--	1,009
Cooling Tower Blowdown	--	-228	--	55	-55
Makeup Water Treatment Net Demand	178	--	178	--	178
Potable Water Demand	2	--	2	--	2
Makeup Water Treatment Discharge	--	--	--	178	-178
Discharge to Sewage	--	--	--	2	-2
Total	**1,579**	**--**	**1,220**	**268**	**952**

5.6 PLANT EMISSIONS

Table 5-5 summarizes the various DICE CRCC plant emissions and control measures undertaken to achieve these emissions. For this report, given the low chloride content (0.01 wt%) in the PRB coal, HCl emissions are estimated to be 0.06 lb/MWh-gross in a worst-case, unabated scenario. However, in the DOE Bituminous Baseline report, SO_2 emissions were utilized as a surrogate for HCl emissions, and HCl was not reported. Similarly, assuming HCl control follows SO_2 emissions control technology per the Bituminous Baseline Report, the HCl emissions for the DICE CRCC plant would be at trace level.

Mercury levels for PRB coal is estimated to be 0.056 ppm on a dry basis. It has been shown in literature than conventional beneficiation methods using cyclones and froth flotation can remove up to 62 percent of the mercury in the coal[6]. Assuming no other mercury control method in the power plant, the mercury emissions as a result of using flotation in the coal beneficiation process is 9 x 10^6 lb/MWh-gross. However, in the presence of emissions control equipment such as the TSS and SCR, whose vanadium-based catalyst promotes the oxidation of elemental mercury Hg to water-soluble Hg^{2+} in the flue gas, which can then be captured in the DCC, the mercury emissions for the DICE CRCC is expected to meet the emissions limits of 3 x 10^6 lb/MWh-gross. If mercury emissions are shown to exceed, the limits, the industry-standard activated carbon injection (ACI) can be utilized to further reduce these emissions. The DOE Bituminous Baseline Report states that a combination of ACI with the above-mentioned control technology can reduce mercury emissions by upwards of 97 percent of mercury, which will easily meet the 3 x 10^6 lb/MWh-gross target.

Table 5-5
Plant Emissions Summary

Pollutant	Env. Target	Est. Emissions	Control Technology
	lb/MWh-gross		
SOx	1.00	Trace (0.000)	DCC + MEA reaction with residual SOx in flue gas to effectively reduce to zero
NOx	0.7	0.7 (estimated)	SCR + MEA reaction with NO_2 to effective scrub out all NO_2, reducing NOx content by 10% (assume 90:10 NO/NO_2 ratio in flue gas) while all NO passes through. While NOx emissions are hard to predict, it has been found that DICE emits half the NOx as engines running on diesel at the same load. Based on CSIRO's experience, DICE exhaust is likely to achieve 350 ppmv NOx or lower, given the longer ignition delay, better mixing of fuel and air, and progressive burn of MRC. At < 350 ppmv NOx in the exhaust, the resulting NOx emissions at the stack will meet the 0.07 lb/MWh-gross emissions limit

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[6] Emissions Control Strategies for Power Plant, Bruce G. Miller, Clean Coal Engineering Technology pp 375-481, 2011

PM	0.09	Trace (0.000)	DCC water wash in PCC plant further scrubs out residual PM in flue gas
Hg	3×10^{-6}	3×10^{6} (estimated)	TSS + SCR + DCC. If mercury is still an issue, activated carbon injection (ACI) can be utilized at a location with appropriate temperature before the cyclone.
HCl	0.010	0.000 (SOx surrogate)	Per Bituminous Baseline Report, SO_2 emissions are used as a surrogate for HCl. Provided the SO_2 emissions limit is not exceeded, it can be assumed per the MATS regulation that the HCL emissions limit is also satisfied as the caustic scrubber and MEA absorber operations are able to remove the HCl.
CO_2	90 percent removal	90 percent removal (221 lb/MWh-net)	30 wt% MEA
VOC	N/A	1 ppm	Water wash at the top of the PCC absorber is expected to remove VOC in flue gas before venting to atmosphere

5.7 POTENTIAL VARIANTS

5.7.1 No Post-Combustion Capture

Implementing post-combustion capture (PCC) to the DICE CRCC system imposes a significant penalty on its efficiency, capital cost, and operating cost, thereby resulting in a high LCOE. A parametric scenario without PCC was evaluated to quantify the performance and cost impact. For this case, exhaust steam from the main steam turbine that would have been diverted to the PCC is sent to a condensing turbine to produce more power, resulting in greater power generation from the steam cycle. Additionally, auxiliary power consumed by the PCC is eliminated, resulting in a 35 percent increase in net power generation. The calculated efficiency of this case is 39.9 percent on an LHV basis (37.7 percent HHV).

Table 5-6 presents a side-by-side comparison of the performance breakdown between the DICE CRCC plant with and without PCC.

Table 5-6
Performance Comparison for DICE CRCC with and without PCC

Description	DICE CRCC with PCC (On-site coal beneficiation)	DICE CRCC No PCC
POWER GENERATION		
DICE	78,730	78,730
Turboexpander	31,787	31,900
Steam Turbine	14,676	31,299
Total Power Generation, kWe	**125,192**	**141,929**
AUXILIARY LOAD SUMMARY, kWe		
Coal Beneficiation	5,472	5,472
Main Air Compressor	26,301	26,277
SCR	88	88
Fabric Filter	69	69
Boiler Feed Water Pump	261	302
Economizer Recirculation Pump	5	310
Steam Turbine Auxiliaries	31	31
DCC Circulating Pump	400	400
CO2 Capture	2,549	0
CO2 Compression	7,838	0
Circulating Water Pumps	2,407	2,117
Makeup Water Pumps	70	60
Cooling Tower Fans	977	859
Wastewater Pumps	15	11
Miscellaneous Auxiliaries	135	135
Transformer Losses	626	710
Total Auxiliaries, kWe	47,243	36,840
Net Power, kWe	**77,949**	**105,089**
As-Received PRB Coal Feed, lb/hr	148818	150435
Coal Slurry Fuel Feed, lb/hr	91934	92932
Diesel Fuel Feed, lb/hr	1651	1669
Natural Gas Feed Flow, lb/hr	10640	12000
Coal LHV Thermal Input, MMBtu/hr	619	625
Diesel LHV Thermal Input, MMBtu/hr	30	31
Gas LHV Thermal Input, MMBtu/hr	216	244
Total LHV Thermal Input, MMBtu/hr	865	899
LHV Efficiency, %	30.8%	39.9%
Coal HHV Thermal Input, MMBtu/hr	643	649
Diesel HHV Thermal Input, MMBtu/hr	32	33
Gas HHV Thermal Input, MMBtu/hr	239	270
Total HHV Thermal Input, MMBtu/hr	**914**	**952**
HHV Efficiency, %	29.1%	37.7%

5.7.2 Centralized Coal Beneficiation Plant

For a small, modular power plant such as the DICE CRCC (< 100 MW for this introductory variant), the performance and cost estimates presented in previous reports suggest that it makes no economic sense to install a coal beneficiation plant on-site, analogous to building a crude oil refinery on-site at every gas station. For the modular DICE CRCC plant to be feasible, there must be multiples of such power plants, each receiving fuel from a centralized coal beneficiation plant, thereby taking advantage of the economies-of-scale benefits that the large central beneficiation plant possesses. The performance and impact of such a scenario is quantified in Table 5-7.

Table 5-7
Performance Comparison for DICE CRCC with On-site and Centralized Coal Beneficiation Plant

Description	DICE CRCC with PCC (On-site coal beneficiation)	DICE CRCC with PCC (Centralized coal beneficiation)
POWER GENERATION		
DICE	78,730	78,730
Turboexpander	31,787	31,787
Steam Turbine	14,676	14,676
Total Power Generation, kWe	**125,192**	**125,192**
AUXILIARY LOAD SUMMARY, kWe		
Coal Beneficiation	5,472	0
Slurry Pumping	incl w/ beneficiation	500
Main Air Compressor	26,301	26,301
SCR	88	88
Fabric Filter	69	69
Boiler Feed Water Pump	261	261
Economizer Recirculation Pump	5	5
Steam Turbine Auxiliaries	31	31
DCC Circulating Pump	400	400
CO2 Capture	2,549	2,549
CO2 Compression	7,838	7,838
Circulating Water Pumps	2,407	2,407
Makeup Water Pumps	70	70
Cooling Tower Fans	977	977
Wastewater Pumps	15	26
Miscellaneous Auxiliaries	135	135
Transformer Losses	626	626
Total Auxiliaries, kWe	47,243	42,282
Net Power, kWe	**77,949**	**82,910**
Coal Slurry Fuel Feed, lb/hr	91934	91934
Diesel Fuel Feed, lb/hr	1651	1651
Natural Gas Feed Flow, lb/hr	10640	10640
Coal LHV Thermal Input, MMBtu/hr	619	619
Diesel LHV Thermal Input, MMBtu/hr	30	30
Gas LHV Thermal Input, MMBtu/hr	216	216
Total LHV Thermal Input, MMBtu/hr	865	865
LHV Efficiency, %	30.8%	32.7%
Coal HHV Thermal Input, MMBtu/hr	643	643
Diesel HHV Thermal Input, MMBtu/hr	32	32
Gas HHV Thermal Input, MMBtu/hr	239	239
Total HHV Thermal Input, MMBtu/hr	**914**	**914**
HHV Efficiency, %	29.1%	31.0%

5.8 ENERGY STORAGE CAPABILITY

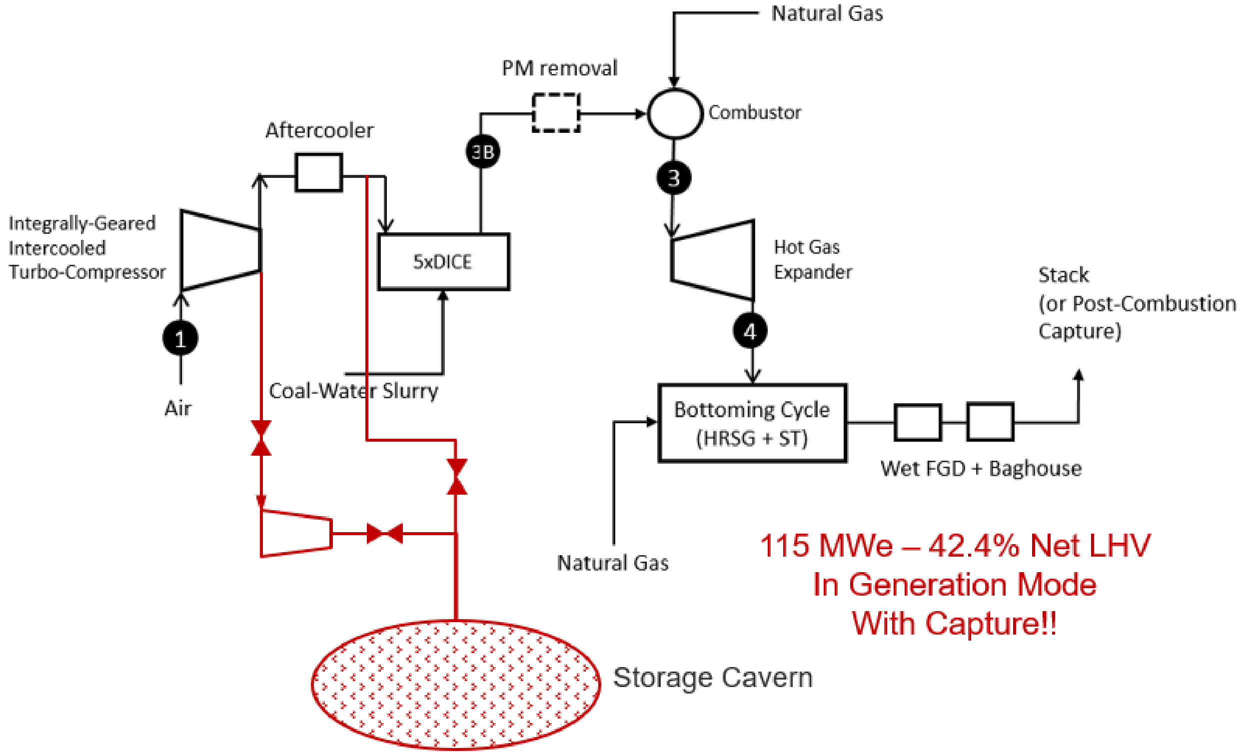
One unique feature of the DICE CRCC concept with separate air compressor and gas turbine/expander trains is its amenability to **compressed air energy storage** (CAES) with *no redesign of plant configuration and/or any major piece of equipment*. The only requirement for DICE CRCC with CAES is the availability of a suitable air storage cavern, e.g., a saline aquifer or depleted natural gas reservoir. DICE CRCC in CAES arrangement is shown in Figure 5-5.

Unlike the existing CAES technology (as demonstrated in Huntsdorf, Germany and McIntosh, Alabama), once constructed and commissioned, DICE CRCC can operate as a straightforward coal-fired power plant or in CAES mode.

In CAES charging mode, the MAC is powered by cheap grid power and supplies air into the storage cavern via a booster compressor (which is the only piece of additional major equipment – the rest is additional piping to/from the cavern and requisite valves), say, at 10 bara.

In CAES generation mode, the MAC is shut down. Charge air to the DICE (at 5 bara) is supplied from the storage cavern through a pressure regulation valve. The rest of the power plant is running in its normal operation mode. In generation mode, even with the PCC on, the plant can deliver 115 MWe at more than 40% net LHV efficiency.

Figure 5-5
DICE CRCC in CAES Mode



It should also be pointed out that the inherent CAES capability of the turbocompound-reheat technology is not limited to DICE (i.e., firing coal fuel). For a standard RICE CRCC with natural gas-fired engines, the same can be accomplished with excellent efficiency (68% net LHV in generation mode) at outputs as low as below 50 MWe (with small, off-the-shelf RICE rated at 5 MWe each). This is described in detail in the Final Report of the DOE/NETL Technical Grant (DE-FE0031618), “Turbocompound Reheat Gas Turbine Combined Cycle”

Section 6 Major Equipment List and Preliminary Plot Plan

Equipment lists for each of the five areas that comprise the overall 100 MWe DICE CRCC plant are provided in this section. These five areas are:

- Coal beneficiation
- DICE CRCC
- CO_2 capture (30 wt%)
- CO_2 compression
- Electrical plant

6.1 COAL BENEFICIATION PLANT

The equipment list for the coal beneficiation plant is provided in Table 6-1.

Table 6-1
Coal Beneficiation Plant Equipment List

Site Quantity	System Code	Description	Rating	Comments
COAL BENEFICIATION EQUIPMENT LIST				
RAW COAL HANDLING				
1	FE-201	Feedstock Coal Receival Dump Hopper Feeder	55 kW	
1	CV-101	Hammer Mill Feed Conveyor	11 kW	Design Capacity/Size: 110 t/h
1	CR-301	Hammer Mill	300 kW	Design Capacity/Size: 42" x 60"
1	CV-201	Surge Bin Feed Conveyor	11 kW	Design Capacity/Size: 110 t/h
1	WT-201	Plant Feed Weigher		
1	BN-301	Surge Bin		Design Capacity/Size: 100 t
1	FE-202	Surge Bin Discharge Feeder	7.5 kW	
PROCESS PLANT				
1	CV-301	Ball Mill Feed Conveyor	7.5 kW	Design Capacity/Size: 110 t/h
1	CR-302	Ball Mill	1,300 kW	Design Capacity/Size: 3.7m x 6.75m
1	PP-301	Ball Mill Cyclones Feed Pump	55 kW	
2	CY-301	Ball Mill Cyclones Cluster		
1	PP-401	Grinding Cyclones Feed Pump	55 kW	
2	CY-401	Grinding Cyclones Cluster		
1	PP-403	Grinding Mill Feed Pump	75 kW	
1	GM-401	Grinding Mill	3,500 kW	Design Capacity/Size: 63 t/h
3	PP-501	Rougher Cell Feed Pump	75 kW	
3	FC-501	Rougher Flotation Cell		
3	PP-521	Cleaner Cell Feed Pump	45 kW	
3	FC-521	Cleaner Flotation Cell		
1	TH-601	Product Thickener	7.5 kW	Design Capacity/Size: 20m ø
1	PP-601	Product Thickener Underflow Pump	11 kW	
1	SM-601	Product Solid Bowl Feed Sump		
2	PP-602	Product Solid Bowl Feed Pump	11 kW	
2	CF-601	Product Solid Bowl	300 kW	Design Capacity/Size: 28 t/h
2	CF-601	Main Drive	200 kW	
2	CF-601	Back Drive	100 kW	
1	PP-605	Solid Bowl Effluent Pump	5.5 kW	

1	CV-601	Product Transfer Conveyor	7.5 kW	Design Capacity/Size: 52 t/h
1	WT-601	Product Weigher		
1	SA-601	Product Cross Belt Sampler	5.5 kW	
1	AN-601	Moisture Meter	1.0 kW	
1	TK-610	Product Slurry Agitation Tank		Design Capacity/Size: 35 m^3
2	TK-620	Product Storage Tank		Design Capacity/Size: 1,000 m^3
1	AG-610	Product Slurry Agitator	15 kW	
1	PP-610	Product Slurry Transfer Pump	7.5 kW	
2	AG-620	Product Slurry Agitator	185 kW	
2	PP-620	Product Distribution Pump	5.5 kW	
1	TH-701	Tailings Thickener	7.5 kW	Design Capacity/Size: 20m ø
1	PP-701	Tailings Thickener Underflow Pump	7.5 kW	
1	PP-901	Process Water Pump	175 kW	
1	PP-510	Plant Water Pump	45 kW	
1	FT-950	Gland Water Filter	0.37 kW	
1	PP-950	Gland Water Pump	22 kW	
2	PP-960	Thickener Area Sump Pump	15 kW	
1	CN-501	Overhead Crane	43 kW	Design Capacity/Size: 20 t
COAL PROCESSING PLANT SERVICES				
1	FL-901	Anionic Flocculant Dosing System	5.55 kW	
1	FL-901a	Polymer Bulk Storage Tank		
1	FL-901b	Blower	3.0 kW	
1	FL-901c	Screw Feeder	0.37 kW	
1	FL-901d	Agitator	1.50 kW	
1	FL-901e	Dust Filter Unit	0.37 kW	
1	FL-901f	Mixing Tank		
1	FL-901g	Dilute Flocculant Storage Tank		
1	FL-901h	Heated Hopper	0.06 kW	
1	FL-901i	Hopper Vibrator	0.25 kW	
2	DP-901	Collector Dosing Pump	0.55 kW	
4	DP-910	Frother Dosing Pump	0.37 kW	
2	DP-930	Dispersant Dosing Pump	0.55 kW	
1	AD-950	Instrument Air Dryer	1.53 kW	
1	AR-901	Air Receiver		

6.2 DICE CRCC MECHANICAL EQUIPMENT

The mechanical equipment list for the main DICE CRCC plant is shown in Table 6-2.

Table 6-2
DICE CRCC Mechanical Equipment List

Site Quantity	System Code	Description	Type	Material	Rating	Capacity (%)	Comments
DICE MECHANICAL EQUIPMENT LIST							
1	AAA	Heat Recovery Steam Generator (HRSG)	Single-Pressure, No-Reheat, Horizontal Gas Flow. With CO Catalyst			1 X 100% Per Unit	276,800 lbs/hr steam @ 668.7 psia & 753.5F
1	AAA	CO Catalyst	Oxidizing Catalyst for 90% CO Reduction			1 X 100% Per HRSG	Provided by HRSG Supplier
1	AAA	HRSG Duct Burner Skid	263 MMBtu/hr			1 X 100% Per HRSG	Provided by HRSG Supplier
1	AAA	Selective Catalytic Reduction (SCR) System For HRSG Flue Gas NOx Reduction	19 % Aqueous Ammonia System			1 X 100% Per HRSG	Provided by HRSG Supplier
1	AB	Steam Turbine Bypass Valve				1 X 100% Per Unit	1
1 Lot	AB	Main Steam Relief Valve Silencers		CS		1 Lot Per HRSG	1 Lot
1	AC	Steam Turbine Generator	Steam Turbine With Separate HP And LP Casings Connected With SSS Clutch		37 MW	1 X 100% Per Unit	Based on Siemens Bid
1	AC	ST Lube Oil Skid				1 X 100% Per Unit	Supplied by STG Vendor
1	AC	ST Control Oil Skid				1 X 100% Per Unit	Supplied by STG Vendor
1	AD	Steam Surface Condenser	Thermal Duty = 64 MW;			1 X 100% Per Unit	
1	AD	Condensate Deaerator	2800 Gallon Storage Volume	CS		1 X 100% Per Unit	
2	AD	Condensate Extraction Pump	Centrifugal, Vertical, CAN Type, Constant Speed, Motor Driven ; 300 GPM @ 130 ft. TDH		15 HP	2X50% Per Unit	

1	AE	Boiler Feedwater Pump	Horizontal Ring-Section Pump, 3600 RPM 600 GPM @ 3000 ft. TDH		655 HP	1 X 100% Per Unit	
1	AG	Hot Gas Expander (HGE)			32 MW	1 X 100% Per Unit	Based on Dresser-Rand Generator Gear E148 Train
1	AG	HE Lube Oil Skid				1 X 100% Per HGE	Supplied by HGE Vendor
1	AG	HE Cooling & Sealing Steam Skid				1 X 100% Per HGE	Supplied by HGE Vendor
1	AJ	Ammonia Dosing Skid	Diaphragm Metering Pumps And Tank	316 / PTFE		1 X 100% Per HRSG	
1	AJ	Oxygen Dosing Panel For HRSG				1 X 100% Per HRSG	
5	ANB	Direct Injection Carbon Engine (DICE)	Wartsila Model 18V46 Modified For Coal Slurry		15.8 MW	5 X 20% Per Site	Tier 3 Machines W/ Coal Slurry Fuel
5	ANB	DICE Auxiliary Module				1 X 100% Per DICE	Supplied by DICE Vendor
1	ANA	Process Compressor	GV(200-3) Compressor Package; Incl. Motor, Air Inlet Filter, Aux. Support & Control Systems		37,000 HP	1 X 100% Per Unit	Based on Dresser-Rand Quote
1	AR	Vacuum Skid	2 Steam Jet Air Ejectors or 2 Liquid Ring Vacuum Pumps			2 X 100% Per Unit	Capacity based on Holding Duty
5	BA	Third Stage Separator (TSS)				1 X 100% Per DICE	Based on UOP Quote
1	BA	Direct Contact Cooler (DCC)	304L SS Column Internals; Sulzer MellapakPlus Packing			1 X 100% Per Unit	Based on Sulzer Chemtech Quote
1	BM	HRSG Blowdown Tank		CS		1 X 100% Per HRSG	
1	BM	Blowdown Heat Exchanger	Shell & Tube Type	CS/ SS Tubes		1 X 100% Per HRSG	
1	BM	Blowdown Tank Vent Silencer		CS		1 X 100% Per HRSG	
1	BS	19% Aqueous Ammonia Storage Tank		CS		1 X 100% Per Unit	Unloading Via Truck Unloading

							Pump (Self Contained).
2	BS	Ammonia Forwarding Pumps	Positive Displacement	316 SS		2 X 100% Per Unit	
1	FG	Fuel Gas Knockout Drum				1 X 100% Per CT	
1	FG	Fuel Gas Drain Tank				1 X 100% Per CT	
1	HA	Boiler Feedwater Pump Maintenance Hoist	Manual Hoist			1 X 100%	
1	HF	Fly Ash Silo				1 X 100% Per Site	Provided by Fly Ash Vendor
2	HF	Fly Ash Blowers				2 X 50% Per Unit	Provided by Fly Ash Vendor
5	HF	Air Lock Feeders				1 X 100% Per TSS	Provided by Fly Ash Vendor
1	PA	Plant Air Compressor	Oil Free Screw		150 HP	1 X 100% Per Unit	Provides Compressed Air to instrument and Service Air Systems
1	PA	Compressed Air Dryer	Dual Tower Heatless Desiccant Type With Dew Point Of -40 Deg. F Or Lower With Pre-Filter, After-Filter, And Bypass Filter			2 X 100% Per Unit	
1	PA	Compressed Air Receiver		CS	150 PSIG	1 X 100% Per Unit	Provides Compressed Air To Instrument And Service Air Systems
1	PF	Electric Fire Pump	Horizontal Centrifugal, 2000 GPM @ 300 ft TDH	316 SS Internals	250 HP	1 X 100% Per Site	Packaged Fire Pump System
1	SL	Gland Steam Condenser				1 X 100% Per Unit	Provided by Steam Turbine Vendor
1	VB	Admin/Control Building HVAC	Air Handling Unit With Heating And Cooling Coils			1 X 100% Per Unit	

1	WBA	Closed Cooling Water Heat Exchanger	Plate And Frame Type, Thermal Duty = 24 MW	316 SS		1 X 100% Per Unit	
2	WBA	Closed Cooling Water Pumps	Horizontal Centrifugal Type; 31,000 GPM @ 65 ft TDH	CI Casing and Impeller	300 HP	2 X 50% Per Unit	
1	WBA	Closed Cooling Water Expansion Tank	Vertical; Atmospheric;	CS		1 X 100% Per Unit	
1	WBA	Closed Cooling Water Chemical Feed System				1 X 100% Per Unit	
1	WBB	DICE Jacket Cooling Water Storage Tank			TBD	1 X 100% Per Unit	
2	WBB	DICE Jacket Cooling Water Pumps	Horizontal, Centrifugal Type	CI Casing and Impeller	TBD	2X 50% Per Unit	
1	WD	Demin Water Storage Tank	Field Erected Bolted Tank	CS W/ Epoxy Lining	50,000 Gal	1 X 100% Per Site	
2	WD	Demin Transfer Pumps	Horizontal, Centrifugal Pumps	SS Casing and Impeller	2 HP	2X100% Per Site	
2	XW	HGE Area Sump Pumps	Vertical Line Shaft	CI Casing and Impeller		2 X 100% Per Sump	Duplex
2	XW	STG Area Sump Pumps	Vertical Line Shaft	CI Casing and Impeller		2 X 100% Per Sump	Duplex
2	XW	Demin Area Sump Pumps	Vertical Line Shaft	CI Casing and Impeller		2 X 100% Per Sump	Duplex
2	XW	Oil/Water Separator (Including 2x100% Effluent Pumps)	Horizontal Centrifugal Pumps Coalescing Type Media Separator			1 X 100% Per Unit	Package by Oil Water Separator Vendor. One Oil/Water Separator With One Positive Displacement Waste Oil Pump and 2x100% Effluent Forwarding Pumps.

2	XW	HRSG Blowdown Sump Pumps	Vertical Line Shaft	CI Casing and Impeller		2 X 100% Per Sump	Duplex

1) The mechanical equipment list provides preliminary data, scope and quantities that may be subject to change during final engineering design

2) Assumptions: STG is not hydrogen cooled; backend recirculation pumps not required for HRSG

6.3 30 WT% MEA CO_2 CAPTURE PLANT

The equipment list for the CO_2 capture plant utilizing 30 wt% MEA is provided in Table 6-3

Table 6-3
30 wt% MEA CO_2 Capture Plant Equipment List

Site Quantity	System Code	Description	Type	Material	Rating	Capacity (%)	Comments
POST-COMBUSTION CAPTURE (30 WT %) EQUIPMENT LIST							
VESSELS & TANKS							
1	C-101	Flue Gas Absorber	Vertical	Kill CS + 304Clad Top		1 Lot Per Unit	Includes overhead wash section (Pall Ring) and absorption section (Structured packing)
1	C-102	Amine Stripper	Vertical	Kill CS + 304Clad Top		1 Lot Per Unit	Includes overhead wash section and stripping section with random packing (Pall Ring)
1	C-103	Stripper OVHD Receiver	Vertical	304Clad		1 Lot Per Unit	
1	C-106	Condensate Flash Drum	Horizontal	Carbon Steel		1 Lot Per Unit	
1	C-108	Carbon Drum(Part of V-102)	Vertical	Carbon Steel		2 Lot Per Unit	
1	D-101	MEA Storage Tank	Cone Roof	Carbon Steel		1 Lot Per Unit	
SHELL & TUBE EXCHANGERS AND AIR COOLERS							
2	E-101	Rich/Lean Exchanger	Plate & Frame	304SS		2 X50% Per Unit	Duty: 274 MMBTU/hr
1	E-102	Lean Amine Cooler	Plate & Frame	304SS		1 X100% Per Unit	Duty: 168 MMBTU/hr
1	E-103	Stripper Condenser	Weld Plate & Frame	304SS		1 X100% Per Unit	Duty: 64 MMBTU/hr
4	E-104	Stripper Reboiler	Kettle	Shell 304SS/ Tube 304SS		4 X25% Per Unit	Duty: 242 MMBTU/hr
1	E-105	Wash Water Cooler	Plate & Frame	304SS		1 X100% Per Unit	Duty: 16 MMBTU/hr
1	E-106	Reclaimer	Kettle	Shell Kill CS/ Tube 304SS		1 X100% Per Unit	Duty: 12 MMBTU/hr

COMPRESSORS, BLOWERS & DRIVERS							
1	K-101	Flue Gas Blower	Centrifugal w/ VFD Motor	304 SS	2,073 BHP	1 X100% Per Unit	
PUMPS & DRIVERS							
2	G-101	Rich Amine Pump	Centrifugal	Impeller: 12 Cr Casing: CS	616 BHP	2 X100% Per Unit	
2	G-102	Lean Amine Pump	Centrifugal	Impeller: 12 Cr Casing: CS	500 BHP	2 X100% Per Unit	
2	G-103	Wash Water Pump	Centrifugal	Impeller: 12 Cr Casing: CS	124 BHP	2 X100% Per Unit	
2	G-104	Stripper Reflux Pump	Centrifugal	Impeller: 12 Cr Casing: CS	11 BHP	2 X100% Per Unit	
1	G-106	Makeup Amine Pump	Centrifugal	Impeller: 12 Cr Casing: CS	28 BHP	1 X100% Per Unit	
1	G-107	Amine Sump Pump	Centrifugal	Impeller: 12 Cr Casing: CS	9 BHP	1 X100% Per Unit	
1	G-108	Soda Ash Pump(Part V-103)	Centrifugal	Impeller: CI Casing: CS	1 BHP	1 X100% Per Unit	
2	G-109	Condensate Return Pump	Centrifugal	Impeller: CS Casing: CS	90 BHP	2 X100% Per Unit	
PACKAGED & MISC EQUIPMENT							
4	V-102	Carbon + Pre&Post Filters	Package	Kill CS		4 X25% Per Unit	
1	V-101	Soda Ash Feed System Pkg	Package	CS		1 X100% Per Unit	
1	L-101	Flue Gas Fd & Exhaust Ducts	Duct	CS		1 X100% Per Unit	

6.4 CO_2 COMPRESSION PLANT

The equipment list for the CO_2 compression plant is shown in Table 6-4

Table 6-4
CO_2 Compression Plant Equipment List

Site Quantity	System Code	Description	Type	Material	Rating	Capacity (%)	Comments
CO2 COMPRESSION EQUIPMENT LIST							
VESSEL & TANK							
1	C-301	1st Stage Compressor Feed KO Drum	Vertical	304SS		1 Lot Per Unit	
1	C-302	2nd Stage Compressor Feed KO Drum	Vertical	304SS		1 Lot Per Unit	
1	C-303	Dryer Feed KO Drum	Vertical	304SS		1 Lot Per Unit	
1	C-304	SuperCritical CO2 Separator	Horizontal	304SS		1 Lot Per Unit	
SHELL & TUBE EXCHANGERS AND AIR COOLERS							
1	E-301	1st Stg Comp CW AfterCooler	Shell & Tube	304SS		1 X100% Per Unit	Duty: 11 MMBTU/hr
1	E-302	2nd Stg Comp CW AfterCooler	Shell & Tube	304SS		1 X100% Per Unit	Duty: 10 MMBTU/hr
1	E-303	3rd Stg Comp CW AfterCooler	Shell & Tube	Shell CS/ Tube 304SS		1 X100% Per Unit	Duty: 19 MMBTU/hr
1	E-304	SC CO2 Product CW Cooler	Shell & Tube	Shell CS/ Tube 304SS		1 X100% Per Unit	Duty: 3 MMBTU/hr
1	E-305	Recycle Cooler	Shell & Tube	304SS		1 X100% Per Unit	Duty: 7 MMBTU/hr
COMPRESSORS, BLOWERS & DRIVERS							
1	K-301	CO2 Compressor	Centrifugal w/ VFD	CS	10,053 BHP	1 X100% Per Unit	

PUMPS & DRIVERS							
2	G-301	Condensate Pump	Centrifugal	Impeller: CS Casing: CS	0.1 BHP	2 X100% Per Unit	
1	G-302	Super-Critical CO2 Pump	Centrifugal w/ VFD	Impeller: CS Casing: CS	409 MHP	1 X100% Per Unit	
PACKAGED & MISC EQUIPMENT							
1	V-301	CO2 Dryer	Package	CS		1 X100% Per Unit	

6.5 ELECTRICAL EQUIPMENT LIST

The equipment list for DICE CRCC electrical plant is shown in Table 6-5

Table 6-5
DICE CRCC Electrical Equipment List

Site Quantity	Description	Type	Comments
6	115kV Circuit Breaker and Associated Buswork	High Voltage Circuit Breaker	115kV, 50kA, 1200A, HVCB with Disconnect Switch and Grounding Switch. Dead Tank SF6 Circuit Breaker
6	115kV System, 84kV MCOV Surge Arrestors	70kV MCOV Surge Arrestors for 115kV System	Switchyard Surge Arrestors
21	115kV PT or CCVT	Potential Transformers or Coupling Capacitor Voltage Transformer	Potential Transformer for Synchronizing and Voltage Measurement
9	115kV CT	Current Transformer, Extended Range	Protection and Metering Current Transformers
1	115kV Motorized Disconnect and Grounding Switch	Disconnect and Grounding Switch	115kV, 50kA, 1200A, 3 pole
1	Switchyard Control Building	Switchyard Electrical Building	Electrical Building for Protective Relaying, SCADA and Switchyard Control Equipment
3	Step-Up Transformer	13.8kV to 115kV Transformer	30/40MVA, 13.8-115kV, ONAN/ONAF, 65 DEG C, Z=8% at 30MVA, HV DETC (STG, Gas Exp, DICE-2)
1	Station Service Transformer	115kV to 13.8kV Transformer	42/56MVA, 13.8-115kV, ONAN/ONAF, 65 DEG C, Z=8% at 42MVA, HV On-Load Tap Changer (Station Service)
1	Step-Up Transformer	13.8kV to 115kV Transformer	45/60MVA, 13.8-115kV, ONAN/ONAF, 65 DEG C, Z=8% at 45MVA, HV DETC (DICE-1)
1	Emergency Diesel Generator	13.8kV, 2MW, Tier 2	2.0MW Emergency Diesel Generator, 13.8kV, Tier 2, with outdoor, sound attenuated enclosure and minimum 12 hour belly tank
1	Boiler Feed Pump VFD	13.8kV Variable Frequency Drive	13.8kV Variable Frequency Drive for 655 HP motor
2	Cooling Pump VFD	13.8kV Variable Frequency Drive	13.8kV Variable Frequency Drive (MV/LV) for 300 HP motor
1	Gas Compressor VFD	13.8kV Variable Frequency Drive	13.8kV Variable Frequency Drive for 37,000 HP synchronous motor. Starting VFD with Bypass Switch.
1	Zig-Zag Grounding Transformer with Resistor	13.8kV Grounding Transformer for Delta System	13.8kV, 250kVA, Zig-Zag Grounding Transformer with Resistor
1	Distribution Transformer	13.8kV - 480V Transformer	Control Building 750kVA transformer, ONAN, Delta-Wye, HV DETC, 5.75% Z
2	Distribution Transformer	13.8kV - 480V Transformer	Common Load Center 2000kVA transformer, ONAN, Delta-Wye, HV DETC, 5.75% Z

1	Distribution Transformer	13.8kV - 480V Transformer	MV EEM MCC 2500kVA transformer, ONAN, Delta-Wye, HV DETC, 5.75% Z
1	DICE MV Switchgear-1	13.8kV Switchgear	Arc Resistant Metal Clad Switchgear, Type 2B, 13.8kV, 3000A, 63kA, 3PH, 3W, 60HZ
1	DICE MV Switchgear-2	13.8kV Switchgear	Arc Resistant Metal Clad Switchgear, Type 2B, 13.8kV, 2000A, 63kA, 3PH, 3W, 60HZ
1	Station MV Switchgear-3	13.8kV Switchgear	Arc Resistant Metal Clad Switchgear, Type 2B, 13.8kV, 3000A, 50kA, 3PH, 3W, 60HZ
1	Common Load Center, 480V	480V Load Center, Arc Resistant	480V Load Center, 480V, 3000A, 50kA, 3PH, 3W, 60HZ with two 2500A ACB incomer & 2000A ACB tie breaker
1	Common MCC-1, 480V	480V Motor Control Center	480V MCC, 480V, 1600A, 65kA, 3PH, 3W, 60HZ, 1600A incomer (10 stacks)
1	Common MCC-2, 480V	480V Motor Control Center	480V MCC, 480V, 800A, 65kA, 3PH, 3W, 60HZ, 800A incomer (6 stacks)
1	MV EEM MCC, 480V	480V Motor Control Center	480V MCC, 480V, 3000A, 40kA, 3PH, 3W, 60HZ, 3000A ACB incomer (8 stacks)
2	Isophase Bus Duct, Gas Exp & STG	13.8kV Isophase Bus Duct	Isophase Bus Duct, 13.8kV, 2000A
1	Non-Seg Bus Duct (DICE Swgr-1 Incomer)	Non-Seg Bus Duct	Non Seg Bus Duct, 13.8kV, 3000A, 63kA
1	Non-Seg Bus Duct (DICE Swgr-2 Incomer)	Non-Seg Bus Duct	Non Seg Bus Duct, 13.8kV, 2000A, 63kA
Lot	Lighting System	Lighting fixtures, panelboards, photocells, transformers, controllers, switches, cabling and raceway	Interior and task lighting shall be 120/208VAC, roadway and floodlighting shall be 480/277VAC. Emergency and egress lighting shall be self-contained battery packs. Lighting is provided at site access points and for all operating areas to support planned maintenance. Perimeter fence lighting is not provided.
Lot	Fire Detection System	System includes Fire protection panels, smoke and fire detectors, horns, strobes, cabling and raceway	Each electrical building is provided with fire alarm panel, smoke and fire detectors, horns, strobes, auditory and visual alarms, and all required wiring and raceway.
Lot	Plant Security & Intrusion Detection System	System includes CCTV, recording & monitoring servers, access points (card readers) for site buildings, gate intercom and controls, cabling and raceway.	Site perimeter and access points monitored by CCTV, video monitoring and recording, card readers for personnel doors in all site buildings, gate access controls, gate card reader, and gate intercom are provided.
Lot	Freeze Protection & Process Heating System	System includes Heat trace panelboards, transformers, thermostats, controllers, power connection boxes, heat trace cabling, cabling and raceway.	Freeze protection system for all exposed piping and equipment subject to damage from ambient temperatures below freezing. Heat trace is 120V, installed directly on pipe and equipment, under insulation, and is controlled by local controllers (mounted on pipe) or from freeze protection panels. Heating and heat tracing required for process fluid temperature regulation and sensitive chemicals will be provided as required.

Lot	Plant Communications System	System includes facility communications and local area network (LAN) including installation of primary phone lines to interface point at plant perimeter, cabling, raceway and outlets for voice and data in all site buildings.	Communications system will provide connectivity for voice and data in all site buildings, including switchyard. Cabling, raceway, data and voice ports are provided, hardware (including telephones) to be supplied by owner.
Lot	DC & UPS System	Batteries, chargers, regulating voltage & bypass transformers, static transfer switch, manual bypass switch, DC switchboard, inverters, and UPS panelboards, cabling and raceway.	DC system will supply DC power to critical loads, including UPS system, STG and Gas Exp turning gear, and emergency lube oil pumps. Chargers are 125VDC, 550A and batteries are UPS system will supply 120VAC single phase power to critical AC loads (including CEMS, DCS, fire protection, communications, security, etc.)
Lot	Welding and Convenience Receptacles	Welding receptacles, disconnect switches, convenience receptacles.	Convenience receptacles (120V, GFCI, weatherproof) provided so that outdoor plant equipment areas are accessible with 100 foot cord. Building interiors provided with receptacles per NEC or as required to support planned maintenance activities. Welding receptacles (480V, 3PH, 3W) are located in all areas where welding is expected to occur.
Lot	Grounding System	Site and switchyard ground grids, including buried bare copper conductors, ground rods, connectors, test wells, and taps to equipment and structure.	Buried stranded copper conductors, ground rods, equipment and structure bonding. Grounding system is designed to NEC, IEEE 142, and IEEE 80 requirements.
Lot	Lightning Protection System	Building, stack, and switchyard lightning protection systems. Air terminals, main conductors, down conductors, connectors, buried conductors and rods.	Building lightning protection systems designed to NFPA 780, but will not be UL Master Labelled. Switchyard lightning protection system designed to IEEE 998.
Lot	Cathodic Protection System	Protection system for buried, coated, carbon steel, cast iron and ductile iron piping. Materials include sacrificial anodes, insulating flanges, over-voltage protectors, test stations, reference electrodes, cable, and cable connectors.	Cathodic protection system is designed to NACE standards.
Lot	MV, LV, Control and Instrumentation Cables	Power, Control and Instrumentation Cables	UL listed cables

6.6 PLANT EQUIPMENT DEVELOPMENT STATUS

6.6.1 Coal Beneficiation Plant

According to Sedgman, each plant unit operation of the flowsheet is currently commercially available and has been demonstrated previously in the mineral processing industry. However, in some cases, the application to coal, or finely ground coal, is novel, and needs to be validated with test work.

6.6.1.1 Flotation Cells

Sedgman C-Cell, an induced air-style flotation cell, was selected as its deep froths with washing is likely to achieve the desired low-ash content in the beneficiated product. Other flotation technologies, such as mechanically agitated flotation cells and column flotation cells may also be suitable for this application. Further test work is required to determine the benefits, if any, of these alternative technologies.

6.6.1.2 Fine Grinding Mill

The FLSmidth VXPMill selected for the concept flowsheet was based on low capital cost, with the tradeoff being that it is a vertical, high intensity grinding mill. Alternate suitable technologies are available from Outotec (HIG Mill) and Glencore Technology (IsaMill). Samples of the coal feed should be provided to these three suppliers to identify which technology provides the most economical solution.

6.6.2 Power Block Equipment

6.6.2.1 Main Air Compressor

Commercially available, procured per material requisition (MR). Siemens Turbocompressor is the potential vendor. Intercooler and aftercooler (shell-tube heat exchangers) are typically in the compressor OEM's scope.

6.6.2.2 DICE

Stock engine is commercially available, procured per MR. (Turbocharger kit is removed to fit into the turbocompound configuration)

Fuel injection system design and development requires R&D as described in Section 3.1.

6.6.2.3 Third Stage Separator

Commercially available, procured per MR. Honeywell UOP is the potential vendor.

6.6.2.4 Hot Gas Expander

Commercially available, procured per MR. Baker Hughes (or Siemens) is the potential vendor.

6.6.2.5 HRSG (Including Duct Burner and SCR/CO Catalyst)

Commercially available, procured per MR. Nooter-Eriksen is the potential vendor.

6.6.2.6 Steam Turbine Generator (Including SSS Clutch)

Commercially available, procured per MR. Siemens Dresser-Rand is the potential vendor. The clutch is manufactured by SSS.

6.6.2.7 STG Heat Rejection System

Commercially available, procured per MR (air- or water-cooled condenser and cooling tower). Many potential vendors.

6.6.2.8 Balance of Plant (BOP) Pumps

Commercially available, each procured per MR.

6.6.2.9 Balance of Plant (BOP) Heat Exchangers

Commercially available, each procured per MR. They can be shell-and-tube or plate-frame type. This includes the MRC slurry preheater.

6.6.2.10 Direct Contact Cooler

Commercially available, procured per MR

6.6.3 **Capture Block Equipment**

6.6.3.1 Flue Gas Blower

Commercially available, procured per MR. Most blower vendors (Howden, Buffalo Blower, New York Blower, Clarage) should be able to provide this piece of equipment.

6.6.3.2 Absorber/Stripper Columns

Commercially available, procured per MR. Packing for these columns are also commercially available with Sulzer as the potential vendor.

6.6.3.3 CO_2 Compressors

Commercially available, procured per MR. Potential vendors are Dresser-Rand, GE, and MAN among others.

6.6.3.4 Pumps

Commercially available, each procured by MR.

6.6.3.5 Heat Exchangers

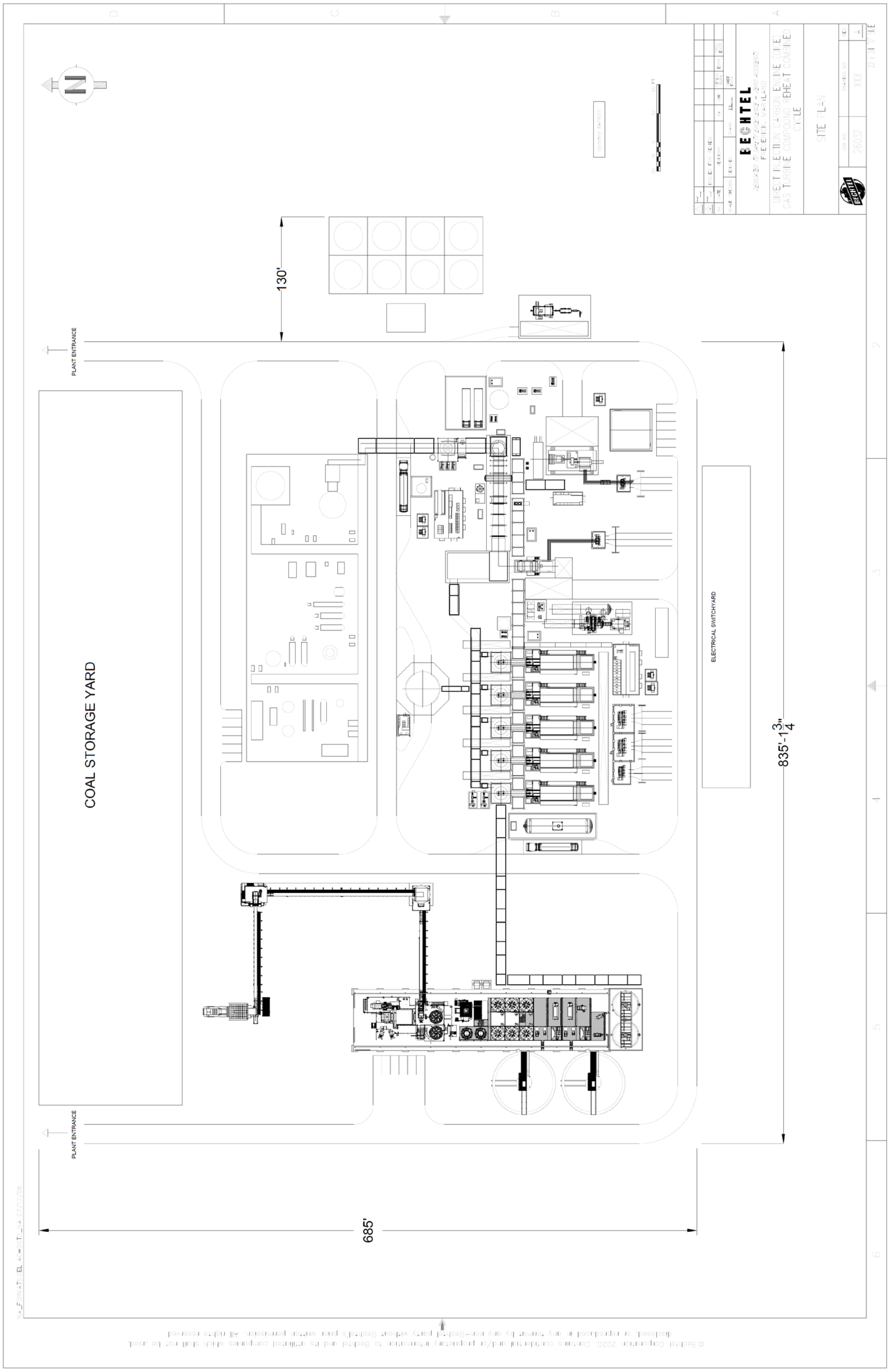
Commercially available, each procured per MR. With the exception of the kettle-type reboiler, heat exchangers will be of plate-and-frame type.

6.7 PRELIMINARY DICE CRCC PLOT PLAN

Figure 6-1 shows the overall plot plan for the coal beneficiation facility, DICE power plant, and carbon capture plant. Also included are a coal yard and cooling tower that will serve as the heat sink for the entire facility.

The complete facility will require approximately 30 to 35 acres of land to accommodate the three parts of the facility as well as administrative and maintenance buildings. The final arrangement for a specific site may change from that shown depending on local conditions.

Figure 6-1
Preliminary Plot Plan for 100 MWe DICE CRCC Plant



Section 7 DICE CRCC Operability

7.1 OPERATION PHILOSOPHY

From a high-level thermodynamic perspective, DICE CRCC is not different from a conventional combined cycle power plant comprising

- a “topping cycle” with one or more “internal combustion” engines and
- a “bottoming cycle” with one “external combustion” engine.

In a conventional gas turbine combined cycle power plant, the topping cycle comprises one or more gas turbines operating in **Brayton** cycle.

In a conventional reciprocating internal combustion engine (RICE) combined cycle power plant, the topping cycle comprises multiple engines operating in **Atkinson** cycle.

In either type of combined cycle, the bottoming cycle is a **Rankine** steam cycle comprising a waste heat recovery boiler (commonly referred to as “heat recovery steam generator” or HRSG) and steam turbine generator.

7.1.1 RICE-Combined Cycle Configuration

Strictly speaking, RICE is not suitable to combined cycle configuration due to its low exhaust energy, flow as well as temperature, which precludes efficient steam generator and turbine design. This difficulty is commonly avoided by using a large number of engines so that the total exhaust energy is commensurate with reasonably efficient bottoming (Rankine) steam cycle design. The number can be as high as 10, 20 or even more than 30 as demonstrated by recent projects in the Middle East and Pakistan.

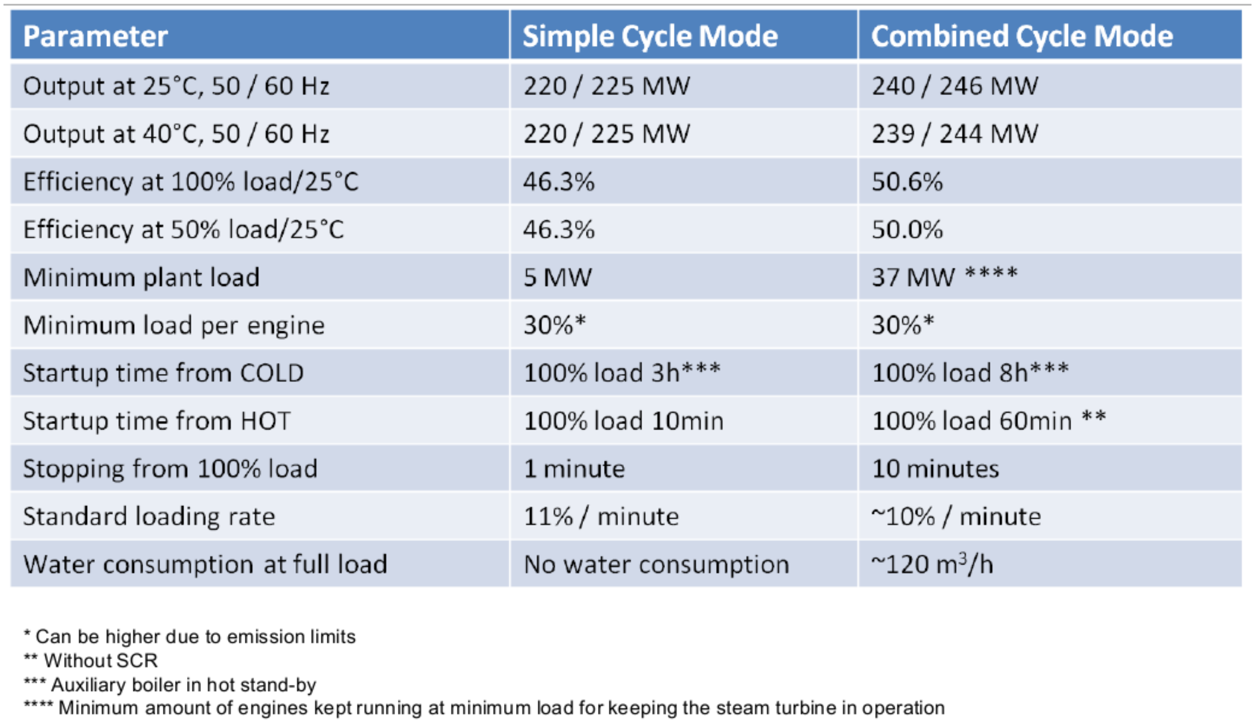
Modern RICE CC power plants almost always utilize modern spark-ignition, medium speed (i.e., about 500 RPM) and large bore engines firing natural gas. Typical rating of these engines is nominally 20 MW with very high thermal efficiency, i.e., 45% or higher. The thermodynamic cycle of these engines can be approximated (for conceptual studies and analysis) by the Atkinson cycle.

High RICE efficiency, pushing towards 50% benchmark in simple cycle, is a direct result of the cycle heat addition process in the cylinder, i.e., constant volume or “explosive” combustion, which simultaneously increases cycle peak temperature <u>and</u> pressure. This limits the parasitic power consumed during the power stroke resulting in high net power output for a given cycle peak temperature.

Furthermore, all modern RICE engines are turbocharged. In this configuration, cycle “charge air”, which otherwise would be at ambient conditions, is compressed to a higher pressure via compression in a centrifugal compressor. If the compressor is driven by taking power directly from the engine shaft through an accessory gearbox, it is referred to as a “supercharger”. If the compressor is driven by a small (usually also centrifugal) turbine utilizing engine exhaust gas, it is referred to as a “turbocharger”, which is essentially a small gas turbine with a balanced shaft – akin to the “gas generator” of an aeroderivative gas turbine. Supercharging increases inlet air density and mass flow for given cylinder volume and enhances engine power output.

Note that multiple engine RICE-CC power plants have large exhaust energy in “quantity” (i.e., high exhaust gas mass flow rate) but not in “quality” (i.e., still relatively low exhaust temperature). This is the reason why the Rankine steam bottoming cycle is still a minor contributor to the overall plant efficiency. For example, for a modern gas turbine combined cycle power plant (GTCC) with advanced class machines, the bottoming cycle enhances simple cycle output and efficiency by almost 50%. In other words, a net 300 MW and 42% simple cycle rating, GTCC performance becomes about 450 MW and nearly 60%. In comparison, the output/efficiency boost in changing from simple to combined cycle is significantly more modest for RICE as demonstrated by the data in Table 7-1.

Table 7-1
Simple and Combined Cycle Performances for Wärtsila’s 18V50SG Engine (12 Engines)



Parameter	Simple Cycle Mode	Combined Cycle Mode
Output at 25°C, 50 / 60 Hz	220 / 225 MW	240 / 246 MW
Output at 40°C, 50 / 60 Hz	220 / 225 MW	239 / 244 MW
Efficiency at 100% load/25°C	46.3%	50.6%
Efficiency at 50% load/25°C	46.3%	50.0%
Minimum plant load	5 MW	37 MW ****
Minimum load per engine	30%*	30%*
Startup time from COLD	100% load 3h***	100% load 8h***
Startup time from HOT	100% load 10min	100% load 60min **
Stopping from 100% load	1 minute	10 minutes
Standard loading rate	11% / minute	~10% / minute
Water consumption at full load	No water consumption	~120 m^3/h

* Can be higher due to emission limits
** Without SCR
*** Auxiliary boiler in hot stand-by
**** Minimum amount of engines kept running at minimum load for keeping the steam turbine in operation

7.1.2 Turbocompounding

Turbocompounding is a technique that removes the turbocharger kit from the stock engine and modifies it so that, instead of being a net 0 kW shaft output accessory, it actually contributes to the plant’s net shaft output and efficiency. When combined with a second combustor between the RICE exhaust and the turboexpander inlet (i.e., “**reheat**” or “reheat combustion”, the impact is fortified via two mechanisms in a combined cycle configuration:

1. higher topping cycle output and efficiency
2. higher bottoming cycle efficiency (higher exhaust gas temperature)

In the introductory version of **DICE CRCC**, which is the subject of the CoalFIRST pre-FEED study, the second (reheat) combustor is eliminated for simplicity. The cycle can still be considered a “reheat” cycle in the sense that the second combustion is moved downstream to the HRSG duct burners. This was necessary for generating enough steam to satisfy the demand of the stripper reboiler in the post-combustion capture (PCC) block. While the five DICE in the power plant are fired with MRC slurry, the HRSG duct burners utilize natural gas. It should be noted that modification requisite for translation from RICE to DICE is exclusively limited to engine accessories, i.e.

1. removal of the turbocharger accessory (its functionality transferred to outside components)
2. replacement of fuel delivery skid and engine fuel injectors

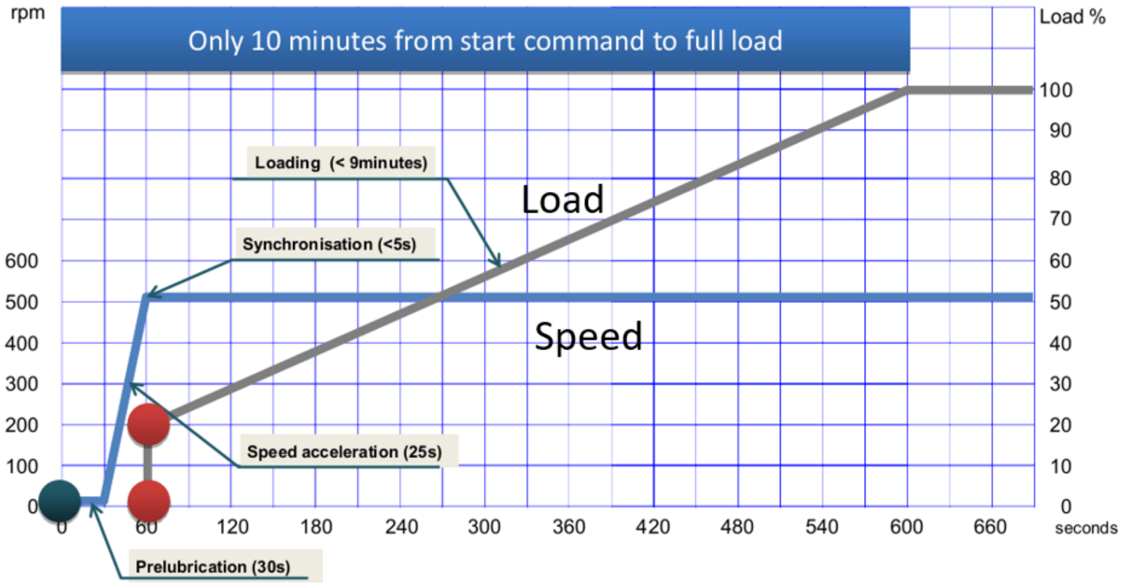
In summary, the DICE CC under investigation is essentially a RICE CC with the only difference being that the five turbocharger accessory kits of the stock RICE engines are replaced by a single air compressor (an intercooled, multi-stage centrifugal process compressor) and a single **hot gas turboexpander**. Consequently, it retains all the operability characteristics of a RICE CC.

7.2 SIMPLE CYCLE RICE/DICE STARTUP

A typical natural gas-fired RICE startup sequence is shown in Figure 7-1. Unlike the gas turbine power plants, overall startup time is 10 minutes or lower. The requirements for the sequence shown are:

1. cooling water is preheated and maintained above 70ºC,
2. engine bearings are continuously pre-lubricated (a "lift" pump supplies oil to the generator bearings) and
3. the engine is on turning gear

Figure 7-1
Typical RICE (or DICE) Starting Speed and Load Curves



If necessary, RICE/DICE can be started "fast", i.e., the engine can be synchronized in 30 seconds (instead of 60 seconds shown in Figure 7-1, and can ramp up to full load in 5 minutes (instead of 9 minutes shown in Figure 7-1), and when needed, be ramped down and stopped in less than a minute.

7.2.1 DICE Startup

It is recommended that engine starting and warm-up to operating temperatures should use fuel oil or diesel. Cold starting of large engines (which tend to use lower quality fuel) is always somewhat marginal, as the heat losses from a cold cylinder and a slow compression stroke, plus cold injection equipment, means that the charge temperature at the start of injection is lower (say 400°C) than when hot and at speed (say 650°C). This is an issue, as all coals have a higher autoignition temperature (530-575°C) than fuel oils (250-375°C).

It is, therefore, unlikely that MRC will be suitable to start a cold engine. Even if the engine started, the higher unburnts from a cold engine would cause problematic contamination of the cylinder bore, with unburnt coal packing behind the piston rings. This packing would cause accelerated ring and cylinder wear, and possibly ring breakage.

The use of diesel fuel oil for starting will require a dual injection system – a small capacity one for starting, and a larger one for MRC. An additional benefit is that the smaller capacity system for diesel fuel oil could also be used for pilot fueling

7.2.2 Pilot Fueling

DICE may require some pilot fueling – an established technology with natural gas engines, especially those needed to operate as dual-fuel engines (i.e., as distinct from lower compression spark ignition gas-only engines – Otto cycle). The amount of pilot fuel required needs experimental data. It will depend on the engine (speed, cylinder size, boost, aftercooling etc., which affect the charge temperature at the start of injection) and the effective volatiles content of the MRC. However, it is expected that a fixed 2-5% of the heat rate at maximum output would be sufficient – which automatically provides a higher proportion of heat input when required at idle and lower load settings.

For low-speed engines (<400 rpm), and based on practical experience, it is expected that the engine could operate reliably on 100% MRC, providing the engine is hot and above (say) 35% load. For lower load and higher speed engines, minimum pilot fueling with fuel oil is likely to be required. As both startup and pilot injection will require a separate injection system, operationally, some minimum pilot injection will likely be preferred to provide cooling of the pilot injector nozzles.

Injection timing for the pilot injection would normally be just before, or at the same time, as the MRC –both being electronically timed to allow optimization for different engine conditions and fuel variations.

In addition to a lower speed, derating the engine by reducing the amount of aftercooling (a higher air inlet temperature would give a reduction in cylinder charge, with a disproportionate increase in compression heating) – which may also reduce the need for pilot fueling.

The requirement for assisting ignition with pilot fuel provides an additional implementation strategy: installation of dual fuel NG engines now, being progressively switched to DICE as required using a retrofit kit.

7.2.3 DICE Shutdown

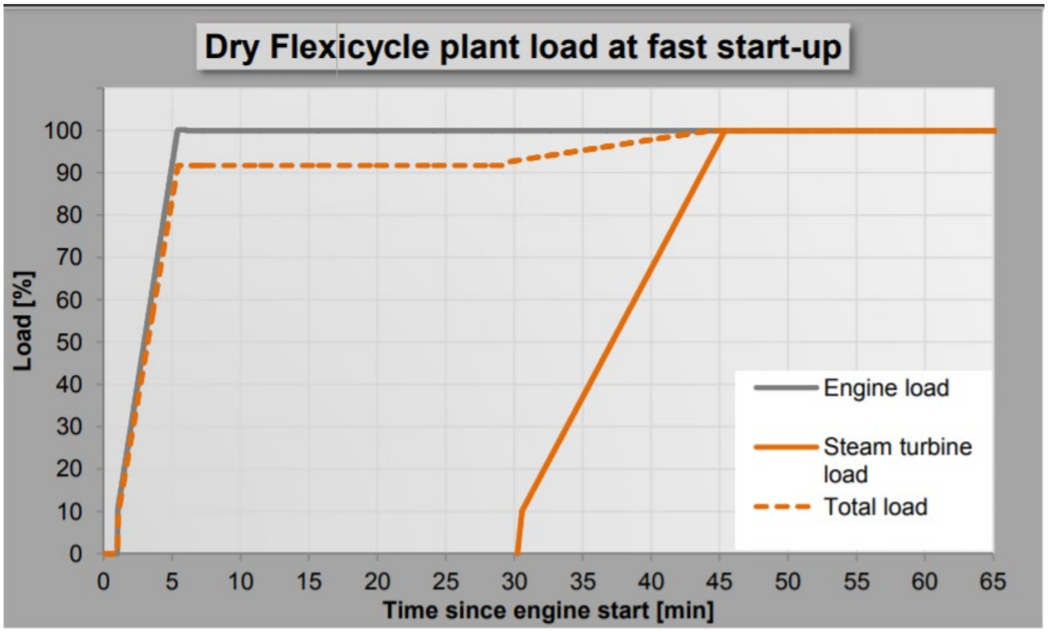
With a correctly designed fuel system, engine shut own can be achieved without any precautions. To achieve this, the fuel system will require some method of controlling a circulating flow of fuel down the injector to the needle valve and back to the service tank – as described in the engine modifications section. If this feature is not included, then a full flush of the fuel system from the feed pump through the injector will be required while the engine is operating to eliminate the possibility of stagnant coal fuel clogging the hot injection system while stopped. With the latter system the engine shut down would be under pilot fueling.

While diesel fuel has been used as the flushing fluid in some previous trials by simply switching the fuel supply to the engine from MRC to diesel, this arrangement is not recommended. In contrast to MRC, diesel fuel requires perfect sealing of valve seats (i.e., the needle or cut off valve in the injector) to ensure that fuel does not leak into the cylinder under the influence of the fuel supply pump. Also, any MRC that is not flushed from the system by the diesel fuel will highly likely result in agglomeration of the residual coal particles, potentially causing blockages. If this method of flushing is chosen, then an alternative flushing fluid should be used, for example, a mixture of long chain polyglycol (e.g., UCON) and water. This fluid would have the advantage of being miscible with MRC. In both cases, the switchover to the flushing fluid needs to be undertaken at less than half-load to avoid overfueling the engine.

7.3 COMBINED CYCLE RICE/DICE STARTUP

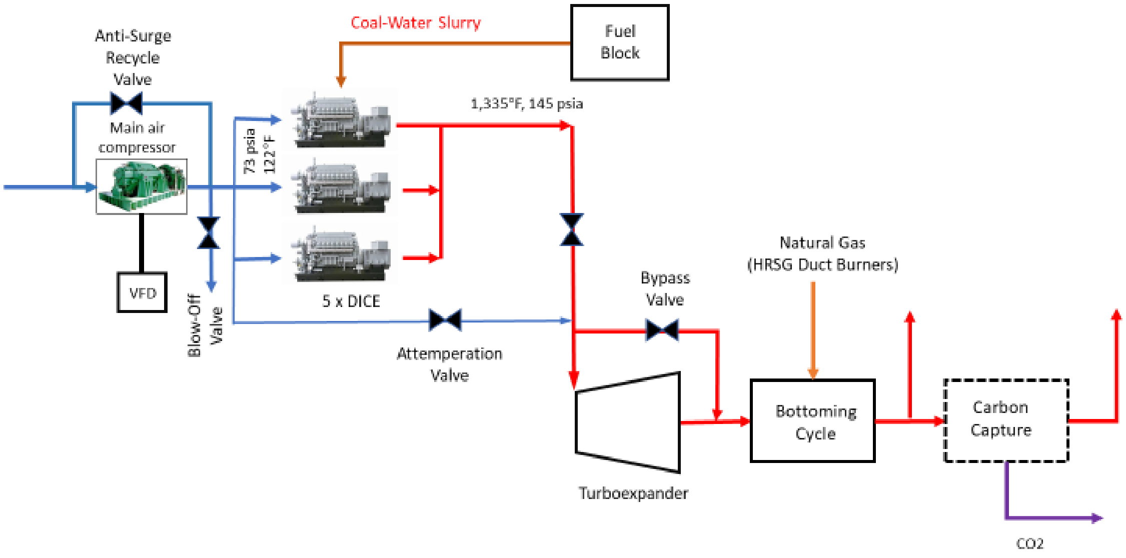
A typical RICE CC fast startup sequence (12 engines) is shown in Figure 7-2. All engines are started simultaneously; thus, 90% of plant full load is reached in slightly over five minutes. Steam turbine roll starts at the 30-minute mark and full plant load is reached 15 minutes after that.

Figure 7-2
Typical RICE CC Startup Speed and Load Trends



A simplified schematic diagram of DICE CRCC is shown in Figure 7-3. During startup the **main air compressor** (MAC) is started by the **variable frequency drive** (VFD). Surge control is accomplished by recirculation and/or blow-off by the MAC controller. Engines are started simultaneously in a manner similar to that shown in Figure 7-1 but in a "fast start" mode.

Figure 7-3
Schematic of RICE CRCC



Note the bypass lines to and around the hot gas expander, which is started using the hot exhaust gas coming from the engines, mixed with air extracted from the MAC to cool it. According to the OEM, the general rule is to control the warming rate at about 100°C/hour until the unit reaches the design temperature.

For a "cold start", the turboexpander startup sequence can be split into four phases after standard pre-start check list including instrumentation, lubrication, etc. (note that the unit is driven by the exhaust gas, i.e., there is no starter motor):

- acceleration to the idle speed (~800-1,500 rpm);
- warming time at idle speed;
- once temperature reaches the 500°C, flue gas valves are set to fully open position, the speed increases to the design value;
- synchronization to the grid is followed by the last temperature increase step, which is completed in few minutes.

At the start of the idle time, gas/air enter into the machine and, in a few minutes, it reaches ~300°C. It takes about 2 to 3 hours for the unit to warm up to 530 °C at idle speed. In this time frame, disc cooling air is activated, machine drains are closed, standard checks are performed (bearing temperatures, vibration readings and so on). During startup, inlet pressure and flow through the unit is controlled by the inlet guide vanes and bypass valve.

Main air compressor startup is straightforward and fast whether it is a “cold” or “hot” start because there is no warm-up period involved. The critical item in process control startup is surge control, which is typically accomplished by recirculation (or recycling) of discharge air through the anti-surge valve into the compressor suction. In intercooled, multi-casing units, each compressor section has its own surge control setup.

Due to the large motor size of the MAC (> 25 MW), a VFD is necessary to prevent current inrush during starting. Typical compressor start sequence is shown in Figure 7-4 using speed and anti-surge valve position trends. The startup process on the performance map is depicted in Figure 7-5. Prior to startup, intercooler circulating water flow starts and anti-surge valves are opened. Unit drains are closed, and standard checks are performed (bearings temperature, vibrations readings, etc.). Typically, inlet guide vanes (IGVs) are set to their lowest setting, which helps with current inrush as well. As shown in Figure 7-5, as the machine is cranked by the VFD, volume flow increases but recycling prevents pressure buildup, which ensures that the unit goes through the low speeds safely removed from the surge line. Once the operating pressure is reached, IGVs are opened and anti-surge valve is closed in a controlled manner to bring the unit to full flow and full load.

The last step is going to be coordinated with the engine startup by the controller. The exact sequence and control algorithm will be determined by dynamic simulation runs during detail engineering. Similarly, dynamic simulation runs are also going to be used to coordinate the turboexpander startup controls with the engines.

Figure 7-4
Typical Centrifugal Compressor Startup – Speed and Anti-Surge Valve Position

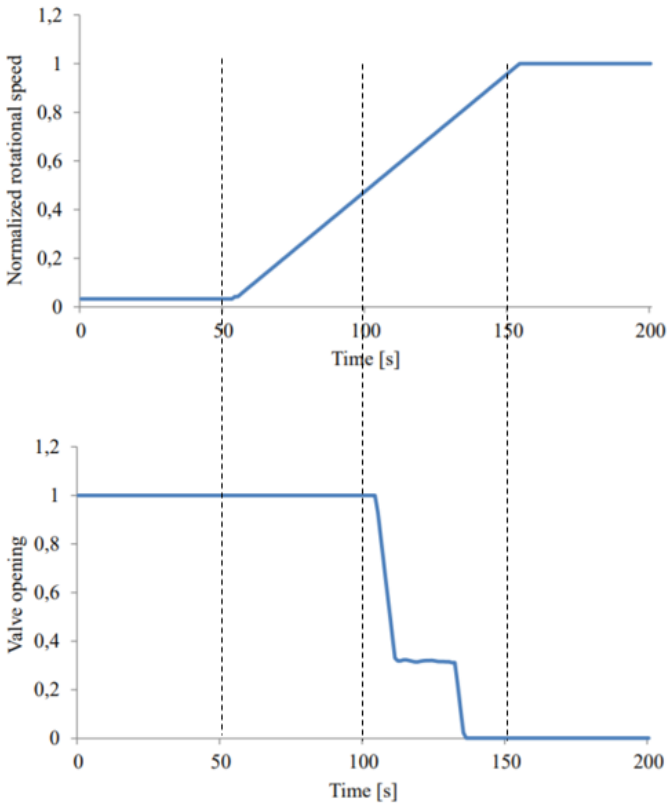
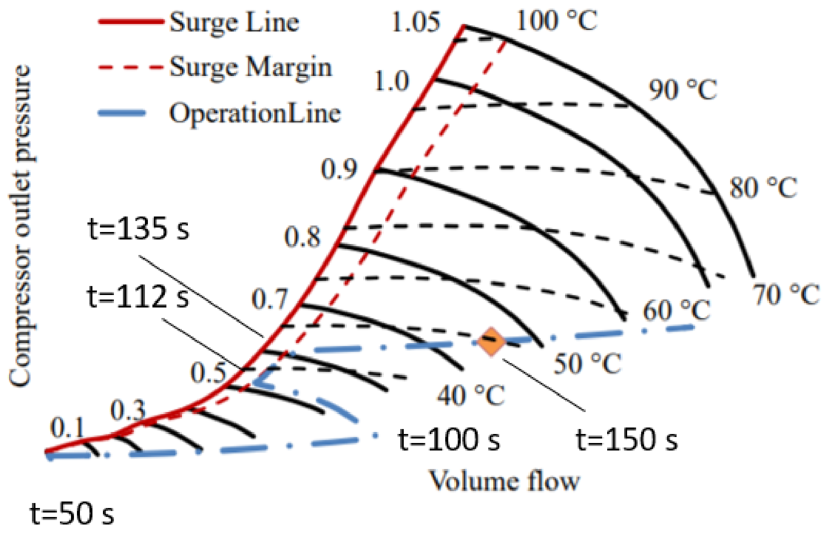
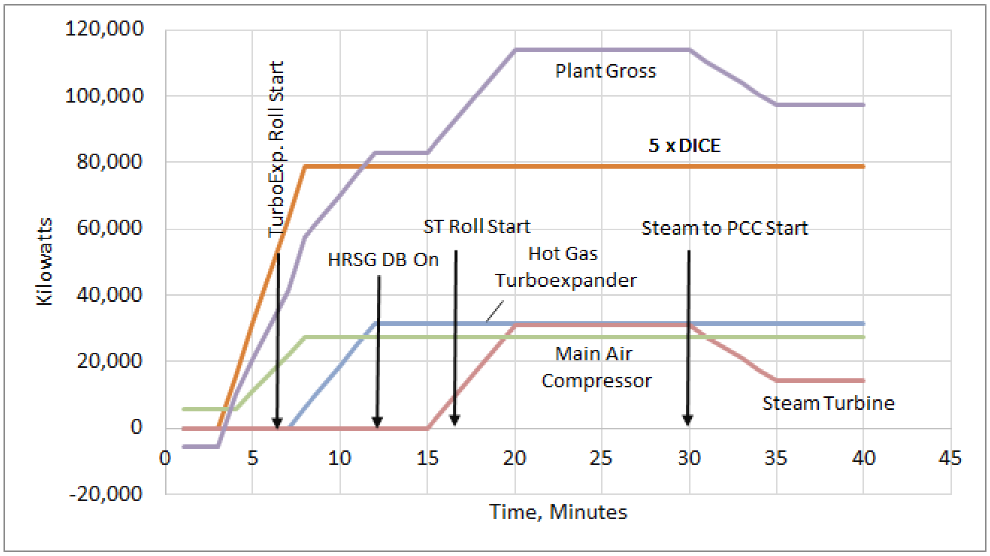


Figure 7-5
Typical Centrifugal Compressor Startup – Pressure and Flow Path



DICE CRCC startup after an overnight shutdown is shown in Figure 7-6. As shown in the figure, MAC is started first by the VFD using power from the grid. Thereafter, first all five DICE are cranked to FSNL, synchronized to the grid and loaded to full load. Once there is enough exhaust gas generated to crank the turboexpander to FSNL, which is about 40% DICE load (equivalent of two engines running at full load), turboexpander roll starts. After the turboexpander is synchronized to the grid and ramped to full load, steam turbine roll and load process starts. Once all the five engines have started, the HRSG receives its full exhaust gas flow. After the turboexpander start has been completed, the duct burners are lit. Steam produced by the HRSG until the steam turbine roll and loading is rerouted to the condenser via the bypass line. Steam turbine is loaded by the controller via synchronized opening and closing of the admission and bypass valves, respectively. Plant full load is reached at twenty-minute mark. During the startup sequence shown in Figure 7-6, the PCC block is off-line.

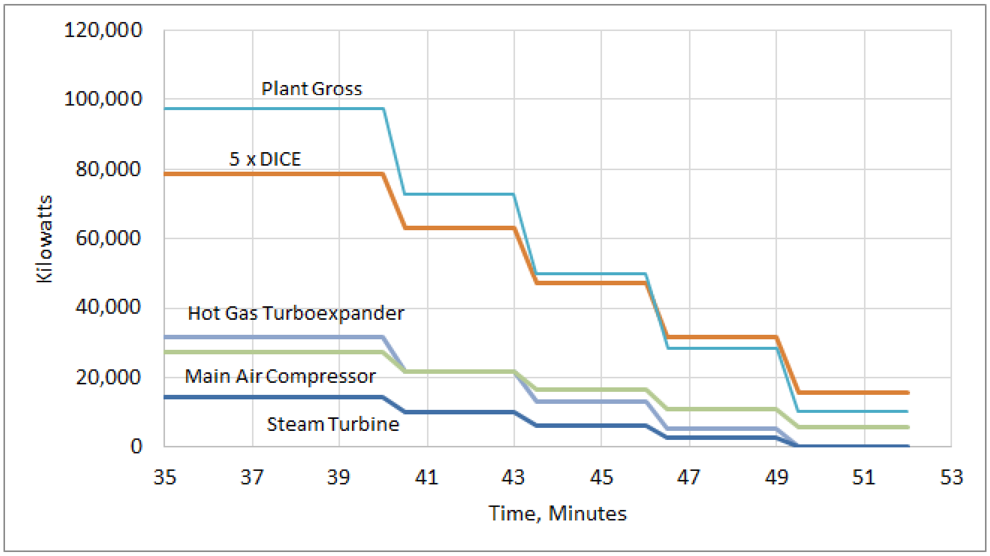
Figure 7-6
DICE CRCC Hot Start



PCC startup is started at the 30-minute mark. Detailed pre-start preparation and startup procedure are described in detail below. Once steam starts to be directed from the HP turbine exhaust to the stripper reboiler, steam turbine starts going down. Once the steam flow through the LP turbine reaches its minimum value, it is taken off-line by the SSS clutch. Steam turbine generator is driven by the HP turbine in a backpressure operating mode.

DICE CRCC can be ramped down to about 30% plant load (two DICE operating) by turning down the engines in sequence. In this mode, hot gas turbo expander and the steam turbine are in a load following mode. This is shown in **Error! Reference source not found.** with a ramp-down rate corresponding to 90 seconds for shutting down one DICE, which is typical and easily doable. Even shorter times are possible based on OEM requirements and input. Note that load ramps (up or down) with all engines in operation are practically instantaneous. As noted above, bringing up an engine from standstill to full load is about 5 minutes.

Figure 7-7
DICE CRCC Load Ramps



Conceptually, as shown in Figure 7-7, the plant can be brought down to one DICE on-line with the plant running at 10% load. This has to be confirmed by the MAC and turboexpander OEMs during detail design, i.e., whether their equipment can run at that low level of load. In the case that this is an issue for the MAC, it can be alleviated during the detail design by specifying two parallel MAC trains. While this would increase the total installed equipment cost, it would be countered by the cost saving from the elimination of the VFD and associated electrical BOP. Even if the plant equipment can take the lowest flow and stay in operation, there is the question of whether the PCC can operate at such low flue gas flow. This requires careful engineering design of the capture block for maximum turndown.

It should be mentioned that the plant can run with only one (or more) DICE in operation. This can be easily accomplished by providing a bypass stack downstream of the DICE (upstream of the hot gas expander) or between the turboexpander and the HRSG. While this is a straightforward plant option, it should be carefully investigated at the beginning of the project based on the environmental regulations at the chosen site. The bypass stack can discharge directly to the atmosphere (the most economic option) or its flue gas can be directed to the PCC (unlikely to be cost-effective).

7.4 STARTUP TIME AND RAMP RATES SUMMARY

A summary of the DICE CRCC startup times for various conditions is shown per the following. The values cited are based on starting up from cold iron to 100 percent load but exclude PCC start.

- Hot start (overnight shutdown) in 30 minutes
- Warm start (48-72 hours down) in 1 to 2 hours
- Cold start (> 72 hours down) in 2 to 3 hours

Exact values for these start up times depend on the hot gas turboexpander allowable ramp rate. Operation at less than 100 percent load can be achieved in 30 minutes, regardless of hot, warm or cold start.

RICE is able to ramp at ~20% per minute from full speed no load (FSNL) to full speed full load (FSFL). From 100% plant (not engine) load to 60% engine load is 4 minutes, at which point the plant is at 50% load. Therefore, the % MCR/min is 12.5% (plant) normal.

On an emergency basis, two engines can be tripped instantaneously, ramping down to 60% engine load (50% plant load). With the inertia of the other systems, at 2 minute maximum, the MCR can be as high as 25% per minute under emergency circumstances.

Appendix A References

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