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

CONCEPTUAL DESIGN FINAL REPORT

U. S. Department of Energy (DOE)
Contract No. 89243319CFE000025, Coal-Based Power Plants of the Future

By

Nexant, Inc
Bechtel Power and Infrastructure
Czero

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Section 1 Business Case

The power plant for this conceptual design study is configured as a 5x1x1x1 Direct Injection Carbon Engine (DICE) Gas Turbine-Compound Reheat Combined Cycle (GT-CRCC) generating nominal 100 MWe of net power while capturing 90 percent of the CO_2 in the flue gas. The breakdown of the process system and power blocks is as follows:

1. Five (5) DICE (nominal 15 MWe each)
2. One (1) hot gas expander
3. One (1) Single pressure, no reheat heat recovery steam generator (HRSG)
4. One (1) Non-condensing (back-pressure) steam turbine
5. One (1) 30 wt percent MEA plant capturing 90 percent of the total CO_2 in the flue gas

Per the design basis set forth in the contract, the conceptual design for the DICE GT-CRCC plant is developed as a greenfield project with a Midwestern U.S location.

1.1 MARKET SCENARIO

1.1.1 Coal Type

The design fuel for the DICE GT-CRCC is low-sulfur sub-bituminous Montana Rosebud Powder River Basin (PRB) coal, with an as-received heating value of 8,564 Btu/lb HHV (8,252 Btu/lb LHV). The coal has an ash content of 11.03 percent by weight (wt%) on a dry basis, and needs to be micronized and de-ashed to an appropriate level in order to protect the moving parts of the engine that are exposed to either the micronized coal-water fuel (which is abrasive), or the solid particulate products of combustion which contain both ash and traces of unburned coal.

The DICE GT-CRCC conceptual design utilizes physical beneficiation to remove the minerals and sulfate/pyritic sulfur in the PRB coal. Physical beneficiation, depending on feedstock and process, is able to bring the ash content down to a few percent by weight. The resulting ash content of the coal is reduced to about 2 wt% on a dry basis, which is considered suitable for combustion in DICE [1, 2] .

The physical beneficiation process produces micronized refined coal (MRC), which is essentially finely ground low ash carbons in a slurry, 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 in a 55 percent coal-45 percent water mixture.

There are a number of steps required to produce MRC [3]. In general, the process comprises:

- Coal washing
- Micronizing (fine grinding/milling)
- Froth flotation (de-ashing)
- Partial dewatering to 55 wt% coal MRC

For the design coal, it is assumed that the cleaned coal ash content is reduced to 2 percent on a dry basis, while also assuming that 20 percent of the sulfur in the coal is inorganic and is thereby removed during physical beneficiation. The resulting coal properties are shown in Table 1-1.

Table 1-1
PRB MRC Coal Properties

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

Cost of MRC fuel is dominated by the cost of the feedstock and the micronizing process. Based on CSIRO research involving Australian coals [4], physical beneficiation is expected to increase the cost of feedstock by about $2.50/MMBtu HHV.

The 2011 Montana Rosebud PRB coal price that is delivered to the Midwest was estimated by DOE to be $36.57 per ton [5]. Based on EIA data, Mountain Region coal pricing remains relatively unchanged in 2018 from 2011, hence it is assumed that the 2018 as-received PRB coal price is $36.6 per ton, equivalent to $2.14/MMBtu HHV. Factoring in the coal beneficiation cost of $2.50/MMBtu HHV, the cost of the MRC fuel is estimated to more than double to $4.64/MMBtu HHV, or $79.4/ton of as-received PRB coal.

1.1.2 Natural Gas Price

Natural gas delivered to power plants in the Midwest, per DOE, was estimated to be about $0.6/MMBtu higher than that delivered to the Texas Gulf Area [5]. 2018 Henry Hub natural gas prices is $3.15/MMBtu, so the estimated 2018 natural gas price delivered to the Midwestern US is $3.75/MMBtu.

In its reference Midwestern NGCC case, DOE assumes that the natural gas feed is delivered to the power plant via a 10-mile long underground, carbon steel gas pipeline [6]. The DICE GT-CRCC plant in this conceptual design accounts for the cost associated with the same pipeline length but for a smaller diameter (6 inch-piping) due to the much smaller natural gas demand.

1.1.3 Renewables Penetration

In order to reasonably compare the conceptual DICE GT-CRCC plant design with the benchmark DOE reference coal plant, this unit cost of electricity (COE) evaluation assumes a similar baseload plant with an overall capacity factor of 85 percent. Part load operation with the penetration of renewable energy sources (e.g. utility scale grid inter-connected solar photovoltaics (PV) and onshore and offshore wind energy) is addressed in the Plant Concept Description section of the report.

1.1.4 CO_2 Constraint

The plant is fully integrated with a post-combustion CO_2 capture (PCC) unit using 30 wt% MEA that captures 90 percent of the CO_2 in the flue gas. The captured CO_2 meets the purity specifications set forth by DOE for pipeline delivery to saline aquifer sequestration, at a pressure of 2,200 psig at the plant battery limit for delivery to the storage site at 1,200 psig.

When the PCC is in operation, the DICE GT-CRCC has a CO_2 emission rate of 208 lb/MWh-net, far lower than natural gas technologies (~800 lb/MWh-net) without capture. Additionally, it is designed for maximum power generation when the PCC is offline with the addition of a low-pressure (LP) condensing turbine generating an additional 13 MW from steam that is normally routed to the PCC when it is in operation. Coupled with the reduced auxiliary load from the offline PCC, the plant can generate up to a total of 28 MW more power, achieving a net efficiency of 41.6 percent LHV (39.3 percent HHV).. The CO_2 emissions rate is estimated at 1,600 lb/MWh-net, far lower than similar supercritical and even ultra-supercritical plants (~1,900 lb/MWh-net).

1.2 ESTIMATED COST OF ELECTRICITY

1.2.1 DICE-GT CRCC Performance

Table 1-2 summarizes the overall performance of the nominal 100 MWe DICE GT-CRCC power plant based on the conceptual design as shown in Figure 2-3. The fuel mix to the plant is 70 percent coal and 30 percent natural gas, on a LHV basis. The efficiency is 32.2 percent on an LHV basis (30.4% HHV) with 90 percent CO_2 capture. This is higher than even a PRB coal-based ultra-supercritical PC plant with CO_2 capture at 29.8 percent LHV efficiency (28.7 percent HHV).

1.2.2 Capital Cost

Costs for the 100 MWe DICE GT-CRCC plant were derived per the following methodology:

- Equipment directly related to the main DICE GT-CRCC plant (e.g. DICE, Air Compressor, Hot Gas Expander, HRSG, etc.) was estimated based on either price quotes from vendors or from a bottoms-up estimate using a commercial cost estimate software (Thermoflow PEACE)
- PCC plant cost was determined via bottoms-up cost estimate based on major equipment sizing and using past quotes from equipment vendors or cost curves derived from commercial cost estimate software (Aspen In-Plant Cost Estimator)
- Systems such as coal handling, feedwater systems, cooling water systems, etc. are expected to be similar to those for the NETL baseline reference cases so these were scaled via capacity factor, using appropriate scaling parameters and capacity factoring exponents stated in NETL's Quality Guidelines for Energy System Studies (QGESS) Cost Scaling Report.

Table 1-3 shows the methodology used to estimate the costs for each of the major accounts and subaccounts of the DICE GT-CRCC plant.

Table 1-4 provides a breakdown of the DICE GT-CRCC total plant cost (TPC), in 2018 dollars, reported in a similar format, with similar code of accounts as the NETL baseline reference cases for combustion-based coal and natural gas-fired power plants.

The estimated TPC for the 100 MWe DICE GT-CRCC plant is $374MM, or $4,267/kW-net, which is comparable to large-scale, 550 MWe type coal-fired plants with CO_2 capture, even though these large plants have a cost advantage due to their economies- of-scale.

Table 1-5 presents the breakdown of the additional costs required to develop the TPC to total overnight cost (TOC), per the assumptions used in the NETL coal and natural gas baseline power plant cases. The resulting TOC is used for the calculation of the first-year cost of electricity (COE).

Table 1-2
100 MWe Nominal DICE GT-CRCC Performance

Power Summary	
POWER GENERATION, kWe	
5 x DICE	78,790
Turboexpander	40,250
Steam Turbine	16,192
Total Power Generation	**135,232**
AUXILIARY LOAD SUMMARY, kWe	
Coal Handling and Conveying	71
Coal Beneficiation	incl w/ BOP
DICE Pumps	6
Main Air Compressor	27,776
SCR	107
Cyclone	163
Boiler Feed Water Pump	325
Economizer Recirculation Pump	9
Steam Turbine Auxiliaries	34
WFGD	428
CO_2 Capture	4,316
CO_2 Compression	8,292
Circulating Water Pumps	840
Ground Water Pumps	20
Cooling Tower Fans	540
Miscellaneous Motors	79
Miscellaneous Balance of Plant (incl MRC Fuel Prep)	3,776
Transformer Losses	676
Total Auxiliaries, kWe	**47,627**
Net Power, kWe	**87,605**
As-Received PRB Coal Feed, lb/hr	79,044
Natural Gas Feed Flow, lb/hr	13,719
Coal LHV Thermal Input, MMBtu/hr	650
Gas LHV Thermal Input, MMBtu/hr	279
Total LHV Thermal Input, MMBtu/hr	**928**
LHV Efficiency, %	**32.2%**
Coal HHV Thermal Input, MMBtu/hr	674
Gas HHV Thermal Input, MMBtu/hr	308
Total HHV Thermal Input, MMBtu/hr	**983**
HHV Efficiency, %	**30.4%**

Table 1-3
100 MWe DICE GT-CRCC Cost Accounts and Estimation Methodology

Acct No.	Item/Description	Cost Estimate Methodology
1	COAL HANDLING	Scaled via QGESS capacity factoring using Low Rank Coal Baseline Report as reference
2	COAL & SORBENT PREP & FEED	
2.1	Coal Beneficiation	Included in coal feed cost
3	FEEDWATER & MISC BOP SYSTEMS	
3.1	Feedwater System	Included in HRSG cost
3.x	Other Feedwater/BOP Systems	Scaled via QGESS capacity factoring using NGCC Baseline Report as reference
4	PC BOILER & ACCESSORIES	
4.1	DICE and Generator (5)	Per description in Section 2.3.3.1 Dice Cost
4.2	Air Compressor	Budgetary price quote (Kobelco)
4.3	Combustor, Expander and Generator	Based on budgetary price quote and typical gas turbine prices
4.4	MRC Preheater	Thermoflow PEACE
5	FLUE GAS CLEANUP	
5.1	WFGD	Thermoflow PEACE (verified with and calibrated to Bechtel data from coal-fired power plant project)
5.3	Cyclone	Thermoflow PEACE (verified with and calibrated to Bechtel data from coal-fired power plant project)
5B	CO2 REMOVAL & COMPRESSION	
5B.1	CO2 Removal System	Nexant bottoms-up cost estimate
5B.2	CO2 Compression & Drying	Nexant bottoms-up cost estimate
7	HRSG, DUCTING & STACK	
7.1	Heat Recovery Steam Generator (w/ SCR)	Budgetary price quote (Nooter-Eriksen)
7.2	Deaerator	Thermoflow PEACE
7.9	HRSG, Duct & Stack Foundations	Scaled via QGESS capacity factoring using NGCC Baseline Report as reference
8	STEAM TURBINE GENERATOR	
8.1	Steam TG & Accessories	Budgetary price quote (Siemens)
8.3a	Condenser & Auxiliaries	Thermoflow PEACE (verified with Bechtel data from past projects)
8.4	Steam Piping	Factored from gas and steam turbine costs
8.9	TG Foundations	Scaled via QGESS capacity factoring using NGCC Baseline Report as reference
9	COOLING WATER SYSTEM	Scaled via QGESS capacity factoring using NGCC Baseline Report as reference
10	ASH/SPENT SORBENT HANDLING SYS	Scaled via QGESS capacity factoring using Low Rank Coal Baseline Report as reference
11	ACCESSORY ELECTRIC PLANT	Thermoflow PEACE (calibrated to GTCC project cost)
12	INSTRUMENTATION & CONTROL	Factored from various plant systems costs
13	IMPROVEMENTS TO SITE	Scaled via QGESS capacity factoring using NGCC Baseline Report as reference
14	BUILDINGS & STRUCTURES	Scaled via QGESS capacity factoring using NGCC Baseline Report as reference

Table 1-4
100 MWe Nominal DICE GT-CRCC Capital Cost Breakdown

DICE GT-CRCC w/ CO2 Capture Total Plant Cost Details (Jun 2018 Basis)

5x1x1x1 90 MW DICE GT-CRCC PLANT WITH 30 WT% MEA CO2 CAPTURE — Cost Basis: 2018 ($x1000); Plant Size: 88 MWe, net

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sales Tax	Bare Erected Cost $	Eng'g CM H.O & Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/kW
1	COAL HANDLING											
	SUBTOTAL 1.	**$5,806**	**$1,687**	**$3,887**	**$0**	**$0**	**$11,379**	**$1,138**	**$0**	**$1,878**	**$14,395**	**$164**
2	COAL & SORBENT PREP & FEED											
	SUBTOTAL 2.		**included in coal feed cost**									
3	FEEDWATER & MISC BOP SYSTEMS											
3.1	Feedwater System	$0	incl w HRSG	$0	$0	$0	$0	$0	$0	$0	$0	
3.2	Water Makeup & Pretreating	$452	$47	$232	$0	$0	$731	$73	$0	$161	$965	
3.4	Service Water Systems	$55	$109	$351	$0	$0	$514	$51	$0	$113	$679	
3.6	FO Supply Sys & Nat Gas	$6,856	$245	$212	$0	$0	$7,312	$731	$0	$1,206	$9,249	
3.7	Waste Treatment Equipment	$182	$0	$105	$0	$0	$287	$29	$0	$63	$378	
3.8	Misc Power Plant Equipment	$172	$23	$84	$0	$0	$279	$28	$0	$61	$368	
3.9	Misc Pumps and Tanks	$550	$100	$125	$0	$0	$775	$78	$0	$0	$853	
	SUBTOTAL 3.	**$8,266**	**$523**	**$1,108**	**$0**	**$0**	**$9,898**	**$990**	**$0**	**$1,605**	**$12,493**	**$143**
4	PC BOILER & ACCESSORIES											
4.1	DICE and Generator (5)	$34,000	$5,100	$6,120	$0	$0	$45,220	$4,522	$9,948	$8,954	$68,644	
4.2	Air Compressor	$7,500	$1,125	$1,350	$0	$0	$9,975	$998	$0	$1,646	$12,618	
4.3	Combustor, Expander and Generator	$13,300	$2,000	$2,400	$0	$0	$17,700	$1,770	$0	$2,921	$22,391	
4.4	MRC Preheater	$100	$25	$25	$0	$0	$150	$15	$0	$25	$190	
	SUBTOTAL 4.	**$54,900**	**$8,250**	**$9,895**	**$0**	**$0**	**$73,045**	**$7,305**	**$9,948**	**$13,545**	**$103,843**	**$1,185**
5	FLUE GAS CLEANUP											
5.1	WFGD	$22,550	$6,750	$10,125	$0	$0	$39,425	$3,943	$0	$4,337	$47,704	
5.3	Cyclone	$3,450	$1,225	$1,825	$0	$0	$6,500	$650	$0	$715	$7,865	
	SUBTOTAL 5.	**$26,000**	**$7,975**	**$11,950**	**$0**	**$0**	**$45,925**	**$4,593**	**$0**	**$5,052**	**$55,569**	**$634**
5B	CO2 REMOVAL & COMPRESSION											
5B.1	CO2 Removal System	$17,205	$14,837	$24,981	$0	$0	$57,022	$5,702	$0	$12,545	$75,269	
5B.2	CO2 Compression & Drying	$11,975	$5,880	$7,311	$0	$0	$25,166	$2,517	$0	$5,537	$33,219	
	SUBTOTAL 5B.	**$29,180**	**$20,717**	**$32,292**	**$0**	**$0**	**$82,188**	**$8,219**	**$0**	**$18,081**	**$108,488**	**$1,238**
7	HRSG, DUCTING & STACK											
7.1	Heat Recovery Steam Generator (w/ SCR)	$5,700	$850	$1,025	$0	$0	$7,575	$758	$0	$0	$8,333	
7.2	Deaerator	$200	$25	$25	$0	$0	$250	$25	$0	$0	$275	
7.9	HRSG, Duct & Stack Foundations	$0	$126	$118	$0	$0	$244	$24	$0	$54	$322	
	SUBTOTAL 7.	**$5,900**	**$1,001**	**$1,168**	**$0**	**$0**	**$8,069**	**$807**	**$0**	**$54**	**$8,929**	**$102**
8	STEAM TURBINE GENERATOR											
8.1	Steam TG & Accessories	$5,000	$750	$900	$0	$0	$6,650	$665	$0	$732	$8,047	
8.3a	Condenser & Auxiliaries	$700	$100	$125	$0	$0	$925	$93	$0	$102	$1,119	
8.4	Steam Piping	$1,918	$0	$777	$0	$0	$2,695	$270	$0	$445	$3,409	
8.9	TG Foundations	$0	$149	$247	$0	$0	$396	$40	$0	$87	$523	
	SUBTOTAL 8.	**$7,618**	**$999**	**$2,049**	**$0**	**$0**	**$10,666**	**$1,067**	**$0**	**$1,365**	**$13,098**	**$150**

Table 1-4 (cont'd)
100 MWe Nominal DICE GT-CRCC Capital Cost Breakdown

DICE GT-CRCC w/ CO2 Capture Total Plant Cost Details (Jun 2018 Basis)

5x1x1x1 90 MW DICE GT-CRCC PLANT WITH 30 WT% MEA CO2 CAPTURE

Cost Basis: 2018 ($x1000)
Plant Size: 88 MWe, net

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sales Tax	Bare Erected Cost $	Eng'g CM H.O & Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/kW
9	COOLING WATER SYSTEM											
	SUBTOTAL 9.	$3,014	$3,786	$3,281	$0	$0	$10,081	$1,008	$0	$1,642	$12,732	$145
10	ASH/SPENT SORBENT HANDLING SYS											
	SUBTOTAL 10.	$3,064	$94	$3,803	$0	$0	$6,961	$696	$0	$789	$8,445	$96
11	ACCESSORY ELECTRIC PLANT											
	SUBTOTAL 11.	$6,900	$1,025	$1,250	$0	$0	$9,175	$918	$0	$1,110	$11,203	$128
12	INSTRUMENTATION & CONTROL											
	SUBTOTAL 12.	$5,257	$595	$4,457	$0	$0	$10,309	$1,031	$0	$1,701	$13,041	$149
13	IMPROVEMENTS TO SITE											
	SUBTOTAL 13.	$1,074	$583	$3,041	$0	$0	$4,698	$470	$0	$1,034	$6,201	$71
14	BUILDINGS & STRUCTURES											
	SUBTOTAL 14.	$0	$2,181	$2,076	$0	$0	$4,257	$426	$0	$702	$5,385	$61
	CALCULATED TOTAL COST	$156,980	$49,415	$80,257	$0	$0	$286,651	$28,665	$9,948	$48,557	$373,822	$4,267

Table 1-5
100 MWe DICE GT-CRCC Total Overnight Cost Breakdown

Description	$/1,000	$/kW
Preproduction Costs		
6 months All Labor	$3,299	$38
1 Month Maintenance Materials	$357	$4
1 Month Non-Fuel Consumables	$525	$6
1 Month Waste Disposal	$12	$0
25% of 1 Months Fuel Cost at 100% CF	$784	$9
2% of TPC	$7,476	$85
Total	**$12,454**	**$142**
Inventory Capital		
60 day supply of fuel at 100% CF	$4,518	$52
60 day supply of non-fuel consumables at 100% CF	$982	$11
0.5% of TPC (spare parts)	$1,869	$21
Total	**$7,369**	**$84**
Other Costs		
Initial Cost for Catalyst and Chemicals	$1,940	$22
Land	$150	$2
Other Owner's Cost	$56,073	$640
Financing Costs	$10,093	$115
Total Overnight Costs (TOC)	**$461,901**	**$5,273**

1.2.3 Operating Cost

Table 1-6 presents a breakdown of the DICE GT-CRCC fixed and variable operating costs, including the cost of fuel, in 2018 dollars, similar in format to the NETL baseline reference cases. The delivered cost of PRB coal to the power plant is estimated at $36.6/ton. Coal beneficiation to MRC is expected to add $2.50/MMBtu, resulting in a fuel cost that is estimated to be $79.4/ton. This beneficiated coal cost has the largest impact on the annual operating cost.

1.2.4 First Year Cost of Electricity

Based on the overall performance, TOC, and annual operating cost of the 100 MWe DICE GT-CRCC plant, its first year COE is estimated to be $163.2/MWh. The assumptions used in estimating the COE are listed in Table 1-7.

At about $163/MWh, the COE for the 100 MWe DICE GT-CRCC is only about 14 percent higher than a large, 550 MWe-scale supercritical plant with CO_2 capture burning similar PRB coal. The high plant net efficiency, at 32.2 percent LHV after factoring in CO_2 capture, coupled with the low costs of the highly modular DICE, is able to mitigate the inherent economies-of-scale disadvantages of a small 100 MW-scale plant versus a large, baseload power plant, from a CAPEX and fixed OPEX (labor) perspective. It is believed and expected that no other conventional combustion-based technology is able to achieve such low costs at this scale.

Table 1-6
100 MWe Nominal DICE GT-CRCC Annual Operating Cost Breakdown

INITIAL & ANNUAL O&M EXPENSES						
Case:	DICE GT-CRCC					
Plant Size (MWe)	**88**					
Primary/Secondary Fuel:	**Wyoming PRB**			**Fuel Cost ($/MMBtu):**		
Design/Construction	3 years			**Book Life (yrs):**		20
TPC (Plant Cost) Year	Jun-18			**TPI Year:**		2018
Capacity Factor (%)	85			**CO2 Captured (TPD)**		1965

OPERATING & MAINTENANCE LABOR					
Operating Labor					
Operating Labor Rate (base):	$39.70 $/hr				
Operating Labor Burden:	30.0 % of base				
Labor Overhead Charge	25.0 % of labor				
Operating Labor Requirements per Shift	**units/mod**		**Total Plant**		
Skilled Operator	1.0		1.0		
Operator	3.3		3.3		
Foreman	1.0		1.0		
Lab Tech's etc	1.0		1.0		
TOTAL Operating Jobs	6.3		6.3		
				Annual Cost $	
Annual Operating Labor Cost				$2,848,253	
Maintenance Labor Cost				$2,430,408	
Administration & Support Labor				$1,319,665	
Property Taxes and Insurance				$7,476,439	
TOTAL FIXED OPERATING COSTS				**$14,074,764**	

VARIABLE OPERATING COSTS					
Maintenance Material Cost					**$3,645,612**
Consumables	Consumption Initial	Consumption /Day	Unit Cost	Initial Fill Cost	
Water(/1000 gallons)	0	237	1.87	**$0**	**$137,545**
Chemicals					
MU & WT Chem (lb)	0	1148	0.30	$0	$106,527
Limestone (ton)	0	21	40.50	$0	$267,383
Lube Oil for DICE					$469,336
Carbon (Mercury Removal) (lb)	0	1	1518.23	$0	$260,051
MEA Solvent (ton)	643	4.0	2721.80	$1,749,531	$3,410,649
Corrosion Inhibitor				$125,501	$432,628
MEA Reclaimer Additive (ton)	361	4.0	181.44	$65,450	$225,621
SCR Catalyst	0	0.01	9979.00	$0	$18,929
Ammonia (19% NH3) (ton)	0	0.23	368.40	$0	$25,784
Subtotal Chemicals				**$1,940,481**	**$5,216,909**
Waste Disposal:					
Ash from Coal Beneficiation	0	64	0.00	$0	$0
Fly Ash (ton)	0	14	28.03	$0	$122,271
Subtotal Waste Disposal				**$0**	**$122,271**
TOTAL VARIABLE OPERATING COSTS				**$1,940,481**	**$9,122,338**
PRB Coal (ton)	**0**	**949**	**79.39**	**$0**	**$23,362,999**
Natural Gas (MMBtu)	**0**	**7401**	**3.75**	**$0**	**$8,610,904**

Table 1-7
First Year Cost of Electricity (COE) Parameters and Cost Breakdown

Plant	**DICE GT-CRCC**
Size	**88 MWe**
Capacity Factor (CF)	**85%**
Years of Construction	**3**
Capital Charge Factor (CCF)	**0.111**
Total Overnight Cost, $MM	462
Fixed Operating Cost, $MM/yr	14.1
Variable Operating Cost @ 100% CF, $MM/yr	10.7
Fuel Cost @ 100% CF, $MM/yr	48.2
Annual 1000 MWh (100% CF)	767
COE (excl. CO2 T&S), $/MWh	**163.2**
COE Breakdown, $/MWh	
Fuel (incl. coal beneficiation)	49.0
Variable O&M	14.0
Fixed O&M	21.6
Capital Charges	78.6
Total COE, $/MWh	**163.2**

Note: 3 year construction for DICE GT-CRCC is consistent with NGCC construction period assumption as used by NETL in its reference reports. CCF used for COE evaluation for such 3 year, high-risk investor owned utilities (IOU) projects is 0.111

1.3 MARKET ADVANTAGE OF CONCEPT

The advantage of such a small DICE GT- CRCC is especially striking for certain markets, such as those with:

1. Small grid unable to accommodate large units
2. High natural gas price (more than $10 to $12 per million BTU)
3. Ability to use diesel fuel (places where gas supply is subject to uncertainty)
4. High ambient temperature and humidity
5. High altitude
6. Combination of the above.

1.4 DOMESTIC AND INTERNATIONAL MARKET APPLICABILITY

It is believed that the DICE GT-CRCC technology is highly suited for the US market due to its relative abundance of coal coupled with low natural gas prices, thus minimizing its feedstock costs.

Countries with relatively lower cost coal but high domestic natural gas prices (China, India, and Australia) may also find the DICE GT-CRCC concept and configuration appealing as the bulk of the fuel consumed is the lower cost coal, while the high efficiency of the system offsets the cost of co-firing more expensive natural gas.

Given the fuel flexibility of DICE and its ability to use diesel as feedstock, it is also applicable in the international market where crude oil prices are lower, such as in the Middle East.

Section 2 Plant Concept Description & Important Traits

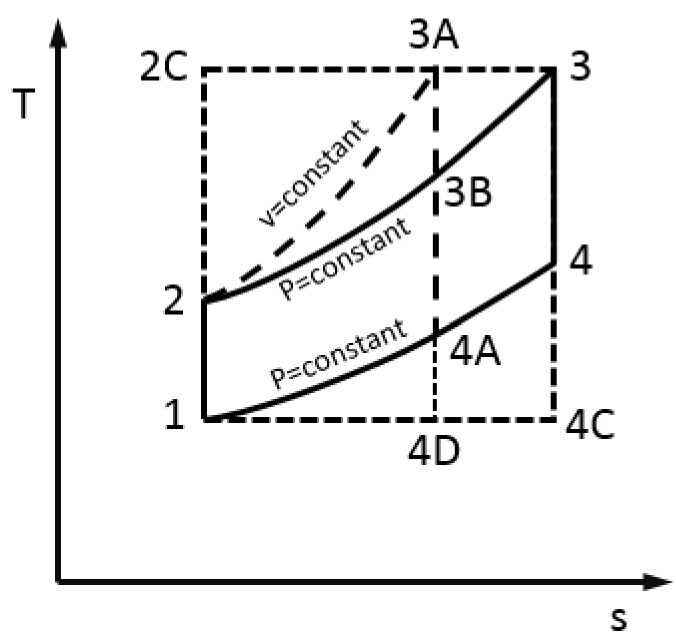
2.1 BASIC OPERATING PRINCIPLE

The thermodynamic driver behind the DICE GT-CRCC plant concept is described in detail in the papers and articles by Gülen earlier, e.g., Refs.[8-10]. The thermodynamic cycle of the power plant is a seamless 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 2-1, 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, not p3A > p3B)
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 2-1
Comparison of CPC {1-2-3-4-1} and CVC {1-2-3A-4A-1} cycles



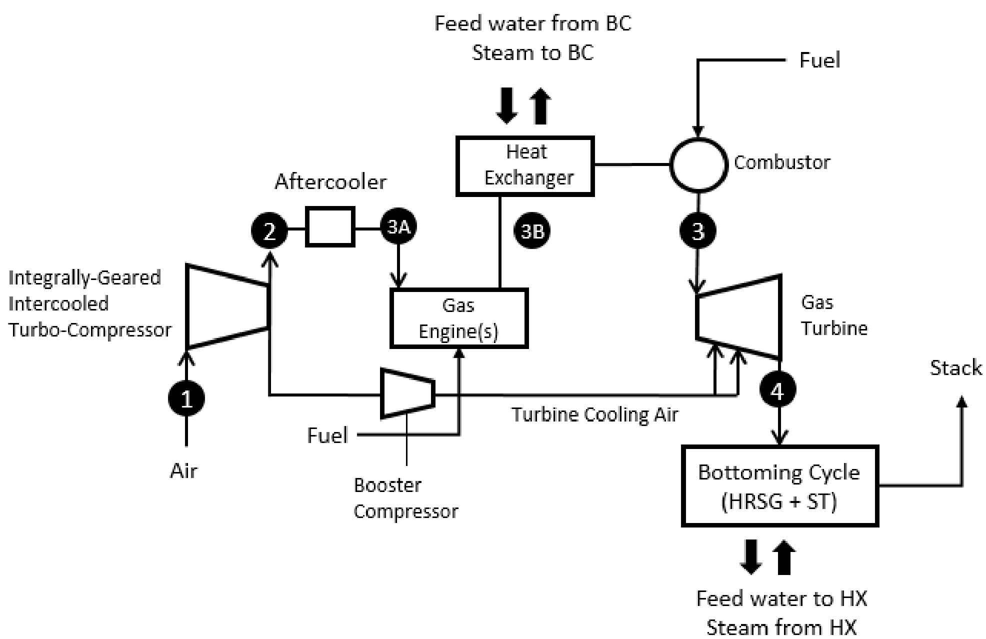
2.2 OVERVIEW OF DICE GT-CRCC SYSTEM

2.2.1 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 2-2):

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



2.2.2 Current Coal-Fired Embodiment

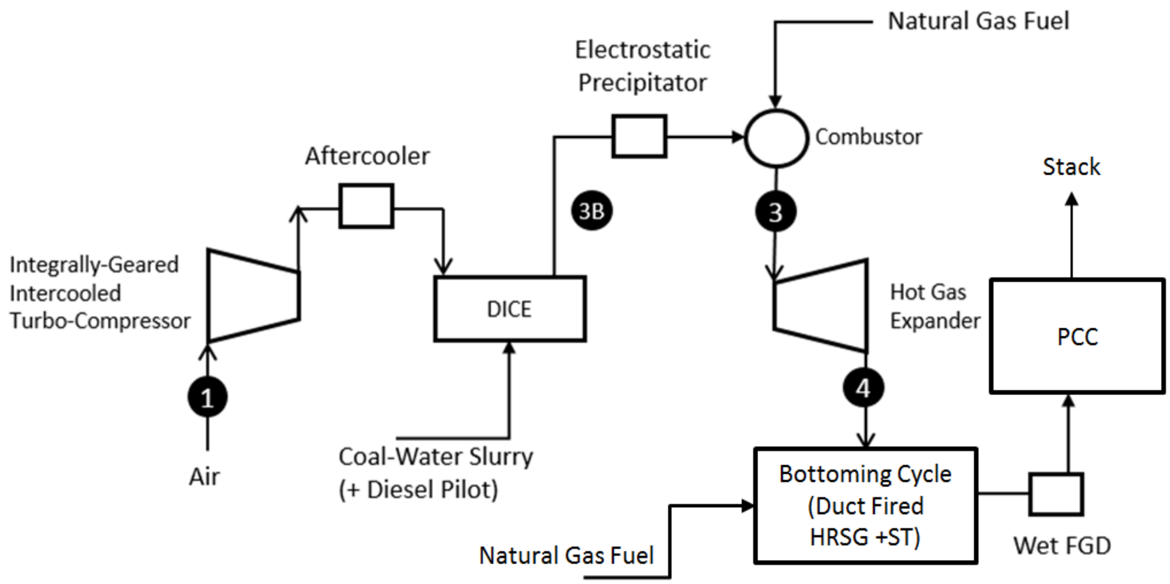
For this conceptual design of the coal-water slurry-fired DICE GT-CRCC a simplified version is considered for the following reasons:

- 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 2-3. For this system, compared to the original embodiment as shown in Figure 2-2:

- The gas turbine is replaced by a combustor plus hot gas expander combination
- The heat exchanger between the DICE and the hot gas expander is eliminated
- Duct-firing heat recovery steam generator (HRSG) is utilized to meet steam demand of PCC system

Figure 2-3
Simplified Schematic Diagram of Coal-Fired DICE GTCC with Hot Gas Expander and Duct-Fired HRSG



These changes are enabled by the following equipment characteristics:

- The hot gas expander is an off-the-shelf equipment widely used in the chemical process industry
- Its low pressure ratio (less than 4:1) ensures that the DICE exhaust (after the removal of the turbocharger unit) is adequate to supply it with hot gas (below the autoignition temperature of the natural gas)

As envisioned in Figure 2-3, 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 to generate power. The DICE exhaust gas temperature, expected to be between 575 and 600 °C, is sent to the hot gas combustor, which burns natural gas fuel (second heat addition or *reheat*) to generate hot gas for expansion in the hot gas expander. Maximum allowable inlet temperature into the hot gas expander is 760 °C (1,400 °F). This should allow for a simple combustor design with very low NOx 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 again and the cycle continues.

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 first desulfurized in a standard wet flue gas desulfurization (WFGD) scrubber system that uses limestone to react with and remove about 95 percent of the SOx in the flue gas, lowering the SOx content to around 15 ppmv.

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.

2.3 MAJOR PROCESS BLOCK DESCRIPTION

2.3.1 Coal Beneficiation

The fundamental technical and operational challenges in modifying and/or operating a standard reciprocating internal combustion engine (RICE) designed for liquid fuel (e.g., heavy fuel oil, HFO) for coal-fired operation are primarily: 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. Particular engine components that need protection are:

- Fuel injection pump system and nozzle tip
- Piston rings and cylinder liners
- Exhaust gas valves and seats
- Crankshaft bearings need protection from any used oil contaminants (e.g. ash)

Preparation of coal-water slurry (CWS) fuel for utilization in DICE entails two key objectives:

- Generate a “fluid” fuel from a “solid” feedstock by
  - Grinding the solid feedstock into fine particles
  - Mixing the resulting “powder” with water
  - Using additives to prevent agglomeration and control the slurry shear viscosity

- “Cleaning” the coal to reduce the ash and non-organic sulfur content

The cleaning process is between grinding and mixing with water. This is so because, in order to remove ash and non-organic sulfur from coal, those particles must be in a form that can be "liberated" from the coal. In order to achieve liberation, the coal must be crushed to a size that is smaller than the particle size of the ash and pyrite inclusions.

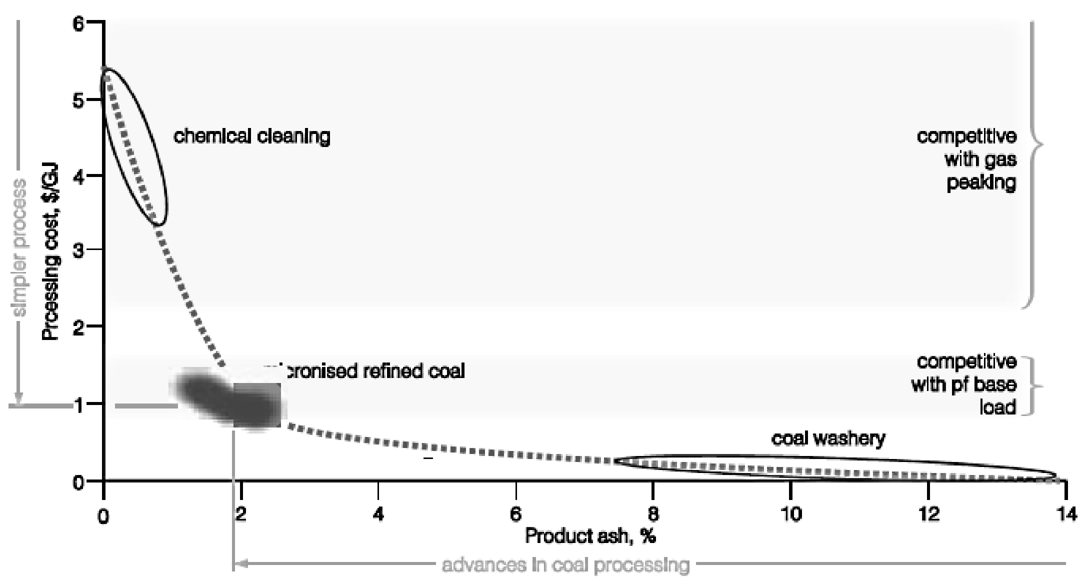
Coal cleaning/washing, commonly referred to as "beneficiation", can be "physical" (e.g., froth flotation, selective agglomeration and dense medium separation) or "chemical" (i.e., using solvents). Physical cleaning can remove only the "minerals" in the coal (and sulfate/pyritic sulfur in the coal). Organically-bound components, which make a contribution to ash formation during combustion, are not affected by the washing processes because they are spread throughout the structure of the coal and cannot be liberated by simply crushing or grinding the coal.

Under the right conditions, e.g., ash content and composition of the feedstock, specific milling process to produce fine particles, etc., chemical beneficiation can reduce ash content to 0.2 wt% but at high cost and undesirable "side effects". Physical beneficiation, again depending on the feedstock and process, can bring the ash content down to a few per cent by weight. In particular, physically-cleaned coals are classified into two main groups:-

- Superclean coals – ash content less than 3 wt%
- Ultraclean coals - ash content less than 1wt%

The aforementioned 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 [1]. 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 2-4 (from [3], original work done by Wibberley in 2013).

Figure 2-4
Product Ash (Dry Basis) of Coal Beneficiation Techniques with Cost



Micronized Refined Coal (MRC) in Figure 2-4 refers to finely ground low ash carbons in a slurry, which is similar in consistency to acrylic paint. There are a variety of MRC production processes, which are described in some detail in other reports [3] In generic terms, for high rank coals, the process comprises (in the order listed) [11]:

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

(Micronizing before de-ashing instead of before injection avoids fuel contamination by the grinding media)

As noted by Wibberley [11], surface-selective separation techniques such as froth flotation are probably not suitable for low rank coals with very low mineral ash content (e.g., Victorian coal with as low as 0.3 wt% mineral ash). A size/density separation would be used for a de-sanding step (mostly to remove relatively coarse sand entrained during mining operations) followed by hydrothermal dewatering.

For effective atomization when injected into the DICE cylinder, MRC should have a maximum size of around 50 microns and a coal concentration of at least 55 percent (i.e. 45 percent water). Average (D50) size is less than 20 microns. Nominal coal properties for MRC from physical cleaned/processed high rank (i.e., anthracite or bituminous) and low rank (i.e., subbituminous or lignite) coals are given in Table 2-1 [4]. The cost of the MRC fuel is dominated by the cost of the feedstock (coal) and the micronizing process. Data in the table is based on CSIRO research involving Australian coals. For a particular coal, petrographic analysis is requisite to determine the mineral and organic ash components. This should be followed by a careful trade-off between the cost of producing the MRC and the engine/plant cost (including CAPEX and OPEX).

Table 2-1
Nominal MRC Properties

	High Rank Coal (HRC)	Low Rank Coal (LRC)
HHV (MJ/l)	21-25	16-19
Mineral ash (%w dry)	1-2	0.2-1
Total ash (%w dry)	1-2	2-3
Viscosity (Pumping), mPa-s	200-500	400-700
Viscosity (Injection), mPa-s	100-300	200-400
D50 (micron)	10-15	10-15
D95 (micron)	50	70
Cost (incl. coal, AUD/GJ)	$4-6	$2-3

After accounting for the original coal price, it is expected that the physical beneficiation process increases the cost of feedstock by about $2.50/MMBtu HHV.

2.3.2 DICE - General

The heart of the coal-fired DICE GT-CRCC is the DICE itself. Typically, pulverized coal is mixed with water to form a "slurry", which is directly injected into the engine cylinders. In the past, a wide range of diesel engines have been used to fire coal-water slurry or MRC, including high-speed designs with up to 1,900 rpm engine speeds ([1], [2], [3], [11]). Nevertheless, according to Wibberley [4, 11], the most suitable engines are the low-speed two-stroke, marine-type engines (10 to 100 MW at 90 to 120 rpm) and largest four-stroke medium-speed engines (20 MW at 400 to 500 rpm). The reason for that is their longevity and tolerance to lower quality fuels (such as residual fuel oils which contain up to 0.15 percent of highly abrasive corundum-like catalyst fines), to allow easier MRC fuel specifications, i.e., higher mineral ash content, coarser coal top size and higher viscosity.

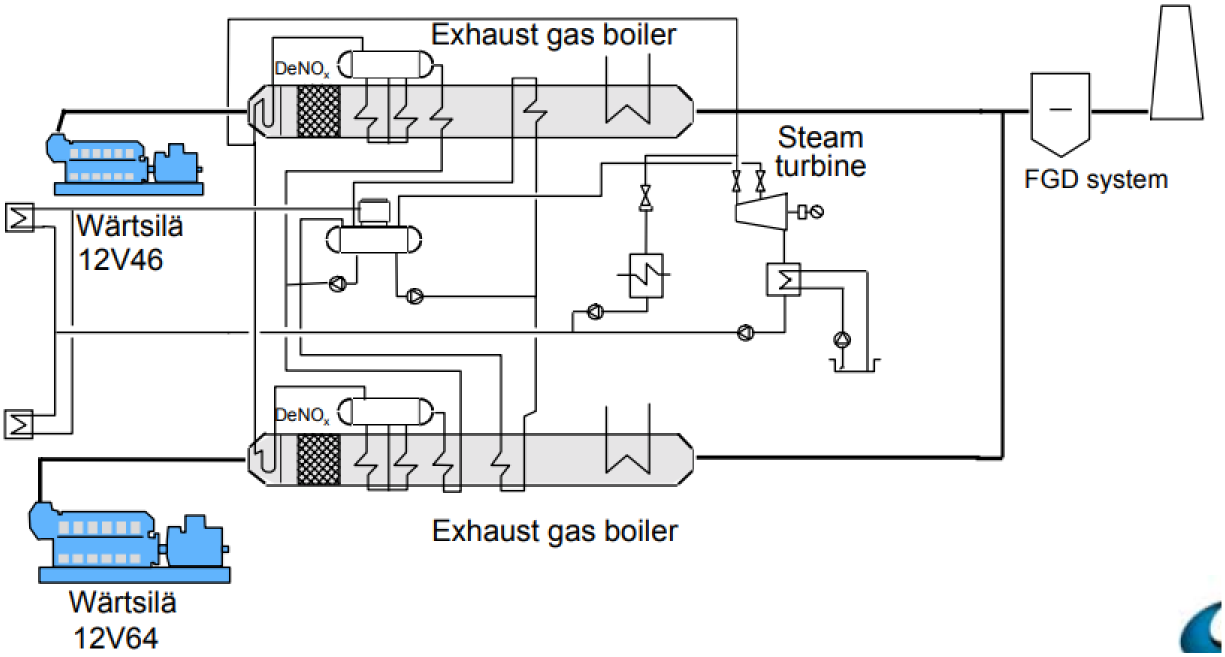
From a commercially proven application perspective, Wärtsila's experience in burning Orimulsion® in medium-speed engines (engine type 46) is of particular interest. *Orimulsion* is a registered trademark name for a bitumen-based fuel that was developed for industrial use by Intevep, the Research and Development Affiliate of Petroleos de Venezuela SA (PDVSA). Orimulsion is made by mixing bitumen with about 30 percent fresh water and a small amount of surfactant. Its properties are comparable to that of heavy fuel oil (HFO), per Table 2-2. It is noteworthy that Orimulsion properties are quite close to MRC except the ash content.

Table 2-2
Comparison of Orimulsion and Heavy Fuel Oil

	Orimulsion®	Heavy Fuel Oil
Water content, %w/w	28 - 30	≤ 1
Median droplet size, µm	13 -15	-
Density (15°C), kg/m³ in air	1000 -1020	930 -1010
Viscosity, mPa.s at 30°C	200 - 350	2,400
at 50°C	145 - 220	500
Net calorific value, kJ/kg	28,000	41,000
Sulphur, %w/w	2.8 - 3.0	1 - 4
Ash, % w/w	< 0.1	< 0.1
Vanadium, ppm	320	100 - 300
Surfactant, % w/w (main component alcohol ethoxylate)	0.2	-

Of particular interest is the *Wasa Pilot Power Plant* in Finland with two Orimulsion-fired 12V46 engines in a combined cycle configuration. A schematic diagram of the power plant is shown in Figure 2-5. Engine differences vis-à-vis the HFO-firing variant are summarized in Figure 2-6.

Figure 2-5
Wasa Power Plant with Two Orimulsion-Fired 12V46 Engines [12]



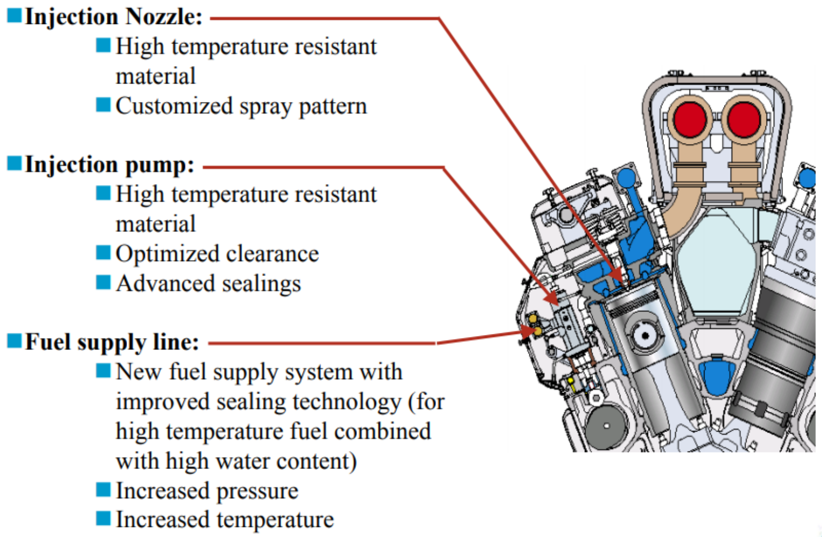
According to Wärtsila, engine performance with Orimulsion did not change much; essentially the same heat rate with about 9 percent lower output due to injection pump restrictions [12]. As far as emissions are concerned, Orimulsion-fired engine had about 30 percent lower NOx and about the same CO and unburned hydrocarbons [12]. SO_2 emissions depended on the fuel (HFO had 4 wt% sulfur). Particle emissions were higher because of higher ash content. Back end cleaning included an electrostatic precipitator (ESP), wet flue gas desulfurization (WFGD) and selective catalytic reduction (SCR).

From a maintenance perspective, service intervals and component lifetimes were somewhat shorter due to the high viscosity, sulfur and ash content [12].

MRC-fired DICE engine retrofit considerations are:

- Atomizer nozzle wear
- Piston ring jamming
- Abrasive wear
- Ignition delay
- Exhaust valve seat wear
- Fuel system blockage
- Fuel stability
- Fuel system corrosion

Figure 2-6
Engine Differences for Orimulsion vs HFO Firing [12]



These problems and possible remedies have been previously discussed [11]. Briefly:

- Known solutions to atomizer nozzle wear include diamond compact or silicon carbide nozzles and the use of lower speed engines (with increased time for combustion giving a higher tolerance to poor atomization).
- US-DOE program and more recent CSIRO tests using four-stroke engines did not experience piston ring jamming – presumably due to better atomization and the increased tolerance of trunk-piston engines to cylinder contamination.
- Abrasive wear can be reduced by plasma-spray carbide coatings.

Rapid ignition after injection is critical to reliable and efficient diesel operation. When fuels exhibit a long ignition delay (say >10 ms), the well-known "knocking" phenomenon can lead to excessive peak pressures beyond the mechanical limits of the engine. This reduces the thermal efficiency of the engine, and can cause overheating and ring failure [4].

Ignition delay and knocking problem can be rectified by pilot injection of diesel to ensure reliable ignition particularly at low load. However, Wibberley reports that experimental work in CSIRO (in Australia) and RWE (in Germany) demonstrated ignition delays below 5 ms have been demonstrated for a wide range of coals, and are comparable to acceptable fuel oils [4].

2.3.3 DICE – Present Study/Concept

In this study, a "generic" medium-speed, four-stroke RICE with performance modified for MRC combustion was chosen. The base engine is Wärtsila's 18V46, which is widely used in power generation applications with HFO. Detailed engine performance (at ISO 3046 conditions, i.e., 25°C ambient temperature, 100 m above sea level and 30 percent relative humidity) with liquid fuel operation is summarized in Table 2-3. It should be noted that:

- Charge air and exhaust flows in the table are ± 5 kg/s;
- Exhaust gas temperature in the table is ± 15°F;
- Electrical output at generator terminals (PF = 0.8) includes engine-driven pumps at 100 percent load;
- Performance (heat rate) tolerance is 5 percent.

Table 2-3
Wärtsila Type 46 Liquid Fuel Engine Data

Performance data			
Engine			18V46
Engine optimisation: NOx (dry @ 15 vol-% O_2)		ppm-vol	900
Electric power		kW	17076
Heat rate [1]		kJ/kWh	7732
Efficiency [1]		%	46.6
High temperature circuit inlet/outlet [2]		°C	79/91
– HTCAC temperature inlet/outlet		°C	83/91
– Cylinder temperature inlet/outlet		°C	79/83
Low temperature circuit inlet/outlet		°C	42/55
– Lubrication oil circuit inlet/outlet		°C	63/80
– LTCAC temperature inlet/outlet		°C	42/47
Charge air flow	± 5%	kg/s	32.1
Exhaust gas flow	± 5%	kg/s	33.0
Exhaust gas temperature	± 15°C	°C	357
Exhaust gas heat	± 10%	kW	11771
High temperature circuit-energy	± 10%	kW	5251
– HTCAC energy	± 10%	kW	3557
– Cylinder cooling energy	± 10%	kW	1694
Low temperature circuit-energy	± 10%	kW	3819
– Lubrication oil energy	± 10%	kW	2294
– LTCAC energy	± 10%	kW	1525
Heat losses by radiation	± 20%	kW	519

Engine technical data is summarized in Table 2-4.

Table 2-4
Wärtsila's 18V46 Engine Technical Data

	Ship Power and Power Plant engines
Cylinder bore	460 mm
Piston stroke	580 mm
Cylinder output	975 kW/cyl
Engine speed	500, 514 rpm
Mean effective	
pressure	24.3, 23.6 bar
Piston speed	9.7, 9.9 m/s

Engine speed for 50/60 Hz power-gen units is 500/514 rpm. Medium engine speed and large cylinder bore (close to half a meter) are imminently suitable to MRC application.

Heat balance analysis of the data in Table 2-3 is summarized in Table 2-5. Mechanical losses are lumped into the generator efficiency (97 percent; without them, generator efficiency is probably closer to 98.3 percent). The significantly large heat balance error of the brochure data is most likely a combination of plant heat rate and exhaust flow/temperature tolerances.

Table 2-5
18V46 Heat Balance Table

		As Listed	Closed HMB	
Heat Consumption	kWth	36,675	37,131	100%
Charge Air Cooler Heat Rejection	kWth	5,082	5,082	13.7%
Lube Oil	kWth	2,294	2,294	6.2%
Jacket Water	kWth	1,694	1,694	4.6%
Surface heat	kWth	519	519	1.4%
Exhaust	kWth	11,711	9,940	26.8%
Shaft Output	kW	17,602	17,602	47.4%
Heat Balance Error	kW	-2,227	0	
HB Error / Heat Consumption		-6.07%	0.00%	
Generator Output	kWe	17,076	17,303	
Generator Efficiency		97.01%	98.30%	
Overall Efficiency		46.56%	46.60%	
Exhaust flow	kg/h	118,800	102,693	
	kg/s	33.00	28.53	
Exhaust Temp	C	357.0	345.6	

For the purposes of this study, specifically for the MRC-fired version, the turbocharger unit is removed so that reliable estimates of the following parameters are needed:

- Charge air conditions, pressure and temperature, at the engine intake valve
- Exhaust gas conditions, pressure and temperature, at the engine exhaust valve.

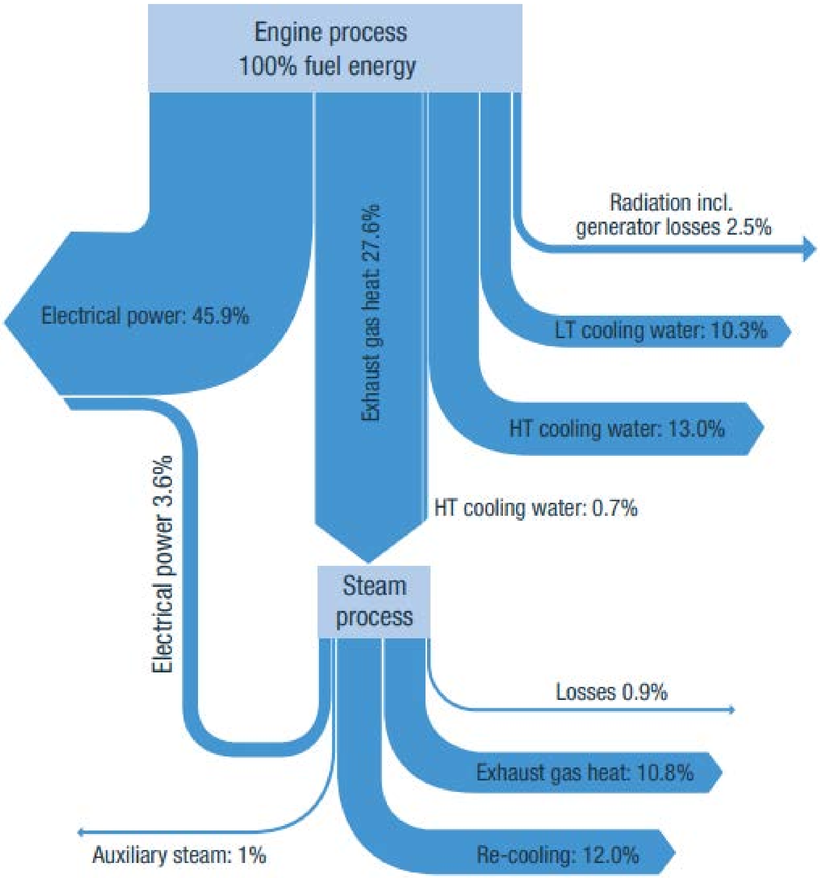
Both sets of parameters require a reasonable estimate of the engine turbocharger performance. Type V46 engines of larger sizes (12, 16 and 18 cylinder versions) use two ABB TPL 76-C model turbochargers. A single-pipe exhaust (SPEX) system is characteristic of Type 46 engines. In this system, exhaust pipes from the same cylinder bank are connected to a common exhaust gas receiver feeding one turbocharger. Hot compressed charge air is cooled by two water-cooled heat exchangers in series, high-temperature and low-temperature charge air coolers, HTCAC and LTCAC, respectively. According to the data in Table 2-3, the total cooling duty of HTCAC and LTCAC is about 5 MWth. TPL 76-C is capable of compressing the charge air up to 5.2 bara. The isentropic efficiency of the compressor is estimated to be in the low seventies range. For 1 bar and 25°C inlet air (32.1 kg/s), with a polytropic efficiency of 78 percent and pressure ratio of 5 (isentropic efficiency 73.08 percent), cooled charge air at the engine intake is calculated as 105°C (222°F), which is rather high.

For heat and mass balance closure, we used the illustrative Sankey diagram of a MAN Diesel & Turbo 18V48/60 engine, which is very similar to Wärtsila 18V46 (from page 61 of *Power Plants – Programme 2015/16*), which is shown in Figure 2-7.

Comparison of data in Table 2-3 and Figure 2-7 clearly indicates that the biggest disconnect is in engine exhaust gas energy. Using this finding as a guideline, Wartsila 18V46 heat balance closure is achieved as illustrated in Table 2-5 . In particular,

- 1.25 percent higher heat consumption
- 4.5 kg/s lower exhaust flow
- 11.4°C lower exhaust temperature
- 15 percent lower exhaust energy

Figure 2-7
Sankey Diagram (Similar MAN Diesel & Turbo Engine, 18V48/60)

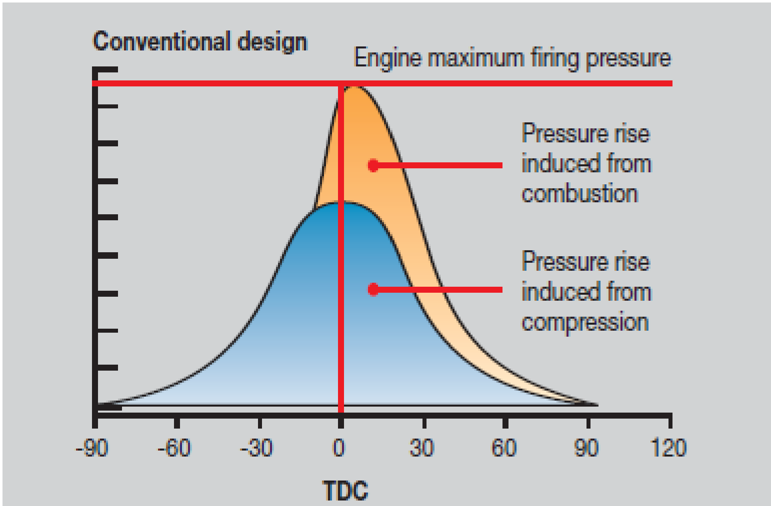


For engine calibration using the THERMOFLEX program, the engine is modeled as a “pseudo” gas turbine with a compressor, combustor and expander. For the core engine, data in the column labeled “Closed” in is used. Cylinder peak pressure of 190 bara and peak temperature of 1,529°C (1,802 K) are estimated from the following information and conceptually described in Figure 2-8:

- 18V46 compression ratio (CR) of 14 (brake mean-effective pressure, BMEP is 24.9 MPa)
- Corresponding pressure ratio (PR) of 20 during compression stroke with moderate Miller timing;
- Pressure rise during constant-volume combustion at the TDC with PR of 1.9.

Exhaust gas temperature at the turbocharger expander inlet was found as 546°C (1,015 °F).

Figure 2-8
Cylinder Pressure versus Crank Angle History



For the performance of the calibrated engine model with the study MRC fuel, it is necessary to estimate performance debit resulting from the fuel change (i.e., from HFO to MRC). Table 2-6, derived from Table 4 from Nicol [3] (originally from Wibberley's 2013 publication), provides a breakdown of efficiency loss for a 50 MWe engine when modified from HFO to MRC. A relative fuel processing debit of 4 percent (not absolute percentage points) accounts for MRC processing (flotation, milling, etc.), which takes place outside the engine control volume. Application of the loss factors in Table 2-6 to the Wartsila 18V46 performance (brochure performance and closed heat balances) in Table 2-5 results in the estimated DICE performance firing MRC as summarized in Table 2-7. Based on THERMOFLEX model runs, MRC preheating from 25°C to 185°C improves engine heat rate by about 3 percent.

Table 2-6
Efficiency Loss Breakdown for DICE

Table 4 Efficiency breakdown for DICE (Wibberley, 2013d)	
	% (LHV)
Mechanical efficiency of 50 MWe engine on HFO in 2019 (with improved processing and larger engine)	56.7
Percentage change in heat rate for MRC-DICE over base HFO engine	
Fuel processing	–4
Dry coal versus diesel fuel (dry coal has higher theoretical efficiency)	+2
Slurry penalty (MRC normally @ 20°C)	–9
Fuel preheat from waste heat	+1.75
Combustion penalties (due to excess jet penetration, poor atomisation and ignition delay)	Nil with suitable design
Generator and balance of plant	–3
Overall generation efficiency of MRC-DICE	50 (48.1 HHV)
CO_2 emissions on a life cycle analysis basis (kg_{CO2}/MWh)	720

Table 2-7
Efficiency Loss Breakdown for 18V46 (HFO to MRC)

	As Listed		Closed HMB	
Base BTE	48.04	48.04	47.41	47.41
Fuel Process	0	0	0	0
Dry Coal	2	0	2	0
Slurry penalty	-9	0	-9	0
Fuel preheat	3	0	3	0
CWS BTE	46.12	48.04	45.51	47.41
Generator & BOP	-3	-3	-1.7	-1.7
CWS Gen Eff	44.74	46.60	44.74	46.60

For the MRC-fired 18V46 in the study, we decided to apply the output debit of 9 percent (based on Wartsila's Orimulsion firing experience cited above). Heat and mass balance calculation results for MRC firing with unheated and preheated fuel are summarized in Table 2-8.

Table 2-8
HFO and MRC-Fired 18V46 Heat Balance Data

		As Listed	Closed HMB	MRC (Fuel preheat)
Heat Consumption	kWth	36,675	37,131	35,407
Fuel Heating	kWth			1,024
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	11,711	9,940	10,593
Mechanical Losses	kW			231
Shaft Output	kW	17,602	17,602	16,018
Heat Balance Error	kW	-2,227	0	0
Generator Output	kWe	17,076	17,303	15,746
Overall Efficiency		46.56%	46.60%	44.47%
Exhaust Flow	kg/h	118,800	102,693	105,732
	kg/s	33.00	28.53	29.37
Exhaust Temperature	C	357.0	345.6	367.3

We decided to go with the more optimistic efficiency in Table 2-7. One reason for that is the availability of Wärtsilä 46 "performance package" comprising engine tuning by means of a unique camshaft modification to Miller timing and an upgrade to ABB TPL76C turbochargers[1]. Another reason is that publications from 1980s and early 1990s describing DICE studies done by various OEMs (papers by Ryan III, Caton & Hsu, McMillian & Webb from the bibliography of Ref. [3]) consistently state that no performance degradation was observed vis-à-vis diesel operation.

A confirmation of these findings was provided by a detailed analysis Fairbanks-Morse MAN 51/60 dual-fuel engine (14.7 MWe, 500 rpm, 14 cylinders) by CZERO. Original gas-fired engine performance is rated at 38% brake thermal efficiency (BTE). CZERO built a detailed engine model in GT-POWER, which is a software package for engine simulation with a detailed cylinder model and combustion analysis developed and marketed by Gamma Technologies, LLC (Westmont, IL). Calibrated engine model was run with CWS (as specified in Ref. [2]) with a diesel pilot. At the same power output as the base engine with natural gas fuel (also using a diesel pilot), BTE was found as 36.77% (no fuel preheating). Exhaust gas conditions at the turbocharger expander inlet was 4 bara and 575.5°C. With fuel preheating to 185C, BTE would increase to 37.87%, i.e., practically no performance debit for CWS firing.

The "pseudo" gas turbine model in THERMOFLEX, calibrated to the HFO-fired brochure performance, is run with study MRC fuel to a generator output of ~15.5 MWe. Exhaust gas conditions at the turbocharger expander inlet are found as 4 bara and 543 to 553°C. Peak cylinder pressure is 190 bara and peak cylinder temperature is 1,448 to 1476°C (1,721 to 1749 K).

A more concrete estimate requires detailed engine and cylinder combustion modeling. Ignition delay and slow burning of MRC fuel is the key problem. As mentioned earlier, experiments undertaken by the US-DOE necessitated diesel pilot (about 12 wt% of total engine heat consumption) to overcome this problem. Researchers in Germany and Australia found that better atomization (e.g., air-blast atomization) was a remedy that obviated the need for a pilot fuel. In particular, ignition delays below 5 ms have been demonstrated for a wide range of coals, and are comparable to acceptable fuel oils and it was shown that coals ignite and burn rather well under diesel engine conditions (e.g., 7-10 MPa and 600°C at the point of injection) [4].

2.3.3.1 DICE Cost

In Ref. [2] (Table 15 on p. 67), a detailed breakdown of cost premium estimate for DICE (vis-à-vis conventional recip engines) is presented. On engine cost basis, the premium was estimated as nearly 50 percent. The largest contributor to the premium was the turbocharger.

[1] In Miller timing, the inlet valves close just before the piston reaches the bottom dead center (BDC). This method, called "Miller timing", reduces the work of compression and the combustion temperature, which results in higher engine efficiency and lower emissions. It should be noted that, with Miller timing, effective compression ratio of the engine is lower than the nominal compression ratio (14 for 18V46). Consequently, the pressure at the end of the compression stroke is somewhere between 80 and 100 bara. (In fact, due to its beneficial effect on NOx emissions (lower peak pressure and temperature), pretty much all modern engines operate with at least moderate Miller timing.)

In the present concept and configuration, DICE comprises the core engine only; there is no integral turbocharger unit. This reduces the estimated premium to about 20 percent. This is another benefit of the turbocompound concept (see section 2.5.1 below for the significant performance benefit).

A typical unit price for RICE is $350/kW, which comes to $6.3 million for an 18 MWe engine and $7.56 million for its DICE version (core engine only). For the study DICE rated at 15.5 MWe, this price corresponds to $485/kW. For five units with 10 percent quantity discount, total DICE equipment price is $34 million. Since the engine comes prepackaged from the factory, installation materials and labor are not expected to include a premium.

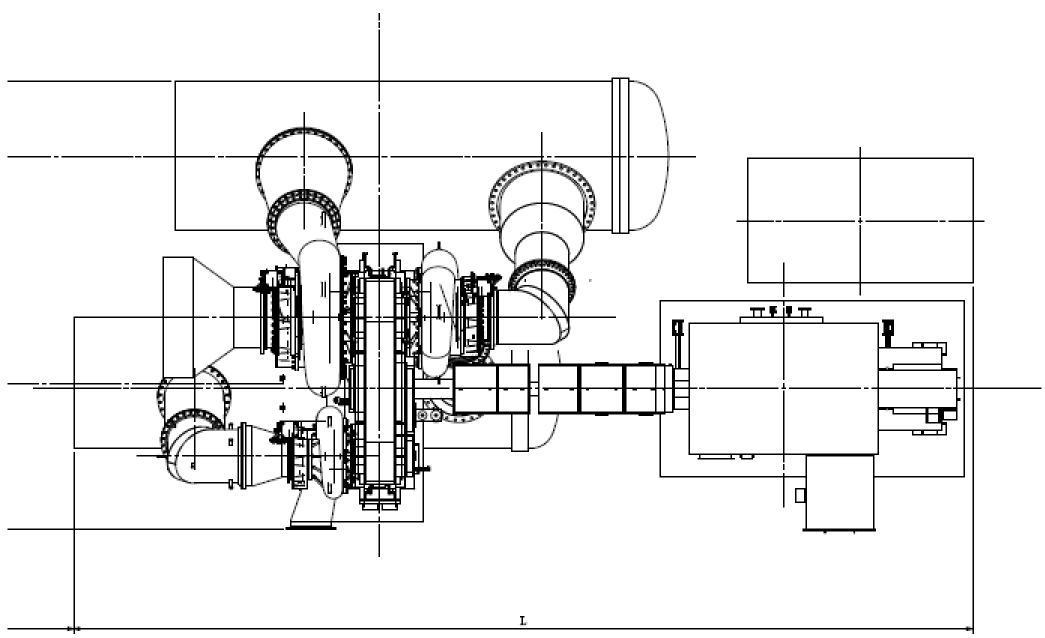
2.4 OTHER PLANT COMPONENTS

The remaining major plant system components are standard off-the-shelf equipment, described briefly in this section.

2.4.1 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, Kobelco's Model VG674 with a synchronous AC driver motor is considered. The compressor has two sections, each with two stages with an intercooler in between. The two sections are combined by an integral gear. Thus, each section's speed is optimized for the best performance (e.g., 5,460 rpm and 6,102 rpm). A plane view of the unit is shown in Figure 2-9. 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 2-9
Main Air Compressor (MAC) Plane View (Kobelco)

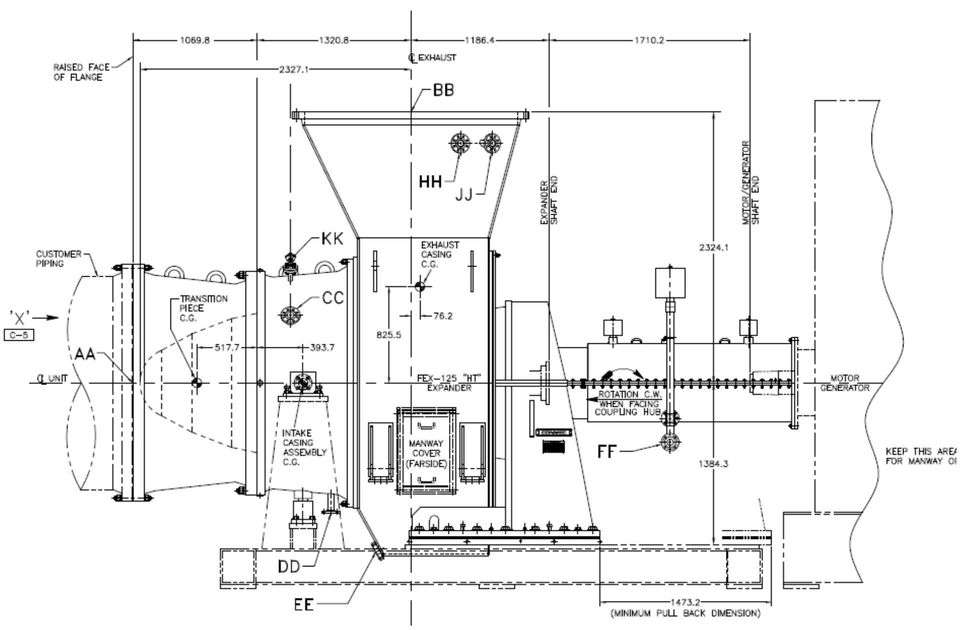


2.4.2 Hot Gas Expander

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 2-10. 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 study concept conditions, i.e., pressure ratio of about 3.5, the specific power output is about 125 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[2]. Otherwise, extremely abrasive particles can catastrophically damage the blades and casing walls within a few hundreds of hours of operation.

Figure 2-10
Baker Hughes Hot Gas Expander (HGE) Elevation View



[2] 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.

For the particular machine herein, BHGE requires that 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 may be the better choice of particle removal equipment (vis-à-vis ESP) in DICE GT-CRCC.

2.4.2.1 HGE Combustor

DICE exhaust gas is expected to be around 1,000 °F (~540°C) based on the preliminary estimates presented above (primarily from heat and mass balance analysis). The gas temperature is raised to 1,400°F in a standalone combustor/gas burner upstream of the HGE. One concern about the combustor design is the O_2 content in the DICE exhaust gas, which is less than 10 percent by volume. From a purely theoretical stoichiometry perspective, the O_2 content is more than enough for the temperature rise. From a practical perspective, however, as a rough rule of thumb, when the O_2 concentration within most fuel-air mixtures falls below about 10 percent by volume no combustion can occur. The exact value of the minimum O_2 concentration (MOC) limit is a function of fuel flammability and minimum ignition energy requirements. The MOC varies with pressure, temperature and type of the inert gas in the mixture, which in this case is primarily nitrogen with about 70 percent by volume along with H_2O (about 10 percent) and CO_2 (about 8 percent). In a gas turbine combustor, there is design flexibility to adjust air-fuel mixture in the flame zone with close to stoichiometric flame temperature and mix it with bypassed gas flow. This eliminates the need for augmenting air to raise the O_2 content but might impact NOx emissions adversely. The alternative is to use air extraction from the MAC discharge and mix it with DICE exhaust gas upstream of the particulate removal equipment. The performance trade-off is with gas flow rate (higher) and combustor inlet temperature (lower) with fixed 70-30 coal-natural gas fuel split (lower). The base case herein assumes 10 kg/s augmenting air to raise O_2 content in DICE exhaust gas above 10 percent by volume.

2.4.3 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.

2.4.3.1 HRSG Duct Burner

The HRSG is supplementary-fired to produce the requisite amount of steam for the MEA stripper reboiler in the PCC plant. The duct burners use the same natural gas fuel as the HGE combustor. The burner grid is placed upstream of the superheater tube bank. Correspondence with a duct burner vendor (De Jong Combustion b.v. in Netherlands) verified that the MOC limit is not satisfied without augmenting air.

Oxygen concentration in the HGE exhaust gas is about 9 percent by volume with N_2 at about 71 percent by volume and H_2O at 11 percent by volume, The exhaust gas temperature is at about 472 °C (882 °F). At 528 °C (982 °F) gas temperature and 8.2% percent by volume O_2 in the incoming flue gas, the duct burner vendor estimated 10 percent augmenting air flow to satisfy flammability requirements, which brought the O_2 concentration to 9.3 percent by volume. Thus, in our calculation, with colder incoming flue gas but higher O_2 concentration, we assumed 16 percent augmenting air to bring up the O_2 concentration above 10 percent by volume. The duct burner is fired to 625 °C (1,157 °F) to generate enough steam to satisfy the PCC stripper reboiler demand (about 50 MWth HHV thermal duty).

2.4.4 Back-Pressure Steam Turbine (BPST)

The study concept incorporates post-combustion carbon capture (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 back-pressure, 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 2-11. 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. The fully-modeled bottoming cycle, including the HRSG, STG and the standalone deaerator, is shown in Figure 2-12.

Figure 2-11
Dresser-Rand DR R/RS Type Steam Turbine

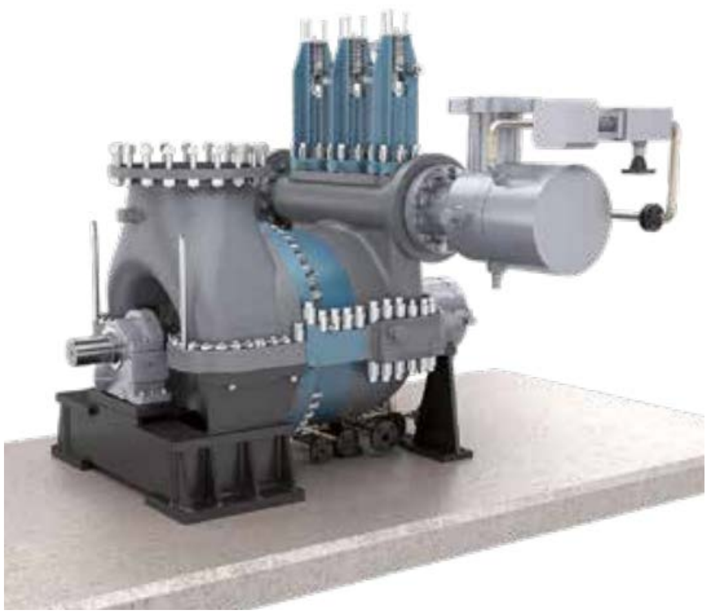
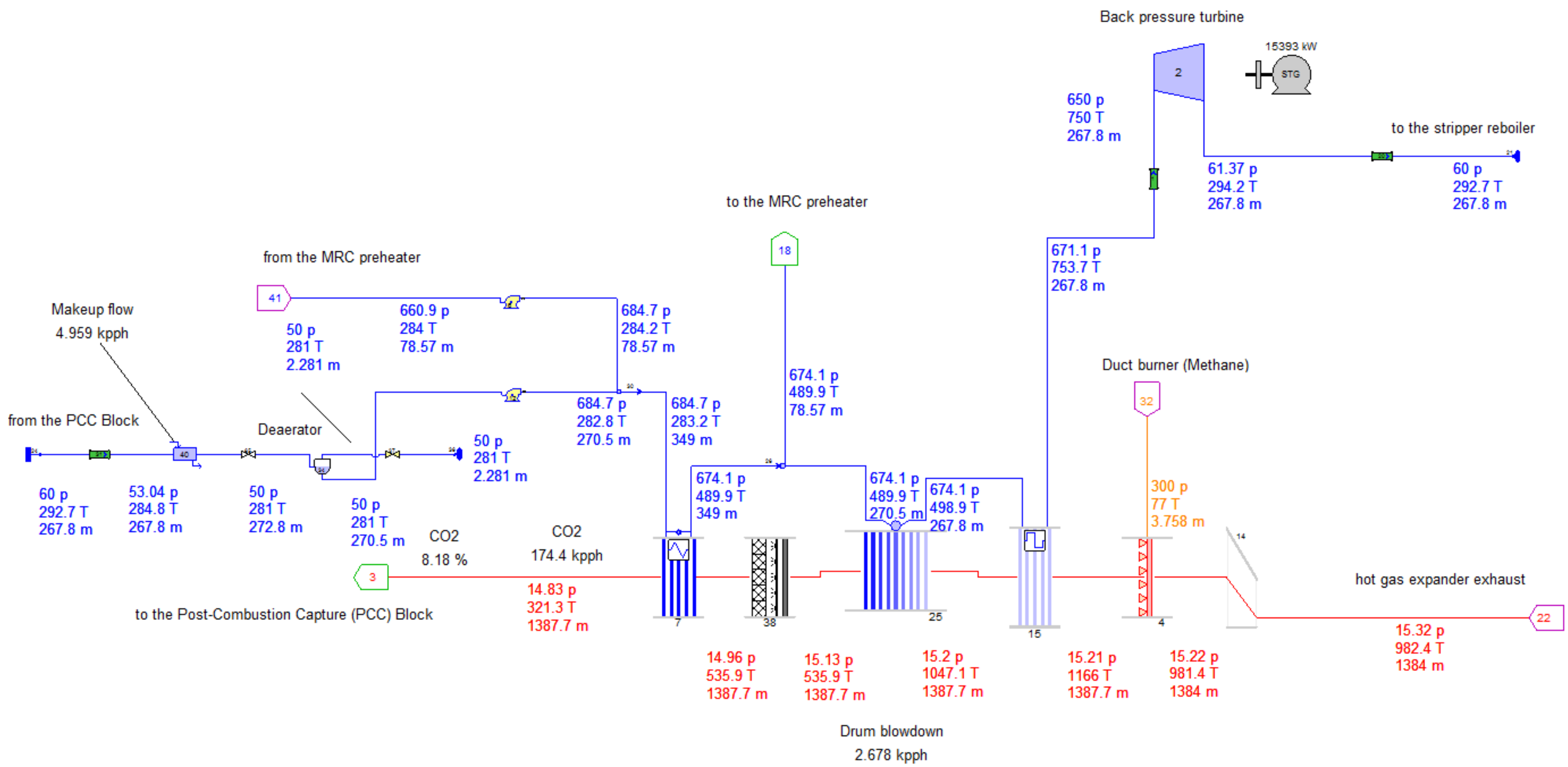


Figure 2-12
HRSG Steam Bottoming Cycle



2.4.5 LP Condensing Turbine and Surface Condenser

Additionally, the DICE GT-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 an additional 13 MW of power from the steam that is normally routed to the PCC when it is in operation. Coupled with the reduced auxiliary load from the PCC that is offline, the DICE GT-CRCC can generate up to a total of 28 MW more power, achieving a net efficiency of 41.6 percent LHV (39.3 percent HHV).

The LP turbine is connected to the generator via a SSS clutch. The clutch separates the LP turbine from the generator when the PCC is online. When the PCC is offline, steam from the back-pressure 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.

2.4.6 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 will be constructed of stainless steel to minimize corrosions associated with 30 wt% MEA.

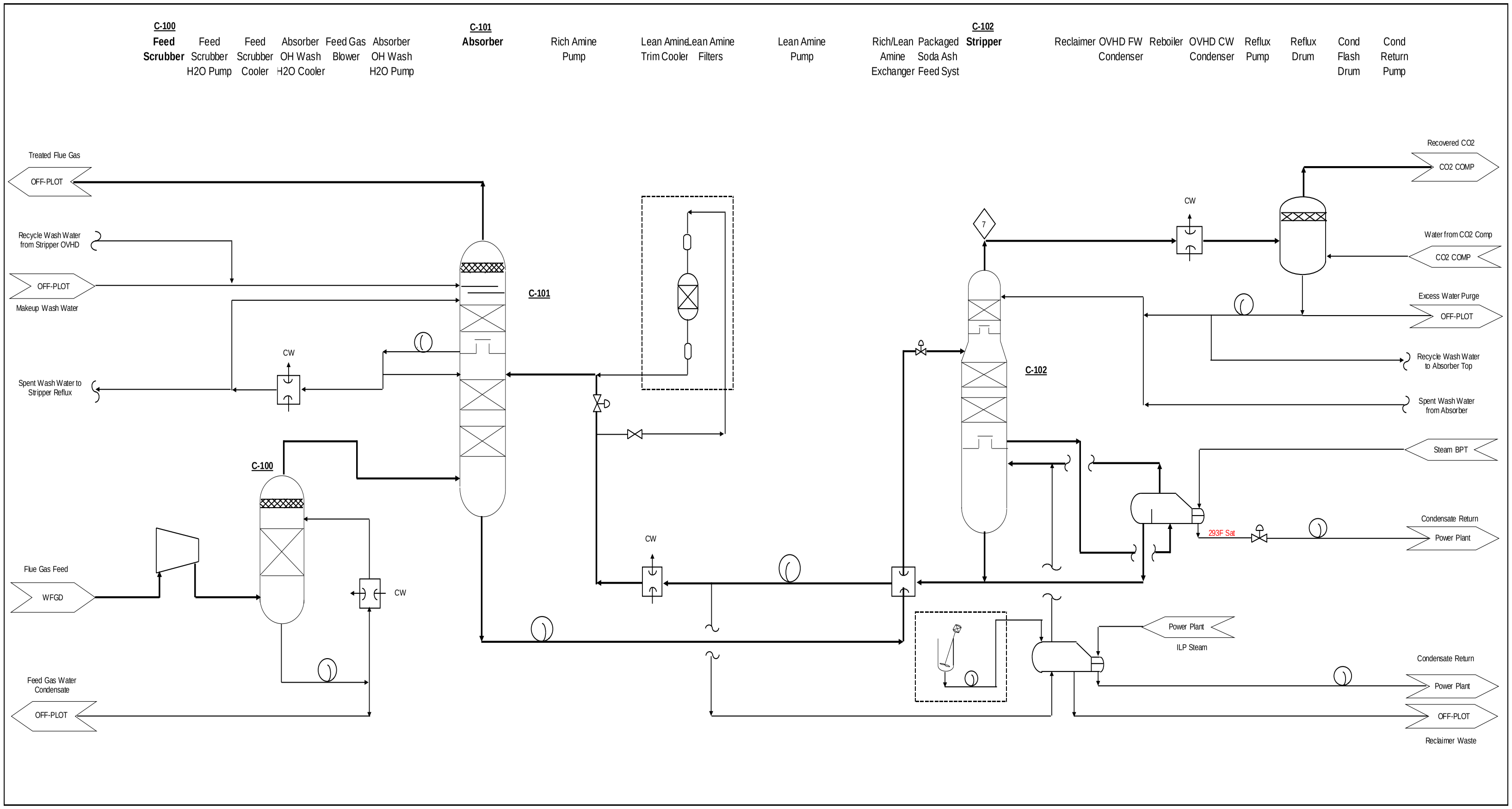
Due to the very large column sizes (~30 feet diameter) required by the single-train CO_2 Capture Plant, overall DICE COE sensitivity for using 4 x 25 percent size CO_2 Capture Plant is included as an option to allow for transportable shop-fabricated design with maximum vessel diameter of 15 feet.

2.4.7 CO_2 Capture Plant

The CO_2 capture plant process scheme consists of three major processing steps: (1) flue gas feed scrubbing, (2) flue gas CO_2 absorption and (3) amine solution regeneration. A process schematic of the DICE GT-CRCC CO_2 capture plant is shown in Figure 2-13.

Flue gas feed from the WFGD enters the bottom bed of the Flue Gas Scrubber. The function of the scrubber is to condense out most of the moisture in the flue gas feed, and to remove solids in the WFGD carry-over droplets. The flue gas moisture is reduced to as low as possible by scrubbing counter-currently with cooled water to minimize heat addition from moisture condensation in the downstream CO_2 absorption section. Carry-over solids need to be removed to avoid foaming in the MEA absorber. The water condensed from the scrubber is relatively clean and can be used as cooling tower or WFGD makeup to reduce overall makeup water demand.

Figure 2-13
MEA-Based CO_2 Capture Plant Process Flow Diagram



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.

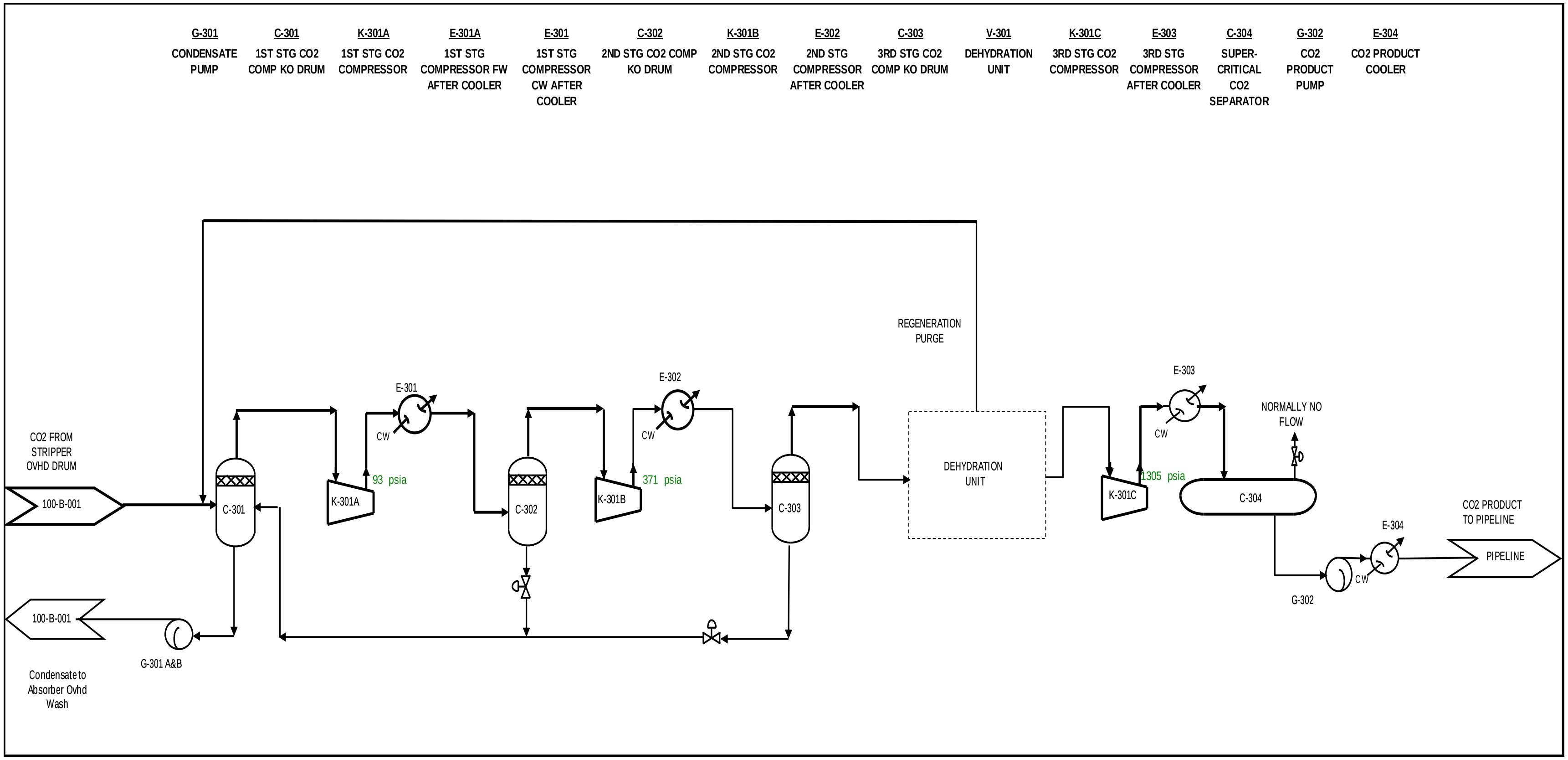
2.4.8 CO_2 Compression Plant

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).

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

A process schematic of the CO_2 compression plant is shown in Figure 2-14.

Figure 2-14
CO_2 Compression Plant Process Flow Diagram



2.4.9 Balance of Plant

In addition to the major pieces of equipment described above, the power block includes the following balance of plant (BOP) equipment:

- Electrostatic Precipitator (ESP) or *Third-Stage Separator* (TSS) for particulate removal
- WFGD for sulfur removal (95 percent)
- Deaerator
- Multitude of feedwater and/or condensate pumps
- Multitude of valves
- Cooling tower and circulating water system
- Electrical equipment (transformers, motor control center etc.)

2.5 EXPECTED PLANT PERFORMANCE

2.5.1 Turbocompound Advantage

In a standard RICE (or DICE) with factory-shipped turbocharger accessory, the only net power generator is the engine itself. The turbocharger is a self-balanced system with the turboexpander driving the charge air compressor on the same shaft. Due to small size and high speed, both components have low efficiencies; i.e., between 70 and 75 percent (isentropic) for the charge compressor and around 80 percent (isentropic) for the expander.

In the turbocompound system, the turbocharger assembly of the stock engine is removed. Charge air to the reciprocating engines is supplied by a single compressor (isentropic efficiency 86 percent) described in Section 2.4.1. The efficiency advantage of the large, integrally-geared, multi-stage centrifugal process compressor with intercooling is significant, at about 25 percent power consumption savings over the stock turbocharger. Exhaust gas from the engines is utilized in the hot gas expander as described above (isentropic efficiency 85 percent). In the overall system:

- HGE generator output is 40,250 kWe
- MAC motor power consumption is 27,776 kWe
- Thus, net power contribution of the HGE-MAC combination is 40,250 – 27,776 = 12, 474 kWe

The total generator output of the five DICE in the plant is 5 × 15,758 = 78,790 kWe. Consequently, turbocompounding provides a performance boost of 12,474 / 77,675 = 15.8 percent.

Fuel consumption of the HGE combustor is 34,830 kWth, which translates into a marginal efficiency of 12,474 / 34,830 = 35.8%. While this marginal efficiency seems paltry at first glance, it should be noted that:

- HGE inlet gas temperature is capped at 690 °C (1,275 °F) in order to maintain 70-30 coal-natural gas fuel split and supply the steam demand of the PCC stripper reboiler;
- Bottoming cycle (steam turbine) contribution is ignored;

- The particular plant configuration examined in this study is not the best possible embodiment of the DICE-GT CRCC concept but one with the fastest track to field deployment of the first prototype.

When the PCC is off-line and the HGE combustor is fired to 760 °C (1,400 °F), marginal efficiency is 37.2% (HGE only) or 80% (with STG contribution and no HRSG duct burning). In that case, the fuel split is 82-18 coal-natural gas and plant net LHV efficiency is 45.6%.

2.5.2 DICE GT-CRCC Plant Net Efficiency

Table 2-9 summarizes the overall performance based on the conceptual design of the nominal 100 MWe DICE GT-CRCC power plant. Overall fuel mix to the plant consists of 70 percent coal and 30 percent natural gas, on an LHV basis. At 32.2 percent LHV efficiency with 90 percent CO_2 capture (30.4 percent HHV), this is significantly higher than even a PRB coal-based ultra-supercritical PC plant with CO_2 capture (29.8 percent LHV, 28.7 percent HHV). It is also comparable to integrated gasification combined cycle (IGCC) plants with more effective pre-combustion CO_2 capture systems, but which are more capital intensive and more complicated to operate and maintain, and which certainly do not have the flexibility and scalability to operate at small-scale.

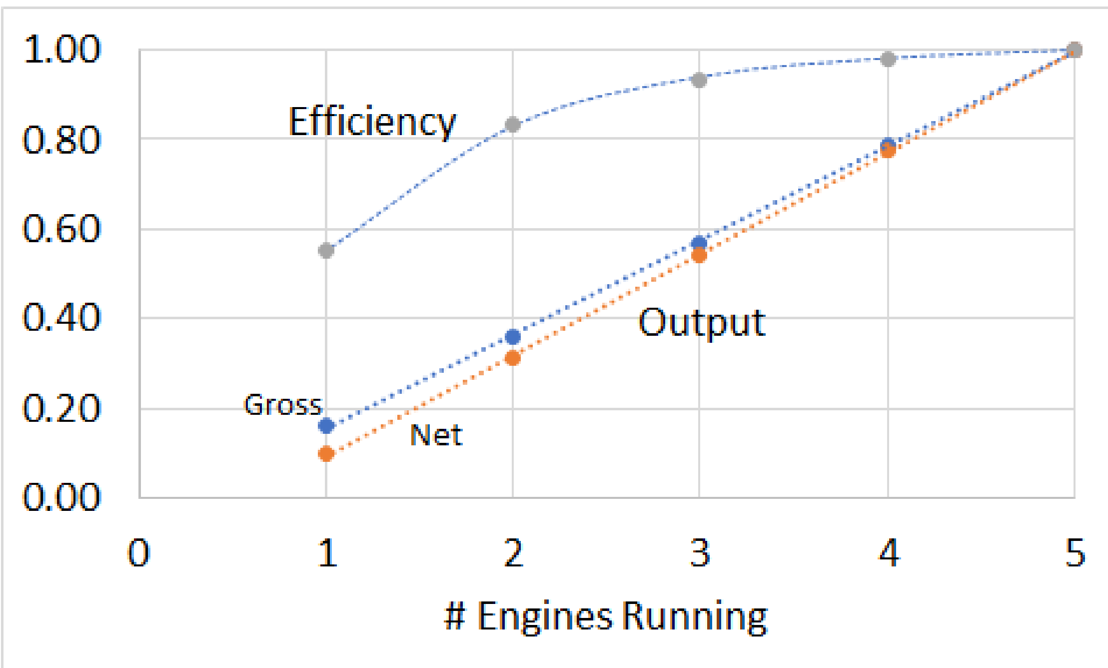
Table 2-9
Power Summary and Net Efficiency

Power Summary	
POWER GENERATION, kWe	
5 x DICE	78,790
Turboexpander	40,250
Steam Turbine	16,192
Total Power Generation	**135,232**
AUXILIARY LOAD SUMMARY, kWe	
Coal Handling and Conveying	71
Coal Beneficiation	incl w/ BOP
DICE Pumps	6
Main Air Compressor	27,776
SCR	107
Cyclone	163
Boiler Feed Water Pump	325
Economizer Recirculation Pump	9
Steam Turbine Auxiliaries	34
WFGD	428
CO_2 Capture	4,316
CO_2 Compression	8,292
Circulating Water Pumps	840
Ground Water Pumps	20
Cooling Tower Fans	540
Miscellaneous Motors	79
8Miscellaneous Balance of Plant (incl MRC Fuel Prep)	3,776
Transformer Losses	676
Total Auxiliaries, kWe	**47,627**
Net Power, kWe	**87,605**
As-Received PRB Coal Feed, lb/hr	79,044
Natural Gas Feed Flow, lb/hr	13,719

Coal LHV Thermal Input, MMBtu/hr	650
Gas LHV Thermal Input, MMBtu/hr	279
Total LHV Thermal Input, MMBtu/hr	**928**
LHV Efficiency, %	**32.2%**
Coal HHV Thermal Input, MMBtu/hr	674
Gas HHV Thermal Input, MMBtu/hr	308
Total HHV Thermal Input, MMBtu/hr	**983**
HHV Efficiency, %	**30.4%**

Plant part load performance (normalized) is summarized in Figure 2-15. The horizontal axis indicates the number of DICE running at full load. Operating points in between can be achieved by running engines at part load. Operation with one engine is subject to the capability of the clean-up equipment (WFGD in particular) and the PCC block at such low loads. Depending on the applicable environmental regulations, it is possible to place the PCC block on standby at such low generation levels. Detailed control philosophy will be developed during detailed design.

Figure 2-15
DICE-GT CRCC Part Load Performance



2.5.3 DICE GT-CRCC Other Utilities Consumption

Table 2-10 summarizes the other utilities consumption nominal 100 MWe DICE GT-CRCC power plant conceptual design. These include the total requisite cooling duty, makeup water demand and wastewater generation.

Raw water demand is minimized by reusing the condensate (243 gpm) from the flue gas DCC column in the PCC plant as cooling tower or WFGD makeup water, thus reducing the raw water needed for these operations.

Table 2-10
Other Utilities Summary

Cooling Duty, MMBtu/hr	
DICE GT-CRCC	*160*
PCC Cooling Loads	*441*
Total Cooling Duty, MMBtu/hr	602
Makeup Water Demand, gpm	
Coal Beneficiation	*87*
Steam cycle makeup	*11*
WFGD	*104*
PCC Process Water	*19*
Cooling Tower Makeup	*108*
Total Makeup Water Demand, gpm	**330**
, 1000 lb/hr	**165**
Wastewater Production, gpm	
Steam cycle blowdown	*5.6*
WFGD blowdown	*5.6*
Cooling Tower blowdown	*88*
Demin System blowdown	*1*
Total Makeup Water Demand, gpm	**99**
, 1000 lb/hr	**50**

2.5.4 Plant Emissions

Table 2-11 summarizes the various DICE GT-CRCC plant emissions and control measures undertaken to achieve these emissions.

2.5.5 Other Plant Waste Streams

A combustible recovery of around 85 percent is achievable in producing MRC [13]. The MRC cleaning steps produces a tailings stream that contains 40 wt% ash with 60 percent combustible (MAF coal). The expected LHV of this tailings stream is about 7,400 Btu/lb. It is expected that the tailings from the coal benefication process, with its inherent heating value, is a saleable product that offsets the disposal cost, so a net cost of 0 is assumed for beneficiation ash disposal.

Similarly, for the WFGD, per the NETL baseline coal-fired PC plant reports, it is assumed that the gypsum is a saleable product that offsets the cost of disposing WFGD waste.

Table 2-11
Plant Emissions Summary

Pollutant	PCC	lb/MWh-gross	Control Technology
SO_2	Offline	0.31	WFGD at 95 percent SOx removal
	Online	Trace	WFGD + MEA reaction with residual SOx in flue gas to effectively reduce to zero
NOx	Offline	1.3	SCR at 90 percent NOx removal. This value is higher than allowable limits but is based on 600 ppmvd NOx in DICE exhaust based on Orimulsion test runs. This can potentially be lowered to 350 ppmvd due to the water in MRC acting as a heat sink to drop flame zone temperatures to meet 0.7 lb/MWh NOx limits. Detailed combustion study by the engine OEM for specific MRC fuel characteristics is required
	Online	1.2	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
PM	Offline	0.09	Cyclone
	Online	Trace	DCC water wash in PCC plant further scrubs out residual PM in flue gas
Hg	Online and offline	N/A	If mercury is an issue, activated carbon injection (ACI) can be utilized at a location with appropriate temperature before the cyclone. An OPEX associated ACI is assumed for the DICE GT-CRCC plant
		lb/MWh-net	
CO_2	Offline	1,600	Unabated, but plant generates 28 MW more net power with condensing LP turbine and elimination of PCC aux loads
	Online	208	30 wt% MEA
VOC	Offline	None	No VOC expected when PCC is offline
	Online	1 ppm	Water wash at the top of the PCC absorber is expected to remove VOC in flue gas before venting to atmosphere

2.6 MODULARIZATION CHARACTERISTICS

The DICE-GT CRCC plant is well-suited for modularization, especially the DICE, which are commercially manufactured engines that offer power outputs below 100 MW. These include the low-speed two-stroke marine-type engines (10 to 100 MW at 90 to 120 rpm) and largest four-stroke medium-speed engines (20 MW at 400 to 500 rpm). It is straightforward to utilize one or more of such engines to achieve 50 to 350 MW power plant unit sizes.

Less straightforward is the other balance-of-plant equipment. The HGE, WFGD and CO_2 capture plants, while able to be scaled to smaller sizes, tend to suffer from economy-of-scale disadvantages. In the case of the PCC plant for this conceptual design, the single-train MEA absorber is about 30 feet in diameter, which is still too large for shop fabrication.

A parametric study was undertaken to understand the effects of modularizing the PCC capture plant. It was determined that a configuration of 4 x 25 percent CO_2 capture plants is required to achieve shop fabrication of the absorber units at less than 15 feet diameter.

The CO_2 capture plant CAPEX increases by about 40 percent as a result of modularization. The subsequent first year COE increases to $171.2/MWh from the base case of $163.2/MWh.

2.7 ENERGY STORAGE CAPABILITY

One unique feature of the DICE-GT 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-GT CRCC with CAES is the availability of a suitable air storage cavern, e.g., a saline aquifer or depleted natural gas reservoir.

Unlike the existing CAES technology (as demonstrated in Huntsdorf, Germany and McIntosh, Alabama), once constructed and commissioned, DICE-GT 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 bar.

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 charging mode, compressor power consumption (including the booster compressor to charge the cavern) is 38,393 kWe.

In generation mode, net power output is, 87,605 + 27,776 (note: the MAC is off-line) = 115,381 kWe with a thermal efficiency of $(115,381 / 87,605) \times 32.2 = 42.4\%$ net LHV with 90% carbon capture. This efficiency is higher than the net LHV efficiency of most modern, gigawatt-scale supercritical/ultra-supercritical coal-fired power plants without capture.

2.8 PLANT START-UP PROCEDURE

The DICE-GT CRCC plant start-up sequence is described in Appendix B.

Section 3 Technology Development Pathway

3.1 CURRENT STATE-OF-THE-ART POWER PLANT

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

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

The proposed concept, DICE-GT CRCC, delivers the efficiency promised by the most advanced USC technology while being

- Modular
- Flexible
- Small (150 MW base, about 100 MW with post-combustion capture, PCC)

This is most dramatically illustrated by the chart in Figure 3-1, which shows the CO_2 emissions and plant efficiency of PC, GTCC and DICE-GT CRCC (without PCC and including their best embodiments) technologies.

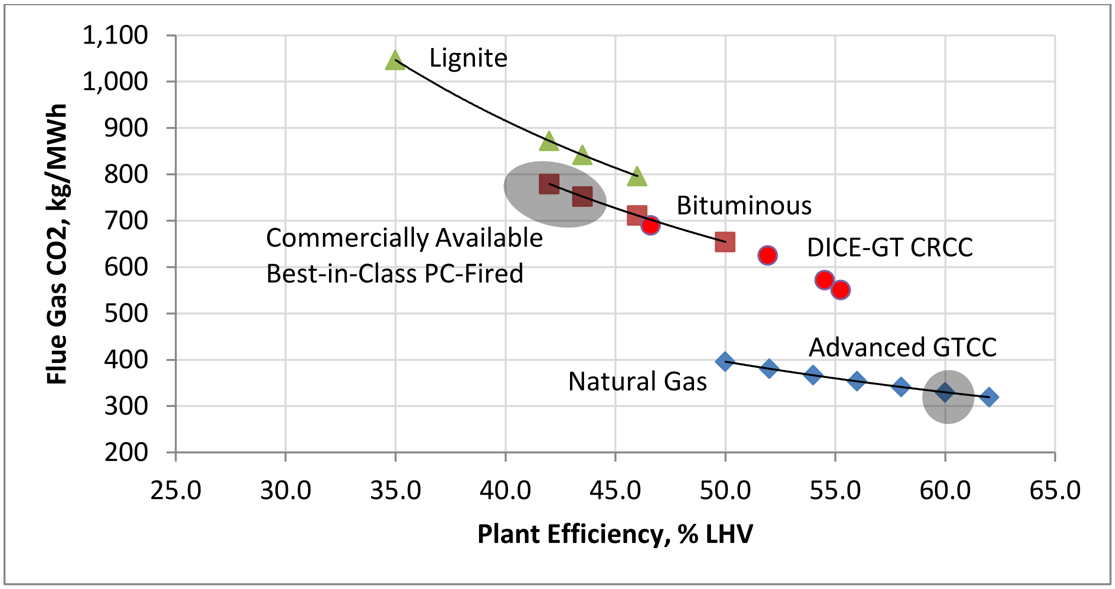
As described in Section 2.1 and references cited therein, DICE-GT CRCC delivers the promised capabilities by combining mostly off-the-shelf equipment with proven technology in a thermodynamically optimum way. The combination of reheat with constant volume heat addition delivers the most efficient heat engine cycle, which can be implemented in the field with multi-equipment configurations for maximum modularity and flexibility with high efficiency at small ratings.

3.2 TECHNOLOGY GAPS AND RISKS

Prima facie, technology gaps and risks associated with the DICE-GT CRCC concept are quite limited. The least-proven part of the cycle is DICE, reciprocating internal combustion engine

(RICE) fired with a coal-water slurry fuel (roughly 45 wt% water). Even DICE has ample R&D and field operation history behind it (e.g., please refer to Ref. [3] cited earlier and the extensive bibliography therein). One prominent example is medium-speed, large-bore RICE by Wärtsila, which has been successfully operated with Orimulsion in Finland.

Figure 3-1
Efficiency-CO_2 Emission Comparison of Fossil Fuel-Fired Technologies



As discussed in Section 2 in more detail, , the concept does not require development of new equipment. There are two technical issues that will require careful engineering design of standard hardware to satisfy the needs of key plant equipment for satisfactory RAM:

- Particulate removal from the DICE exhaust gas prior to admission into the downstream equipment, i.e., the HGE and the HRSG. The particular risk associated with this technical issue is shortened component life (e.g., expander rotor blades) via erosion/corrosion and/or fouling caused by ash particles. This requires a detailed characterization of the MRC ash content, i.e., particle composition and size, upon which the proper PM removal equipment (ESP or TSS) can be designed and procured with the assistance of the equipment vendors. There is a potential trade-off between CAPEX and OPEX that will be investigated during detail design (e.g., less aggressive ESP specification, i.e., less CAPEX, with slightly reduced expander blade life, i.e., more OPEX).

- Augmenting air requirement for stable combustion in the HGE combustor and the HRSG duct burner. Especially due to the high moisture content of the DICE exhaust gas (primarily as a result of water in the MRC fuel), O_2 concentration is insufficient for combustion with natural gas (< 10 percent by volume). For the HGE combustor, this can be circumvented by the combustor design, i.e., via adjustment of the fuel-air ratio in the flame zone. For the HRSG duct burner, flue gas O_2 concentration has to be augmented by additional air blown into the duct (as verified by our discussions with a duct burner

OEM). In our calculations, we accounted for this feature on a preliminary basis. Exact requirements will be determined during detail design with input from the combustor/burner vendors. Since this issue has to be addressed during detail design and procurement phases, no technology risk is foreseen during field deployment.

One can also cite the plant distributed control system (DCS) to facilitate the seamless integration of DICE with the gas turbine/expander as a technical risk. In the sense that such a DCS is more complex than a straight engine plant, *prima facie*, this can indeed be a true statement. Nevertheless, “turbocompounding” is a known technology going back to the 1930s and is currently implemented in truck engines (former Scania). With the current state-of-the-art in dynamic system simulation, the entire plant can be modeled and exercised in a timely/accurate manner to develop the optimal control philosophy. The high-level control philosophy for the “turbocompound-reheat” concept has already been developed under auspices of the US DOE Grant DE-FE0031618, Turbo-Compound Reheat Gas Turbine Combined Cycle (Principal Investigator S.C. Gülen, Bechtel). A benchtop test system and plan to develop the control system (Phase 2 of the said Phase 1 project) is part of the deliverables.

The most significant technology gap, which requires **development – not research** – to be closed, is a readily available DICE product from a major OEM (e.g., MAN or Wärtsila). The primary technical concerns for coal-fired diesel engines are:

- Successful and rapid injection, atomization, ignition and complete combustion of coal-based fuel
- Adequate components life in presence of ash, unburned coal particles and sulfur compounds in combustion products
- Emissions control (NOx/SOx, PM)

There are four areas of technology development to address those concerns:

- Coal-based fuel (i.e., coal-water slurry or MRC) production, storage and handling
- Combustion modeling and control
- Injector and engine materials and construction
- System integration and performance.

The fourth area of technology development is the subject of the current work. Previous work on injection/atomization and combustion extending back four decades (in General Electric (GE) on locomotive engines, Cooper-Bessemer (C-B), Southwest Research Institute (SwRI), etc.) highlighted the suitability for low/medium speed (to accommodate the longer characteristic time of coal-water slurry combustion, i.e., as high as ~10 ms) and large bore (to minimize piston ring and cylinder liner wear) engines for coal-fired duty.

Coal-water slurry or MRC production is touched upon in Section 3.3. In terms of storage and handling of the coal-water slurry or MRC fuel, the specific concerns are settling of coal particles in the storage tank and in the piping. Solutions include fuel recirculation in the storage tank and piping system design to eliminate segments with low fluid velocity (e.g., smooth pipes, no dead volumes, no sudden changes in flow area, etc.).

Based on the US-DOE's "Technology Readiness Assessment Guide" (Office of Management, 2011), it can be stated with full confidence that, based on published information (please see references cited above), DICE is at TRL 6 (technology demonstration). The next step, system commissioning, comprises TRLs 7 and 8, described in Table 3-1.

Table 3-1
Technology Readiness Levels 7 and 8 Descriptions

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

The specific engine development needed to reach TRL 7 (mostly design work by the OEM engineering team) to deploy a coal-burning diesel engine for commercial operation in the field is two-fold:

- A reliable coal-water slurry fuel atomization and injection system to replace the standard fuel injector suitable to liquid fuels such as number 2 fuel oil or heavy fuel oil (HFO). This is and has been the primary technical hurdle to overcome for widespread commercial development of coal-fired diesel engines.

- Wear prevention in key engine components for acceptable parts life, i.e., cylinder liners, piston rings and exhaust valves. The wear in question is caused by ash and unburned coal particles in the combustion products. Prior work in the field demonstrated that tungsten carbide-coated ring and liners exhibited acceptable wear characteristics during operation. Furthermore, it was also routinely demonstrated that combustion efficiencies of 99% or higher was readily achievable (with a diesel pilot if necessary) so that unburned coal particle problem is not significant.

There is enough knowledge acquired over the last four decades, including recent activities by major engine OEMs (e.g., see the work done by MAN described in Ref. [3]), to the extent that a "motivated" OEM can easily put a product in the field within two years to demonstrate TRL 7 and TRL 8.

3.3 PLANT CONCEPT DEVELOPMENT PATHWAY

Preparation of high-quality coal-water slurry (i.e., low ash and sulfur content) to be burned in DICE is a key factor to the success of the DICE-GT CRCC concept. While the plant concept itself is only dependent on the quality of the fuel "as delivered" to the fuel injectors, from an overall "making use of coal" perspective, a wider "control volume" should be considered. In this respect, there is ample evidence that existing "physical beneficiation" technologies are perfectly adequate to produce "clean" coal for DICE consumption without adverse parts life or RAM concerns. Even higher quality coal can be produced with "chemical" beneficiation technologies albeit at significantly higher cost.

During extensive research done by GE, C-B, SwRI and US-DOE, optimal coal-water slurry (CWS) specification for high-speed engines was determined as bituminous coal feedstock, low ash/sulfur (1 percent by mass), fine grinding (5 microns D50, 15 microns top size), > 300 cP viscosity at 1,000 s^{-1} with dispersant additive. For the low/medium speed engines, these requirements can be relaxed, e.g., up to 12 microns D50 and 65 microns top size and up to 2 percent by weight sulfur/ash content.

There is no technology gap *per se* in terms of producing CWS/MRC fuel of adequate quality. Individual beneficiation steps comprise mature, field-proven technologies, e.g., milling, grinding, froth flotation or heavy media separation. It is noteworthy that there were at least eleven suppliers of CWS in 1985 (some of them went out of business by 1988). For example, AMAX Coal Company's Extractive R&D Center produced CWS with up to 55% solids loading, which was burned with combustion and thermal efficiencies comparable to that with diesel fuel in research engines. At the end of the day, with low petroleum prices, research and development activities by the DOE and OEMs fizzled out around 1990 primarily due to the high cost of CWS fuel.

Obviously, at the time of writing, there is no existing CWS or MRC "factory" analogous to a refinery producing diesel fuel or heavy fuel oil. This presents a fundamental dilemma: Without sufficient CWS/MRC fuel, DICE cannot be demonstrated to pass through TRLs 7 and 8. Without commercial deployment of DICE, on the other hand, no investment will be made into a CWS/MRC fuel factory. For the pilot/demo plant and probably for the first few units, the fuel production unit will either have to be an integral part of the facility or contracted to a third-party technology provider to manufacture and transport to the site. The ideal scenario, of course, is widespread commercial deployment of DICE technology, which would make central fuel plants economically feasible.

The conceptual DICE-GT CRCC plant presented herein consumes 44 t/h of MRC; in other words, for eight hours of base load operation, ~350 metric tons of MRC supply is required. For an 8,000 hour demonstration period, requisite MRC supply is 350,000 metric tons. If only one DICE (out of a total of five) is MRC-fired in the first demo plant, MRC supply requirement can be slashed by 80 percent. At nearly $80/ton estimated fuel cost, this still adds up to nearly $6 million in fuel cost.

In light of the dilemma elaborated upon above, it is not realistic to propose a full-blown coal-fired diesel plant from the get-go. It is our belief that the judicious approach is to propose an introductory version of the DICE-GT CRCC for immediate deployment in a pilot/demo plant with staged introduction of the DICE technology. In this context, the following steps are considered:

1. Limit the RICE modification only to the removal of the turbocharger assembly (charge air will be delivered by the plant's main air compressor). Thus, the exhaust gas pressure will be around 4 bara (about 58 psia).

2. Replacement of the industrial heavy duty "gas turbine" (without the axial compressor) with a fired hot gas expander (which is the basis for cost and performance presented in this report).

3. For cost saving/simplicity, the hot gas expander can be "unfired" at a sacrifice of some efficiency. The plant can be laid out, however, for a subsequent addition of the combustor/gas burner.

4. Only one RICE (say, out of five) will be CWS or MRC-fired and it will be a half-size version, i.e., with nine of out of 18 cylinders operational to reduce the MRC consumption and fuel production cost. The system will be tested for one year (or 8,000 hours) to verify that the coal-fired engine works trouble-free.

5. Upon successful demonstration of the first DICE in the demo plant, the remaining RICE can be converted to DICE in a staged manner.

The worst outcome is that there will be a working power plant fired with diesel/natural gas combination or all natural gas with respectable efficiency for distributed power. In that vein, it is noteworthy that the efficiency of a fully natural gas-fired DICE-GT CRCC in a configuration as presented in this report is 50.7 percent net LHV (113.5 MWe net output).

3.3.1 Design, Construction and Commissioning Schedule Reduction

The DICE portion of the plant is modular by design (engine-generator sets come as a package ready to drop onto the foundation block and make the connections) and can be on-line generating megawatts in a relatively short timeframe. Size and construction characteristics of all the other pieces of major equipment are amenable to shipping as shop-fabricated packages/trains for easy erection on site, e.g., the MAC, the HGE and the STG. Even the HRSG can be added to this list (subject to verification by the OEM during detail design), since even the largest three-pressure, reheat systems (much larger than the one-pressure, no-reheat HRSG of this plant) have been assembled prior to loading on a barge and transportation to the site for several recent US projects on crowded sites.

For even faster construction and commissioning schedules, it is possible that the DICE trains can be commissioned and operating with mostly natural gas feed first before the PCC comes on stream. In all likelihood, this will require the replacement of the fuel injection system before the switch-over to MRC firing. On the other hand, it is possible that DICE can be fired with diesel fuel without a need for changing the fuel injectors. The feasibility of fuel-switch features can only be made the engine OEM.

3.3.2 Reduced Maintenance and Forced Outages

The modular nature of the DICE-GT CRCC pretty much precludes the loss of full generating capability due to forced outages. For example,

- If the STG fails, the plant can operate in a full bypass mode i.e.,
  - steam generated in the HRSG is sent to the condenser (PCC block is off-line);
  - steam generated in the HRSG is sent to the PCC block without power generation.
- If the HGE fails, it can be bypassed as well for operation in combined cycle mode with a duct-fired HRSG and the STG generating power (PCC block can be on-line or off-line).
- Since there are five DICE, their maintenance can be scheduled in a staggered manner to keep the plant running during scheduled or forced outages.

From an equipment (scheduled) maintenance perspective, DICE maintenance is expected to be costlier than its HFO-fired counterpart (in terms of labor hours and materials). However, this should be compensated by significantly reduced maintenance needs of the other major equipment. The expander, HRSG and the STG are rugged components designed for long operation in process plants with high reliability and availability. In order to ensure that this feature is preserved in the DICE-GT CRCC concept, the critical component is the PM removal equipment (ESP or TSS).

Sulfur removal (WFGD) and PCC block have their own RAM characteristics, which would be no different for the DICE-GT CRCC than any other coal-fired generation technology.

Section 4 Technology Original Equipment Manufacturers

4.1 MAJOR EQUIPMENT ORIGINAL EQUIPMENT MANUFACTURERS

The technology OEMs for major equipment including standard and off-the-shelf equipment are provided:

- Major equipment needed
  - Reciprocating internal combustion engines (RICE)
    - Medium-speed, large-bore
    - MAN, Wärtsila
  - Hot gas expander (HGE)
    - Baker Hughes
  - Process compressor
    - Integrally-geared, with intercooling
    - Kobelco, Dresser-Rand
  - HRSG
    - Single-pressure, non-reheat with duct burner and SCR/CO catalyst
    - NEM, Nooter Eriksen, Vogt
  - Steam turbine generator
    - Back-pressure (non-condensing)
    - GE, Siemens (Dresser-Rand), Elliott
  - Electrostatic precipitator or cyclone(s)
    - Babcock & Wilcox
    - Amec Foster-Wheeler
  - Flue gas desulfurization unit (wet)
    - Amec Foster-Wheeler

- All major pieces of equipment are standard (off-the-shelf) and mature products <u>except:</u>
  - Combustor (gas burner) of the HE
    - No R&D necessary, made-to-order (Zink Co., Florida Turbine Tech.)
    - For the pilot/demo plant, this component can be omitted to save time and money
  - RICE modification to DICE
    - New injector
    - Cylinder/piston coating (with carbide)
    - We are planning to cooperate with CSIRO on this modification

It should be noted that:

- Bechtel has worked with all major OEMs of major equipment used in power generation and process

- Bechtel has access to information on the equipment included in the proposed concept

- During the (optional) FEED study – if awarded – the project team is planning to cooperate with CSIRO (selection of DICE manufacturer)

4.2 DICE OEM OBSERVATIONS

Commonwealth Scientific and Industrial Research Organisation (CSIRO) is Australia's national science research agency. CSIRO has been actively engaged in DICE research demonstrating the feasibility of the technology at laboratory and pilot scale [3, 4 and 11], achieving efficiencies similar to diesel operation, and cooperated with engine OEMs such as MAN. As part of that, solutions have been developed for adapting fuel systems and managing engine wear. Their research extended to DICE fuel preparation and engine modification as well. For instance, suitable MRC has been produced from 17 coals (black, brown, tailings and biochar), including a new method of coal processing to produce MRC fuel.

During this study, the lead investigator corresponded with Dr. Louis Wibberley, the leader of the DICE program in CSIRO regarding questions concerning engine suitability and fuel preparation challenges.

As discussed in more detail in Sections 2 and 3, major engine OEMs have been involved in developing the DICE technology going back to 1980s (e.g., General Electric developing coal-fired diesel technology for application in locomotives). In terms of technology pertinent to DICE-GT CRCC in the last decade or so, one can mention

- Wärtsila experience with Orimulsion (see Section 2.3)
- MAN Diesel & Turbo (as part of a consortium including RWE, a utility in Germany, and CSIRO)
- Winterthur G&D (as told by Dr. Wibberley, they operated an 8 MW engine on a MAERSK ship with an injection system designed by CSIRO)

MAN D&T in Germany seems to have pulled out from DICE research. So far, we have not been able to identify a channel into their engineering or marketing team to inquire about their interest. We have contacted Wärtsila through our contact in the USA. Since most of the engineering personnel was out on vacation in August, a reply from them is not expected until mid-September.

The low interest of major engine OEMs in coal-fired product development is an unfortunate fact. Similar observations were made by EPRI and JGC Corporation (a Japanese company developing CWS from low-rank coals for boiler applications). The underlying reason is the low cost of natural gas and increasing interest in gas-fired diesels for power and cogeneration applications, which ensures that OEM order books are full and they have no resources to spare for development work involving a "dirty" fuel (as stated by our Jenbacher contact) with no future in their traditional markets, e.g., Europe and Americas (as they see it).

CSIRO in Australia is currently working with a Chinese engine manufacturer (not specified) and Yancoal Australia (Australia's largest pure-coal producer) to develop DICE. In this context, it is noteworthy that Winterthur G&D, descendent of Sulzer in Switzerland and once a subsidiary of Wärtsila, is now owned by *China State Shipbuilding Corporation* (CSSC). As suggested by Dr. Wibberley of CSIRO, we have recently reached out to the main China office of Winterthur G&D

to inquire about their interest in cooperation with us towards further development of DICE-GT CRCC. Considering the world-class experience and heritage of the company in large diesel engine design and manufacturing and the large Chinese market for clean coal-fired power generation, this seems to be a promising lead.

As mentioned in Section 3, the main challenge towards commercialization of DICE technology is simultaneous tackling of fuel production and engine component development problems. This is a classic "chicken-egg" dilemma; without adequate supply of one, the other cannot be developed to a state of commercial readiness. The issue here is not that there are no CWS production technologies. In fact, there is a wide range of suppliers of coal "micronizers" for land or ship-based power applications. One example is Seapower, Inc. in San Diego, CA (https://www.seapower-inc.com). There is also a company in Austria, Effective Energy Technologies GmbH (EET GmbH), which was established in Vienna at 2010 with products and systems for CWS production and combustion (https://www.cwstech.eu/about).

The issue is the availability of a technology that can be directly procured to produce the CWS fuel in quantities requisite for a commercial power plant similar to the subject of the present report (burning CWS at a rate of 44 t/h at ISO base load).

In conclusion, we believe that a technology for CWS supply for a limited-size demo engine as outlined in Section 3 is readily procurable. A full-fledged CWS production "block", akin to the gasification island of an IGCC power plant, can be one solution for subsequent commercial offerings. (In this study, this was considered as a "black box" with its capex translated into fuel cost in the COE evaluation.) This requires a careful investigation of the suppliers out there and cooperation with selected ones to plan a phased development from a pilot size CWS system to a full-blown CWS block.

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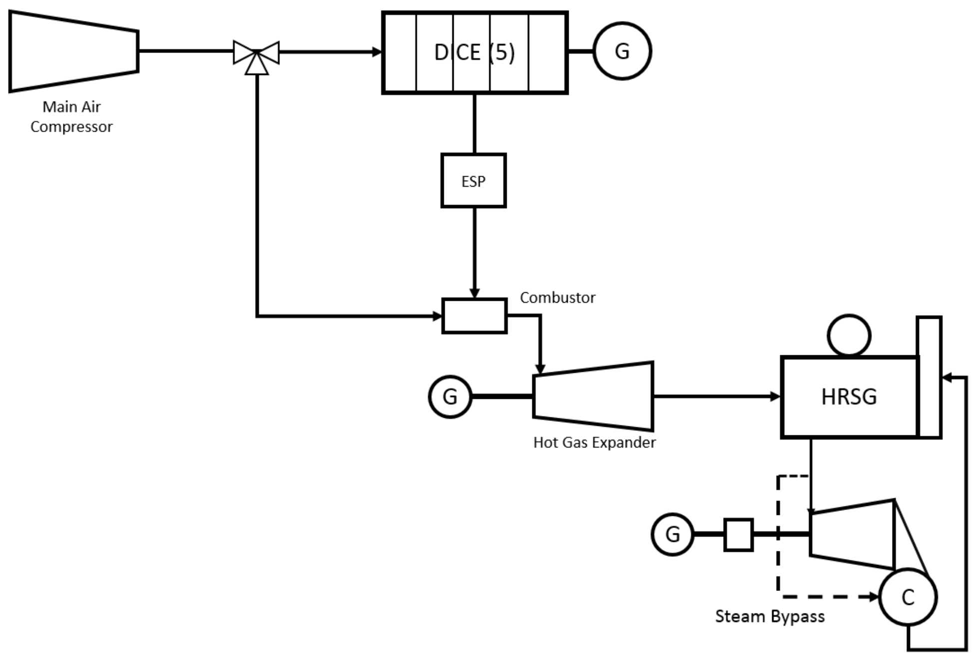
Appendix B Plant Startup Procedure



The basic startup sequence is described below:

Initial State

- HGE and STG units on turning gear
- Main air compressor (MAC) OFF
- Gas engines (DICE) preheated

Hot Gas Expander Start

- START command
- MAC motor ON – DICE bypassed
- HGE brought to purge speed (~15%)
- HRSG purge for 15 minutes
- HGE to ignition speed
- Ignition
- HGE rolled to FSNL – assisted by BOC motor
- Self-sustaining at about 90% speed

- HGE reaches FSNL
- Generator synchronized
- Circuit breaker closed
- HGE loaded

DICE Start

- START command
- Pre-lubrication
- Engine #1 started by its compressed air starter system (after 45 seconds)
- Acceleration to FSNL
- Synchronization (after 95 seconds)
- Circuit breaker closed
- Loading to FSFL (full load at 300 seconds)
- The sequence repeated for the remaining four (4) engines
- Engine exhaust bypasses the auxiliary steam generator (kettle-type evaporator)

HGE Flow Control

- As gas engines start in sequence, the DICE inlet pressure regulating bypass valve progressively closes as airflow is taken by the DICE units

Bottoming Cycle Start

- HGE exhaust gas passes through the HRSG (no bypass stack)
- Steam generated in the HRSG is bypassed to the condenser
- When HRSG steam (flow and temperature) is ready, STG starts rolling by steam admission
- Rolling rate is controlled by steam flow (via admission and bypass valves)
- STG reaches FSNL
- Synchronization
- Circuit breaker closed
- STG loading by admission flow control

PCC Start

The following is a simplified description of the major steps to startup a cold PCC after shutdown for maintenance of either the PCC or the main DICE-GT CRCC plant:

- Check to ensure CW and FW flows are established through all coolers, and LP steam flow to reboilers are shut off.
- Fill the Flue Gas Scrubber/DCC with Water Condensate from offsite storage tank via back flow through the existing condensate purge line, if necessary.
- Start Flue Gas Scrubber/DCC Circulation Pump to establish water circulation through Flue Gas Scrubber/Cooler Heat Exchanger and Flue Gas Scrubber/DCC.
- If necessary, fill MEA Absorber with solution pumped by the Make-Up MEA Pump from MEA Storage Tank.
- Start Rich MEA Pump to establish MEA circulation through the Rich/Lean Exchanger to fill MEA Stripper.
- Start Lean MEA Pump to establish MEA flow through Rich/Lean Exchanger, but bypass around Lean MEA Trim Cooler initially, before return back to the MEA Absorber to complete MEA circulation between the Absorber and Stripper.
- When MEA levels in the Absorber and the Stripper bottom reaches the desired set point, shutdown Make-Up MEA Pump to stop flow from MEA Storage Tank.
- Start Wash Water Pump to establish wash water circulation through Wash Water Cooler back to Absorber overhead wash section.
- Start Reflux Pump to pump water from Overhead Reflux Drum to establish water recirculation through Overhead Feedwater Condenser) and Overhead Cooling Water Condenser back into Overhead Reflux Drum.
- Start LP steam flow to Stripper Reboiler to heat up the Absorber/Stripper system.
- When the Absorber bottom reaches 120 °F, close bypass around Lean Amine Trim Cooler to cool Lean Amine to approximately 100 °F before return into the Absorber.
- Start flue gas flow from WFGD and start Flue Gas Blower.
- Slowly close off Startup Vent from Feed Scrubber overhead, and from Overhead Reflux Drum overhead.
- After the CO_2 Capture Plant reaches stable operation and producing enough CO_2 to pressurize the Stripper Overhead to about 20 psia, open the CO_2 line to and condensate line from the CO_2 Compression Plant, and start the VFD driven CO_2 Compressor slowly and in total recycle mode.
- After sufficient liquid level is built up in the Supercritical CO_2 Separator, start the Supercritical CO_2 Pump in total recycle mode.
- When level in the Supercritical CO_2 Separator reaches the set point, the Supercritical Pump recycle will be shutoff and supercritical CO_2 product can be routed to the pipeline for delivery.