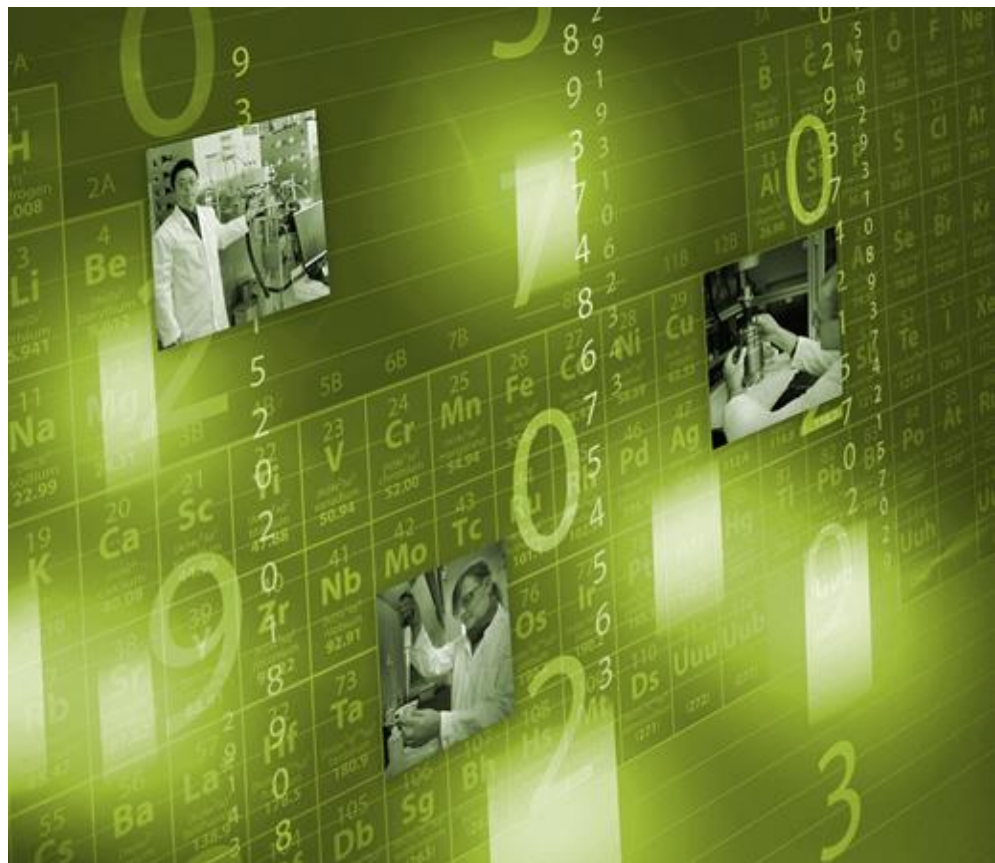


COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

SELCUK CAN UYSAL



January 21, 2021

NETL/DOE - 2021/2644

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PERFORMANCE IN NGCC CONFIGURATIONS

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Suggested Citation:

S.C. Uysal, "Comparative Study for Pressure Gain Combustion-Gas Turbine System Performance in NGCC Configurations," National Energy Technology Laboratory, Pittsburgh, January 21, 2021.

This report was prepared by MESA for the U.S. DOE NETL. This work was completed under DOE NETL Contract Number DE-FE0025912. This work was performed under MESA Activity 201.005.016.

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ACRONYMS AND ABBREVIATIONS

AACE	AACE International (formerly Association for the Advancement of Cost Engineering)	MWe	Megawatt electric
		MW	Megawatt
		MWh	Megawatt-hour
AFAPL	Air Force Aero Propulsion Laboratory	NASA	National Aeronautics and Space Administration
AFRL	Air Force Research Laboratory	NETL	National Energy Technology Laboratory
Aspen	Aspen Plus®	NGCC	Natural gas combined cycle
atm	Atmosphere (14.696 psi)	NGPH	natural gas pre-heat
BEC	Bare erected cost	NOx	Oxides of nitrogen
Btu	British thermal unit	P-v	Pressure-specific volume
CC	Combined cycle	PDE	Pulse detonation engine
CEI	Chemical Engineering Index	PGC	Pressure gain combustion
CFD	Computational fluid dynamics	PGGTm	Pressure Gain-Gas Turbine Model
CGTM	Cooled Gas Turbine Model		
CH ₄	Methane	psi	Pounds per square inch
CJ	Chapman-Jouget	psia	Pound per square inch absolute
CO ₂	Carbon dioxide		
COE	Cost of electricity	QGESS	Quality Guidelines for Energy System Studies
deg	Degree	RDE	Rotating detonation engine
DLN	Dry low NOx	RPC	Resonant pulse combustor
DoD	Department of Defense	s	Second
DOE	Department of Energy	SCR	Selective catalytic reduction
DOL	Department of Labor	ST	Steam turbine
EPRI	Electric Power Research Institute	T-s	Temperature versus entropy
ft	Foot	TASC	Total as spent cost
ft ²	Square foot	TBC	Thermal barrier coating
ft ³	Cubic foot	TOC	Total overnight cost
GE	General Electric	TPC	Total plant cost
GT	Gas turbine	TRL	Technology readiness levels
h, hr	Hour	U.S.	United States
HP	Higher pressure	UTRC	United Technologies Research Center
HRSG	Heat recovery steam generator	UTSR	University Turbine Systems Research
kW	Kilowatt	V	Volume
kWh	Kilowatt-hour	WBS	Work breakdown structure
lbm	Pound-mass	WRC	Wave rotor combustor
LHV	Lower heating value	YSZ	Yttria Stabilized Zirconia
LP	Lower pressure	ZND	Zeldovich-von Neumann-Doring
MESA	Mission Execution and Strategic Analysis		
MM	Million	°F	Degrees Fahrenheit
MPa	Megapascal	°R	Degrees Rankine

EXECUTIVE SUMMARY

The Department of Energy (DOE) has a goal to increase natural gas combined cycle (NGCC) plant efficiency to greater than 70 percent on a lower heating value (LHV) basis. Most of the technology pathways that have the potential to achieve that goal involve improving gas turbine (GT) efficiency. While many of the traditional improvement methods (higher firing temperature, advanced materials, improved cooling methods, etc.) will continue to increase current GT and NGCC efficiencies, combining these traditional advancements with breakthrough technologies such as pressure gain combustion (PGC) could provide step change, rather than incremental, improvements.

PGC is a combustion process that results in a net pressure increase across the combustor (up to pressure ratio of 2.2) rather than the traditional (<5%) pressure drop. There are multiple PGC technologies being developed that create the pressure rise phenomena, including resonant pulse combustors (RPCs), pulse detonation engines (PDEs), wave rotor combustor (WRC) engines and rotating detonation engines (RDEs). These technologies have the potential to increase simple cycle efficiency by 4–6 percent (absolute) and NGCC efficiency by 2–3 percent (absolute) based on the results of the current study.

To understand the potential benefits of using PGC techniques on gas turbine and NGCC performance, steady-state analytical models are required. In this study, a simplified PGC model (PGC-Sim) was developed in MATLAB Simulink for the analysis and comparison of four PGC concepts and for further analyses involving PGC-GT integration.

The PGC-Sim model uses algorithms for the Resonance Pulse Combustor (RPC) and Pulse Detonation Engines (PDE) that are based on the models developed by Heiser and Pratt. [1] The PDE model algorithm also uses a surrogate model developed by General Electric (GE) Global Research [2] for fuel-to-air ratio calculations and corrections to calculated pressure gain. The Wave Rotor Combustor (WRC) model uses an algorithm developed by Akbari et al. [3] with slight modifications and the RDE model uses the ideology from Shah [4], Kaemming [5], and Braun et al. [6, 7] but uses Heiser and Pratt's model for detonation wave speed calculations and also includes an oblique shock solver [8, 9] for the required post-shock state calculations. Developed algorithms were validated against the results of the models presented in their respective resources; however, because the RDE algorithm is a mixture of several models from the literature it was validated with both experimental studies and some higher-level analytical models from the open literature. After completing the validations and calibration of the PGC-Sim model, it was integrated into an H-Class GT model developed in MATLAB/Simulink as its combustor section. The resulting Pressure Gain Gas Turbine Model (PGGTM) was developed from the uncooled on-design section of the Cooled Gas Turbine Model (CGTM), which was previously developed for analyzing the effects of turbine cooling on H-Class GT performance. [10, 11]

The PGC engine concepts were first evaluated independently. Consistent with other researchers in this field, the turbine section inlet and exit conditions were kept the same as the typical H-Class GT values. In order to have constant inlet and exit conditions at the turbine, the

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compressor pressure ratio is different for each PGC-GT configuration. For the PGC systems, the turbine isentropic efficiency is 70–80 percent [12, 13], which is lower than the typical values for conventional gas turbines due to the flow irregularity and flow swirl introduced by PGCs. [13]

A comparison of the analyzed systems is made in Exhibit ES-1, including the PGC-GT system shaft power output, thermal efficiency, heat rate, sensitivity to decrease in turbine efficiency, sensitivity to increase in PGC exit temperature, and ease of improving the current (baseline) performance. The sensitivity values are the slopes of the sensitivity curves calculated and higher values mean higher dependence on the indicated parameter.

Exhibit ES-1. PGC-GT system specifications used in the analysis

Parameter	RPC-GT	PDE-GT	WRC-GT	RDE-GT
Power Output (kW)	340,880	588,280	372,199	465,592
Thermal Efficiency (%)	43.0	45.7	43.2	46.3
Heat Rate (Btu/kWh)	7,931	7,460	7,894	7,363
Compressor Pressure Ratio	23.1	5.2	19.9	11.4
PGC Pressure Ratio	2.35	11.73	1.63	4.51
Sensitivity to Decrease in Turbine Efficiency due to inflow pressure fluctuations	1.09	0.37	0.69	0.35
Sensitivity to Increase in PGC Exit Temperature	0.34	0.19	0.25	0.50
Best Way to Improve Current Performance	Increase turbine efficiency by reducing PGC exit flow unsteadiness	Reduce purge fraction	Increase turbine efficiency by reducing PGC exit flow unsteadiness	Higher RDE exit temperatures

Among the PGC types considered in this study, RDE and PDE hybrid GTs give the highest potential to increase the GT efficiency and power output. When the potential for improving the baseline performance is considered, the RDE system provides an advantage over the PDE system and, therefore, it was the configuration selected for the NGCC integration (See Chapter 4 for details).

The NGCC steady-state plant simulation model used in this study is called NGCC-Sim and is based on the NETL Bituminous Baseline (Revision 4) Case B31A Aspen model previously developed for F-Class GT coupled systems. [14] Several changes were made in the base Aspen Plus model to simulate the PGC integrated H-Class gas turbine based on the previous cooled gas turbine model integration study used H-Class gas turbines for NGCC integration. [15] PGC is modeled as an Aspen calculator block that includes a surrogate RDE model, which is developed by using curve-fits from running the PGC-Sim model with various detonation heights and inlet to exit temperature and pressure conditions. HRSG and Steam Turbine models were calibrated to

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match a typical H-Class gas turbine integrated performance. In all RDE integrated analysis cases, the gas turbine exhaust temperature is the same as the temperature of a conventional H-Class gas turbine's exhaust temperature.

The NGCC performance parameters are presented in Exhibit ES-2. The first column shows the NGCC performance with a conventional H-Class GT, which is identical to the values from previous NGCC analysis for turbine cooling. [15] The second column shows the corresponding NGCC performance parameter changes when the RDE coupled H-Class GT is used in the same NGCC power plant.

Exhibit ES-2. Performance parameters comparison for RDE-GT integrated NGCC with conventional GT integrated NGCC (Cycle: 2 GT x 2 HRSG x 1 ST)

Parameter	NGCC with H-Class GT (Conventional)	NGCC with H-Class RDE-GT Hybrid	Change (from Conventional GT)
Combustion Turbine Power	685 MW	926 MW	+35.2%
Steam Turbine Power	336 MW	337 MW	+0.3%
Total Gross Power	1020 MW	1263 MW	+23.8%
Balance of Plant	17483 kW	18264 kW	+4.5%
Net Power	1003 MW	1244 MW	+24.0%
LHV Net Plant Efficiency	61.7%	63.5%	+1.8% (absolute)
LHV Net Plant Heat Rate	5531 Btu/kWh	5373 Btu/kWh	-2.9%
LHV GT Efficiency	42.1%	47.0%	+4.9% (absolute)
Steam Turbine Efficiency	40.5%	40.4%	-0.1% (absolute)
Steam Turbine Heat Rate	8405 Btu/kWh	8436 Btu/kWh	+0.4%
Condenser Duty	1603 MMBtu/hr	1609 MMBtu/hr	+0.4%
Natural Gas Feed flow	273343 lbm/hr	331182 lbm/hr	+21.2%

The greatest change from the conventional GT integrated NGCC is the increase in the combustion turbine power with the RDE-GT system, which is about 35 percent, and is directly reflected in the increase in the net power output.

To understand which GT and RDE parameters have the most potential to increase the NGCC efficiency, a sensitivity analysis was performed on the following parameters:

- Turbine efficiency (70 to 90%)
- RDE exit temperature through increased equivalence ratio (3260 to 3560 R)
- RDE inlet pressure loss (-0.5 to -15%)
- Compressor efficiency (92 to 94%)

Based on the results of the sensitivity analysis, six RDE-Gas Turbine system configurations were selected and are compared in Exhibit ES-3.

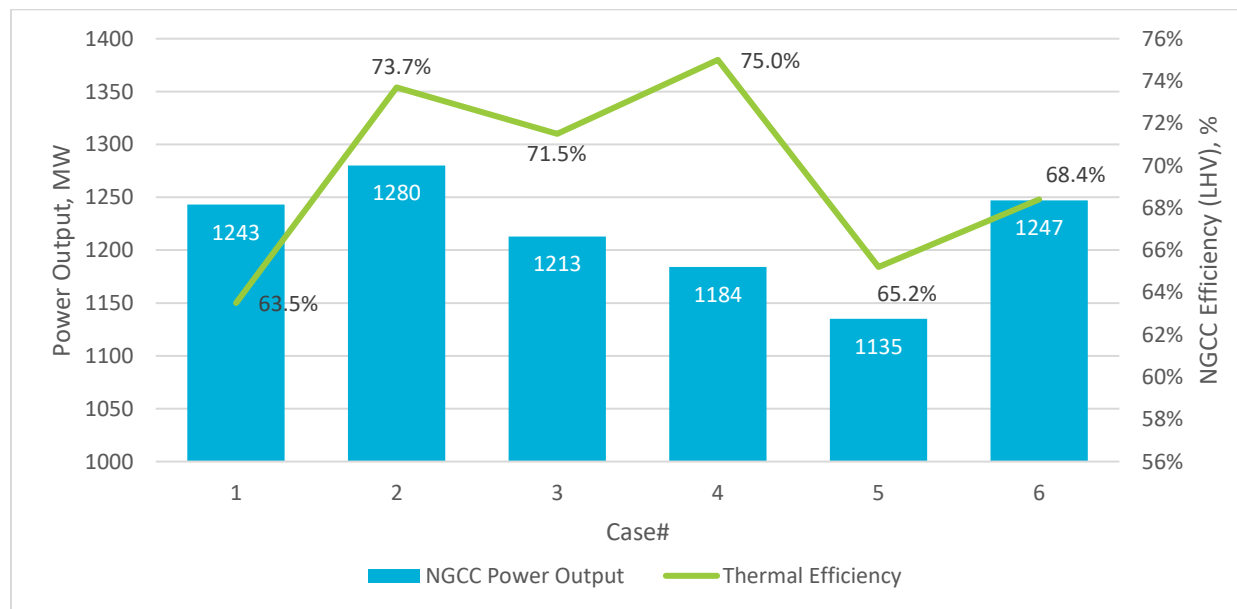
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Exhibit ES-3. Feasible RDE-GT Configuration Specifications for Techno-Economic and Performance Analysis

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Compressor Pressure Ratio	11.1	8.0	11.1	13.0	17.1	11.1
Compressor Isentropic Efficiency	92%	92%	92%	92%	94%	92%
Injector/Plenum Loss	-0.5%	-0.5%	-15%	-0.5%	-0.5%	-0.5%
RDE Total Pressure Ratio	5.81	3.73	2.12	1.86	1.98	5.95
RDE Exhaust Temperature	3260 °R	3260 °R	3260 °R	3560 °R	3260 °R	3560 °R
By-Pass Cooling	None	None	None	Yes	None	Yes
Turbine Isentropic Efficiency	70%	89%	89%	89%	81%	71%
Turbine Inlet Temperature	3260 °R	3260 °R	3260 °R	3260 °R	3260 °R	3260 °R
Turbine Exit Temperature	1610 °R	1610 °R	1610 °R	1610 °R	1610 °R	1610 °R
Turbine Exit Pressure	15.5 psia	15.5 psia	15.5 psia	15.5 psia	15.5 psia	15.5 psia

Each configuration might represent either a particular stage in the historical development of the RDE-GT system, or a preferred technological development path due to challenges encountered in developing some of the RDE-GT system components. The performance comparison of each engine scenario is shown in Exhibit ES-4 for the net power output and NGCC efficiency.

Exhibit ES-4. RDE-GT system case configurations plant power output and LHV thermal efficiency comparison



Based on the power output, Cases 2 and 6 provide the highest values. Whereas the efficiency is highest for Case 4, followed by Case 2, and Case 3. Although Case 3 had the highest injector pressure losses, increased RDE pressure gain and compressor pressure ratio is enough to compensate for the losses. The following results can be deduced from the analysis:

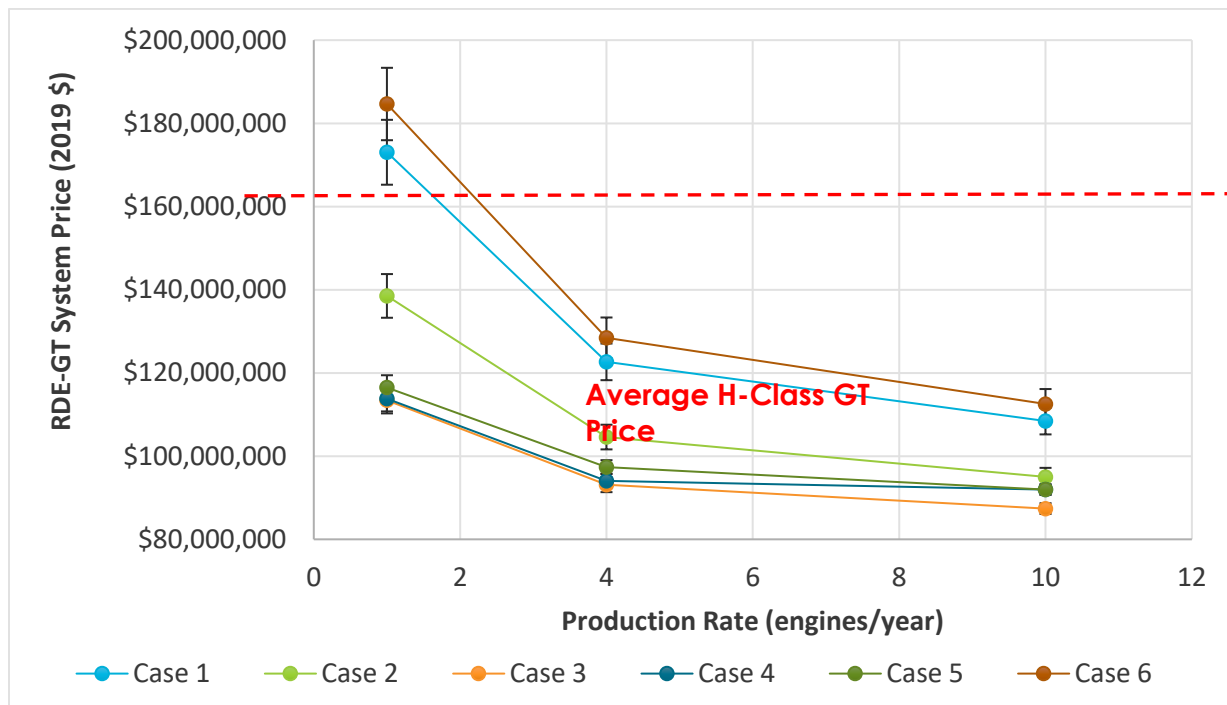
COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

- The highest power output cases are the ones with moderate to high RDE pressure gains
- The highest efficiency cases have the highest turbine efficiency values
- If the RDE pressure gain is low, having a higher exit temperature while having advanced turbine blades and coating that allow for these temperatures provides a significant advantage

A major challenge in performing techno-economic analysis for an NGCC power plant with the RDE-GT system is determining the capital cost of the RDE components and subsequently calculating the capital cost of the RDE-GT system. The literature on RDE cost estimates is scarce due to low technology readiness levels (TRL). However, RDEs are very similar to ramjets in terms of the type of the components used. Therefore, cost estimation methods developed for ramjets [16, 17] were used in this study with several modifications including applied safety factors to determine RDE capital costs. The total RDE cost was calculated by summing up the sub-component costs for the inlet, RDE combustor and nozzle section, fuel control system and inner assembly, and final assembly. The cost range of RDE was calculated by varying the material options for the inlet and RDE-nozzle sections.

The total RDE cost is different for different production rates with unit cost decreasing as production volume increases. There is an inflection point at four engines per year (Exhibit ES-5) where the unit engine cost increases rapidly for fewer engines and decreases more slowly for more engines. The reference RDE cost used in this study, \$108,787,000, is the average of the six cases at a four engine per year production rate.

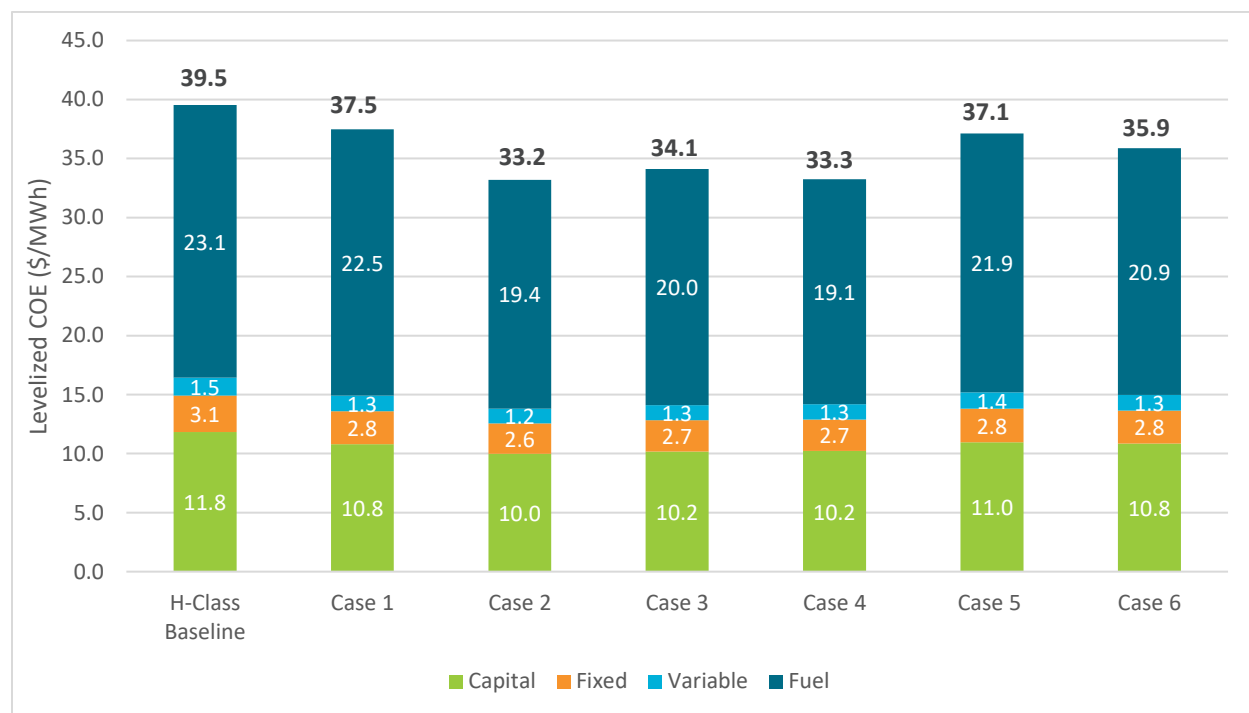
Exhibit ES-5. Capital cost values of RDE-GT system configuration cases for different production rates



COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

The levelized cost of electricity (LCOE) calculated for each RDE-GT configuration is compared in Exhibit ES-6. The RDE-GT systems provide a 5 to 16 percent reduction in the LCOE compared to a conventional GT. From the comparison of LCOE values, the lowest costs are obtained for Case 2 and Case 4, where the NGCC efficiency is the highest among all cases. The ordering of the cases based on LCOE does not follow the ordering based on the capital cost due to the differences in the pressure gain levels and therefore efficiencies of each configuration.

Exhibit ES-6. LCOE comparison for each RDE-GT configuration case



The performance and cost summary for each RDE-GT configuration is shown in Exhibit ES-7.

The results show that cases with successful turbine integration (highest turbine isentropic efficiency) give the highest cycle efficiency and lowest LCOE. Three of the cases examined achieve the DOE goal of greater than 70 percent combined cycle efficiency. Research and development priorities were also identified. If the maximum pressure gain from the RDE is limited, then increasing the RDE exit temperature while using advanced turbine blades and coating materials that allow for safer operation in these temperatures is the next best possible alternative. If the injector and plenum losses are inevitable, then focusing on increasing the turbine efficiency would reduce the negative impact.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM
PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit ES-7. RDE-GT system configuration cases performance and cost analysis comparison

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Power (Net), MWe	1,243	1,280	1,213	1,184	1,135	1,247
CC Efficiency (LHV), %	63.5%	73.7%	71.5%	75.0%	65.2%	68.4%
COE, \$/MWh	36.10	31.99	32.91	32.17	35.81	34.41
TOC, \$/kW	704	652	668	677	717	701
Fixed Operating Costs, \$/kWh	\$19.2	\$17.9	\$18.4	\$18.7	\$19.8	\$19.2
Variable Operating Costs, \$/MWh	\$1.26	\$1.17	\$1.21	\$1.23	\$1.30	\$1.25
Natural Gas Price Sensitivity	6.00	5.13	5.30	5.06	5.80	5.53
Capacity Factor Sensitivity	-16.14	-15.21	-15.21	-15.57	-16.29	-16.07

1 INTRODUCTION

Most of the technological advancement paths that have potential to increase the efficiency of natural gas combined cycle (NGCC) plants beyond 70 percent involve improving gas turbine (GT) efficiency. Efficiency of GTs increases with the following developments:

- Increasing combustor exit temperature and using advanced combustor designs to improve fuel efficiency, while reducing the combustor pressure losses
- Improving compressor blade designs (to reduce aerodynamic losses and improve the blade stall margin and reducing end-wall losses)
- Improving turbine blade and flow path designs to minimize aerodynamic and heat transfer losses
- Using advanced turbine cooling techniques to reduce the impact of cooling-related losses and improve component efficiencies and endurance

The listed developments increased GT efficiency levels from 18–20 percent in the 1950s to more than 42 percent in recent years, which yields more than 62 percent NGCC efficiency. [18] The traditional improvement methods, however, have limits for further improvement either due to the existing material limits or due to reaching the potential ceiling for certain components, such as the case for conventional combustion technologies where the current combustion efficiency levels are more than 99 percent with pressure losses less than 2 percent.

Although the traditional improvement methods will continue to further increase current GT and NGCC efficiency levels, combining these traditional advancements with breakthrough technologies such as pressure gain combustion (PGC) could increase the pace of the improvement and could enable NGCC efficiencies beyond 70 percent in a shorter time.

This study aims to carry out a scoping analysis on the application of several PGC concepts to fossil-fueled power generation, such as NGCC. The following PGC systems are of interest in this study:

- Resonant Pulse Combustors
- Wave Rotor Engines
- Pulse Detonation Engines
- Rotating Detonation Engines

The primary focus of this study is to find PGC-GT configuration concepts that can achieve 70 percent NGCC efficiency (lower heating value [LHV]-based) goal. To perform the assessment of the PGC technologies, analytical models from literature are used to model the performance of the PGC systems under H-Class GT operational conditions. The PGC system that both provides the highest GT efficiency and has the most potential for further improvement is then selected to assess its performance in an NGCC power plant without carbon capturing.

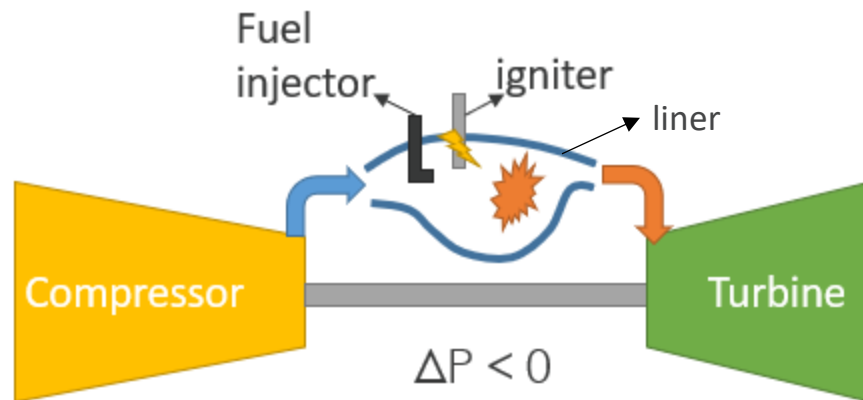
Sensitivity analysis for key NGCC performance parameters on PGC-GT parameters is used to develop feasible PGC-GT system configurations, where each configuration represents possible technological advancement paths. A techno-economic analysis that includes capital cost estimation of the selected PGC system is performed to assess the potential cost improvements from conventional NGCC power plants with H-Class GTs.

2 TECHNICAL BACKGROUND

2.1 COMPARISON OF CONVENTIONAL COMBUSTOR AND PGC SYSTEM CONCEPTS

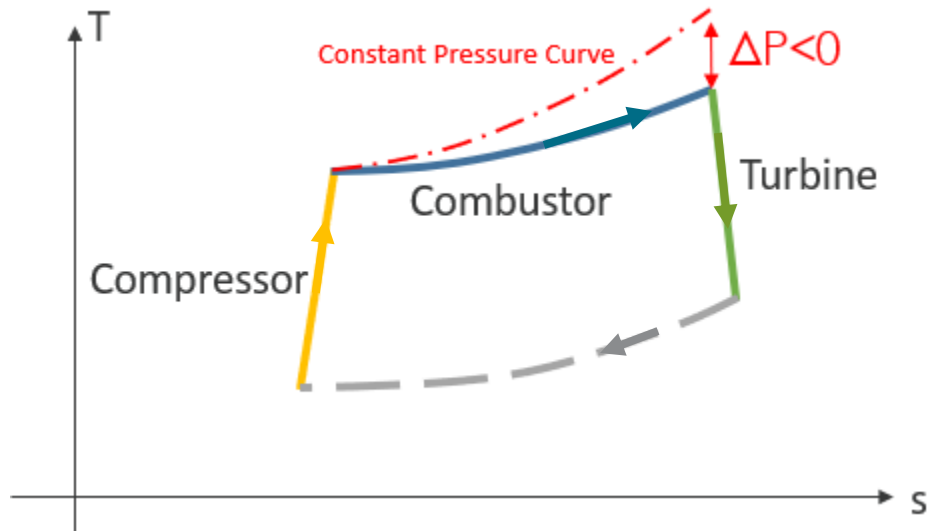
Conventional gas turbine (GT) engines (illustrated in Exhibit 2-1) operate on the Brayton cycle which is a thermal gas power cycle with air typically as the working fluid and the combustors used in GTs have total pressure loss as part of the combustion process. Conventional combustors used in GTs are an open system.

Exhibit 2-1. Illustration of a conventional combustor used in a GT



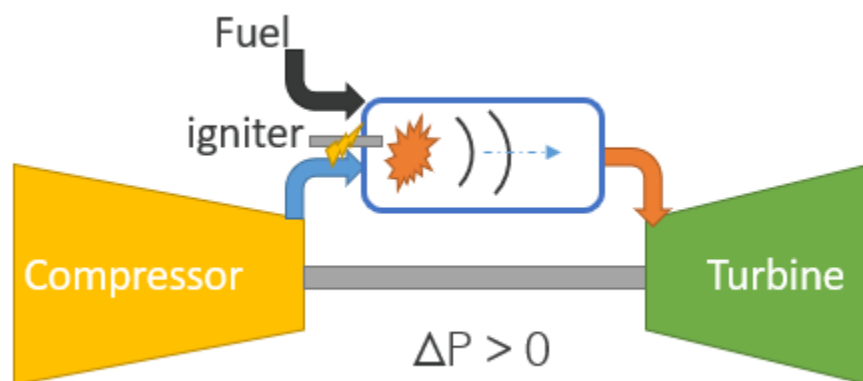
In these combustion systems, the igniter does not operate continuously; once the combustion starts it is sustained unless there is a flame blowout. The pressure drop from the inlet to the exit of the combustor is due to friction and changes in the fluid momentum due to the core flow acceleration increasing its total temperature through combustion. [8, 19, 18] The momentum loss is in addition to the inlet/diffuser, dome and liner losses [8, 19], and produces an overall pressure loss in a conventional combustor of approximately two to five percent. [8] The temperature versus entropy (T-s) diagram of a Brayton cycle GT with a conventional combustor is illustrated in Exhibit 2-2. In Exhibit 2-2, the gray dashed line that closes the Brayton cycle shows the constant pressure heat rejection process that in reality the exhaust of the combustion gases and ingestion of fresh air.

Exhibit 2-2. Illustration of the T-s diagram of the Brayton cycle with conventional combustor (not to scale)



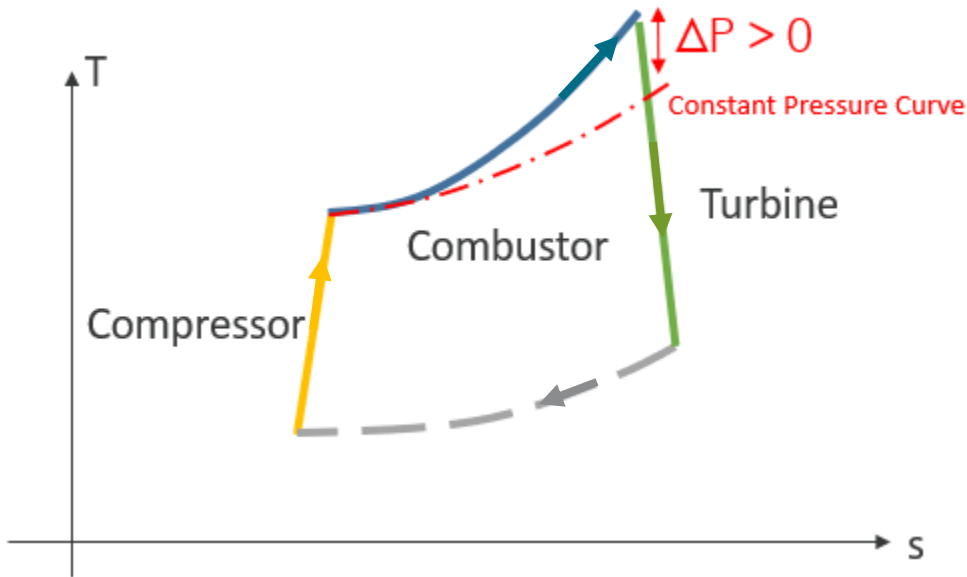
In general, Pressure Gain Combustors use a constant volume combustion process, which is also described as confined combustion in a closed control volume, to increase the exit pressure. [18, 20] A deflagration or detonation wave inside the PGC increases pressure and temperature at the exit. [18] The concept of a PGC-GT hybrid system using a theoretical pressure gain combustor is illustrated in Exhibit 2-3. Some particular pressure gain combustor types such as pulse combustors and wave rotor combustors are actually a mixture of both confined and open combustor systems. In the pulse combustion system, the combustion relies on the coupling between the heat release and the acoustics of the process and the downstream diffuser. Whereas for the Wave Rotor Combustion, the ram compression in the channels of the combustor is used to obtain the pressure gain in the combustion process.

Exhibit 2-3. Illustration of a PGC-GT hybrid system



Most PGCs operate on specific thermodynamic cycles—usually Humphrey or Zeldovich-von Neumann-Doring (ZND) cycles [20], which are synced with the Brayton cycle (i.e., compression and expansion processes of the classic Brayton cycle is integrated to the PGC cycles). The T-s diagram of a GT (Brayton Cycle) with PGC is illustrated in Exhibit 2-4.

Exhibit 2-4. Illustration of the T-s diagram of the Brayton cycle with PGC (not to scale)

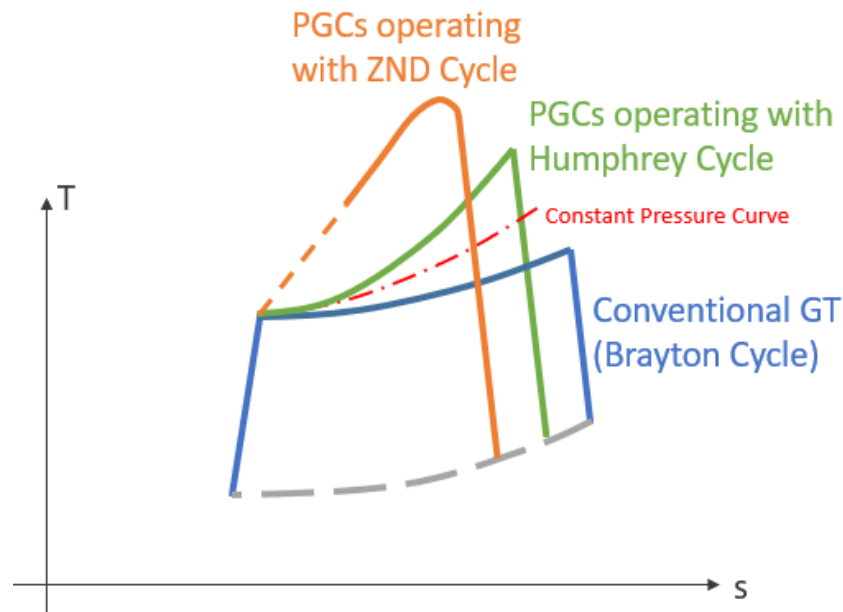


As illustrated in Exhibit 2-4, the pressure across the combustor increases, resulting in higher turbine inlet pressure and more power output. Increased power output mainly comes from the higher expansion ratio of the turbine. For the turbine, using of a pressure gain combustor is similar to using a compressor with higher compression ratio. The increase from the PGC for the cycle pressure ratio can also be used to reduce the number of stages of the compressor, eventually reducing the compressor power input. Reduction in the compressor power requirement also increases the net work output from the cycle, even if the pressure gain from the combustor compensates only the compression from the removed compressor stages (i.e., same turbine inlet pressure). Therefore, using of pressure gain combustion is expected to provide higher cycle work output than any conventional gas turbine cycle.

2.2 ADVANTAGES AND DISADVANTAGES OF PGC SYSTEMS OVER CONVENTIONAL COMBUSTION SYSTEMS

PGC integrated Brayton cycles yield higher net work output and thermal efficiency than the conventional cycle mainly due to the increased turbine inlet pressure and temperature (see Exhibit 2-5). Comparison of the PGC cycles with the Brayton cycle demonstrates the ability of these cycles to produce similar or higher temperatures than the Brayton cycle with less entropy generation, eventually increasing the cycle efficiency. The decrease in the entropy is associated with the increase in the total pressure.

Exhibit 2-5. Comparison of the T-s diagram of the PGC integrated Brayton Cycle with conventional cycle (not to scale)



In the Zeldovich-von Neumann-Doering (ZND) cycle, the undisturbed fuel-oxidizer mixture in the combustion chamber is penetrated by the detonation wave consisting of a normal shock wave, followed by the heat release in a constant-area region (Rayleigh flow). The strength of the leading shock wave is dependent on the initial conditions and the amount of the heat added. The entire process is constrained by the Chapman-Jouget condition, which implies that the local Mach number is equal to 1 after the heat addition-area. The heat addition region is followed by a complex flow region, where the non-steady Taylor expansion waves take place. [21]

The Humphrey cycle is a modification to the Brayton cycle, where a constant-volume heat addition process replaces the constant-pressure heat addition process of the conventional Brayton cycle. [1] The analytical modelling and more details for pressure gain cycles are presented in Chapter 3.

An alternative way to increase the turbine inlet pressure is to add extra compressor stages to the compressor, which could increase compressor work input requirement and reduce the gains in thermal efficiency. Using a PGC, however, is similar to adding extra compression stages to the compressor, without increasing the compressor work input, which could theoretically add 15 percent more thermodynamic efficiency. [18, 22]

Theoretically, some PGCs could also reduce NO_x emissions due to the minimal time spent at peak combustion temperature. This is the expected case for the RDEs, which offer the potential of low NO_x as a result of residence times that are an order of magnitude shorter than conventional GT combustion producing similar combustion efficiency. However, for the PDEs, which has longer residence times at high temperatures could produce higher NO_x than conventional GT combustion. [23]

The main disadvantage of PGC systems is the unsteady flow field at the exit of the PGC device. Particularly for the RDE and PDEs, the unsteady flow field is induced by the shock waves

generated as part of the detonation process. Development of advanced nozzles/diffusers that could minimize the pressure losses to stabilize the PGC exit flow might be challenging. For some PGC devices, start-up with methane or natural gas fuels is challenging with the existing injector technologies. Moving parts used in some PGC techniques might be disadvantageous over conventional combustors in terms of system reliability and long-term maintenance. The ability of load following, turndown capability, start-up or partial load of the PGC systems are also not well understood as transient control of PGC systems is still an active area of research as of the time of writing this report.

2.3 BACKGROUND ON THE CURRENT PGC CONCEPTS

Current PGC technologies are the resonant pulse combustors (RPCs), pulse detonation engines (PDEs), wave rotor combustor (WRC) engines and rotating detonation engines (RDEs). While different in their implementations, all PGC devices could provide improved thermodynamic performance through an increase in the combustor exit pressure. [18, 24, 25] All PGC devices experience highly unsteady flow and pressure field at the exit of the combustor, which is the main challenge in modeling and in performance estimations with experiments. [24, 25]

For each current PGC technology, the main advantages, disadvantages, base thermodynamic cycle, and pressure gain generation mechanism are compared in Exhibit 2-6.

Exhibit 2-6. Comparison of the current PGC technologies

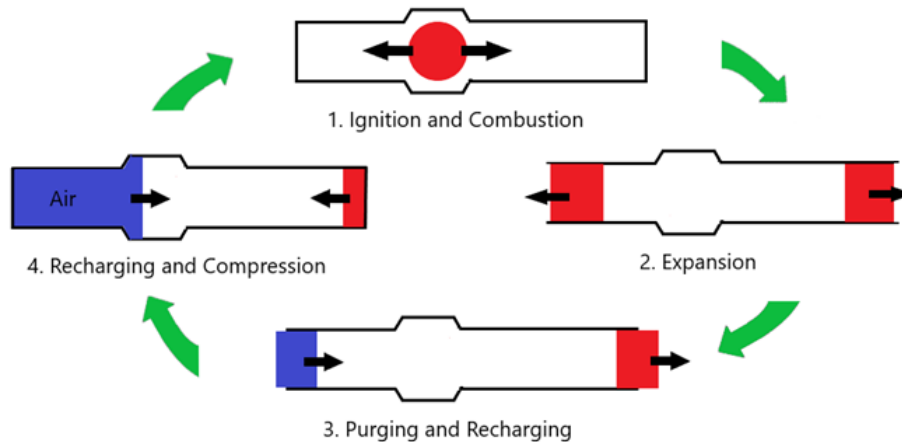
	RPC	PDE	WRC	RDE
Main Advantages	No Detonation Wave [24], less complex structure [24]	Highest pressure gain potential [24], 10% improvement in thermal efficiency [24]	Provides nearly steady flow [24], generates work if run at constant pressure	No moving parts, potential for low NOx emissions, self-sustained detonation [24]
Main Disadvantages	Lowest pressure gain potential [24]	Highest fuel consumption, ionized flow behind the shock, reduced reliability from moving high-speed valve [24]	Moving parts, buffer gas effect reduces the efficiency (flow leakage)	Start-up and wave travel issues [24], highly complex flow-field at the exit [25]
Thermodynamic Cycle	Humphrey Cycle [20, 1]	ZND Cycle [20, 1]	Humphrey Cycle [3]	ZND Cycle [20]
Pressure Gain Generation Mechanism	Pulsing flow frequency match with combustion	Constant Volume Combustion + Detonation Wave	Confined Volume Combustion + Hammer Shock + Expansion Wave	Constant Volume Combustion + Detonation Wave + Oblique Shock

Brief details of each pressure gain combustion system are presented in the subsequent sections.

2.3.1 Resonant Pulse Combustor (RPC)

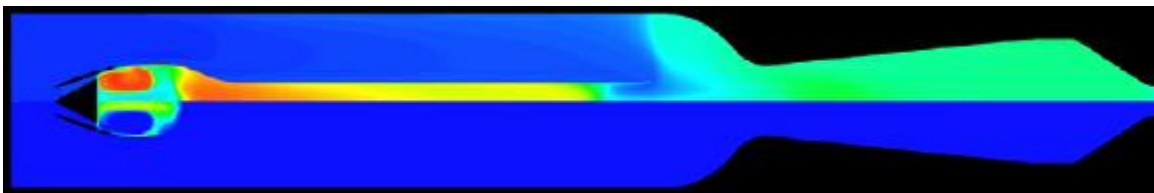
RPCs use a process in which gas expansion by heat release is constrained, which causes rise in the exit stagnation pressure. [26] The operation steps are illustrated in Exhibit 2-7. RPC relies on a reed valve in the inlet in order to isolate the pressure gain from the inlet plenum and to emphasize the “pulse.” The reed valves are the main point of flue in RPCs. The pressure gain occurs by matching the frequency of pulsing flow as subsequent heat release with the acoustic properties of the combustion.

Exhibit 2-7. RPC operating principle



RPCs have stable operation, few moving parts, and operate self-sustained. [26] Several experimental rigs exist at the National Aeronautics and Space Administration (NASA) [26], University of Cambridge, and previously at the National Energy Technology Laboratory (NETL). [18] The design used in NASA experimental rig is shown in Exhibit 2-8.

Exhibit 2-8. RPC design used by NASA



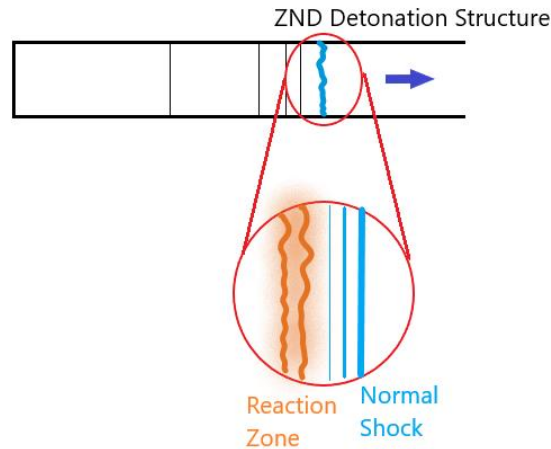
Source: NASA [26]

Experiments at NASA showed 1.4 times static pressure gain for typical GT inlet conditions. [26]

2.3.2 Pulse Detonation Engine (PDE)

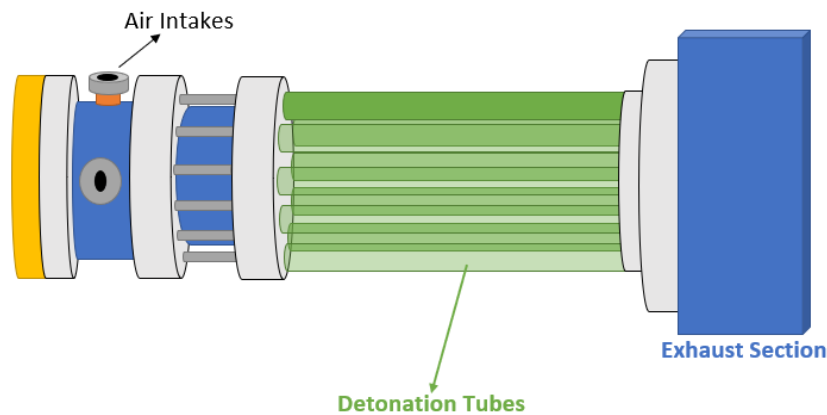
A PDE uses detonation tubes in which the detonation traps the combustion behind a normal shock wave, which generates much higher pressure gain than RPCs [18], illustrated in Exhibit 2-9.

Exhibit 2-9. ZND detonation structure illustrated for each PDE tube



The static pressure gain could be 5–8 times the inlet pressure for typical GT combustor operating ranges. [2, 27] Some of the experimental rigs featuring this PDE concept exist at General Electric (GE) Global Research, Oregon State University, University of Texas, and Naval Research Laboratory. [18] The PDE design used by GE Global Research is illustrated in Exhibit 2-10.

Exhibit 2-10. PDE design used by GE Global Research

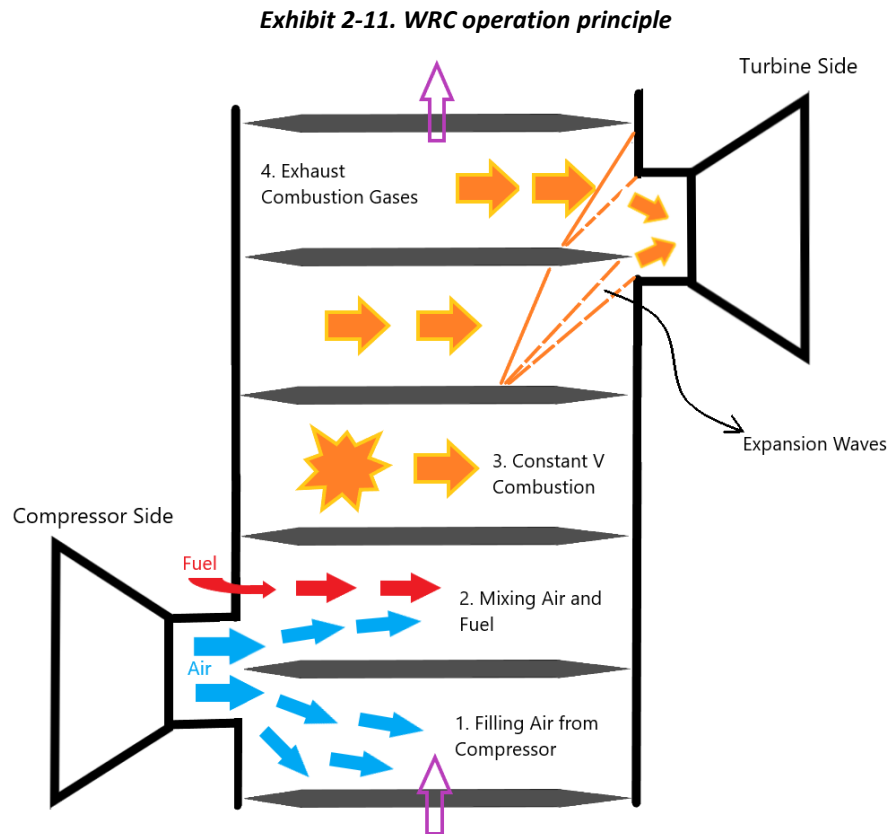


Experiments by GE Global Research showed that a PDE integrated turbine showed no reduction in performance metrics from the conventional combustor integrated turbine performance values. [2]

2.3.3 Wave Rotor Combustor (WRC)

The WRC is developed by Rolls Royce Liberty Works and Purdue University and consists of several combustion channels on a drum that rotates between two stationary end plates. [28, 29] WRC relies on “Hammer Shock” or ram compression to increase the pressure of the reactants at the moment of combustion.

The geometry of WRCs resemble a turbine in which the combustion takes place within the blade channels, which are on a drum that rotates between two stationary end plates. Each channel is periodically charged and discharged through timed opening and closing of the inlet and outlet ports as the combustor rotates. [28, 29] The operation principle is illustrated in Exhibit 2-11.

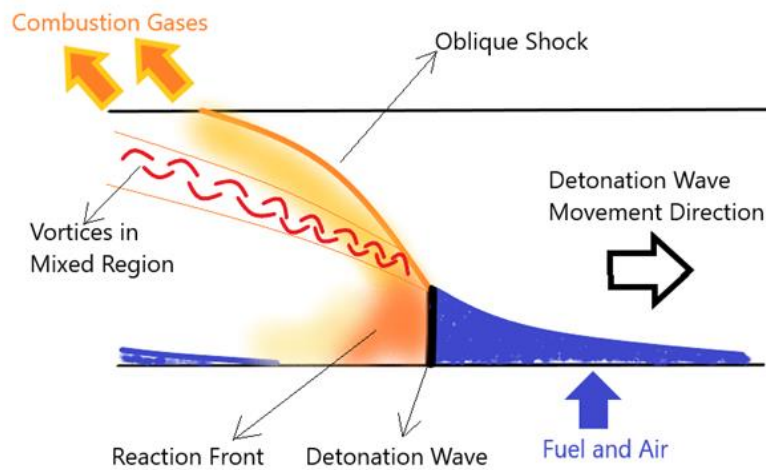


WRCs generate almost steady airflow and can also transfer work energy to the fluid, if the pressure gain is kept low. The device works as a secondary turbine where the combustion takes place in its rotor blade channels. The heat energy generated from the combustion is partially used to increase the combustor exit pressure and produce the necessary torque to rotate the channels, which eventually generates shaft work. If a WRC is designed such that most of the heat energy is used to generate pressure gain, then the portion that can be used for the shaft work would be reduced. The total pressure gain from this device is estimated to be between 1.4 and 1.6 times the inlet pressure. [28]

2.3.4 Rotating Detonation Engine (RDE)

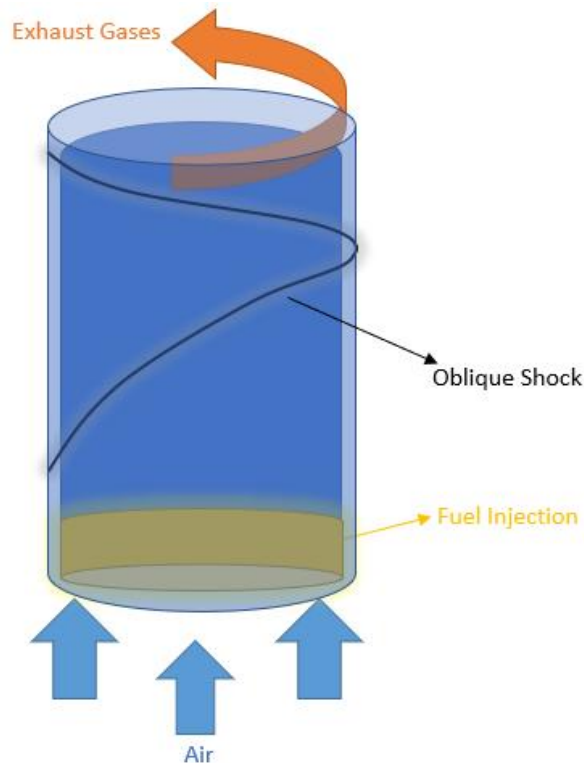
RDEs have the same operating principle as PDEs [18, 24] but the detonation takes place in a disk-like (annular) combustion chamber to improve the exit flow steadiness. [22] The detonation continuously propagates and is formed by the compound wave structure, illustrated in Exhibit 2-12.

Exhibit 2-12. Compound wave structure in RDE



The compound wave structure is formed by a detonation wave, an attached oblique shock and very weak expansion waves in the mixing region. This type of PGC requires shorter combustor length than a PDE [22, 24] and has higher combustion efficiency. [30] The RDE concept is illustrated in Exhibit 2-13.

Exhibit 2-13. RDE operation concept



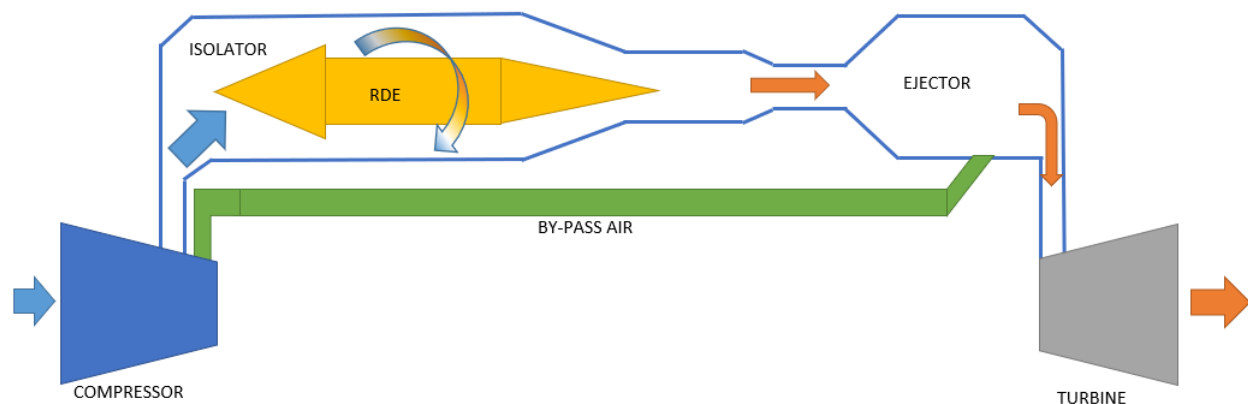
Examples of the experimental rigs exist at NETL, the Air Force Research Laboratory (AFRL), University of Michigan, and Purdue University. The total pressure gain with the current RDE experimental rigs are on the order of 1.7-2.2.

2.4 INTEGRATION OF PGCs TO GTs

In the current literature, PGC techniques are mostly considered for aerospace propulsion as the combustion section of ramjets, scramjets, or rocket engines, where no moving engine parts are attached to the exit of the PGC. Although very promising, fewer applications of PGCs to GTs exist, due to the low technology readiness level (TRL) and challenges in sustaining turbine performance. [13, 12] Air Force Research Laboratories (AFRL), Aerojet-Rocketdyne, GE Global Research, Naval Research Laboratory, and Yokohama University are some of the institutions currently working on PGC integration to GTs. AFRL and NETL use the existing T63 gas turbine, which is originally a turboshaft engine developed by Allison Engine Company and also known as Allison 250, for RDE integration studies. [12, 31, 32]

Aerojet-Rocketdyne is specifically working on RDE integration to industrial GTs in NGCC configurations. An illustration of their RDE-gas turbine integrated system is presented in Exhibit 2-14. The hybrid system consists of a J-Class gas turbine's turbomachinery that is modified here for the RDE integration. The design turbine inlet temperature is 2950 °F and compressor pressure ratio is 12.0 with exit flow temperature of 683 °F, which is lower than a typical J-Class engine value because of the existence of the RDE. RDE design pressure ratio is 1.94 and flow equivalence ratio is 0.45. The turbine exit flow pressure to the HRSG is 14 psia. For the initial design, all of the compressor exit flow is used in the RDE; by-pass flow is used for transient operation controls. [33]

Exhibit 2-14. Illustration of Aerojet-Rocketdyne's RDE-GT integration concept

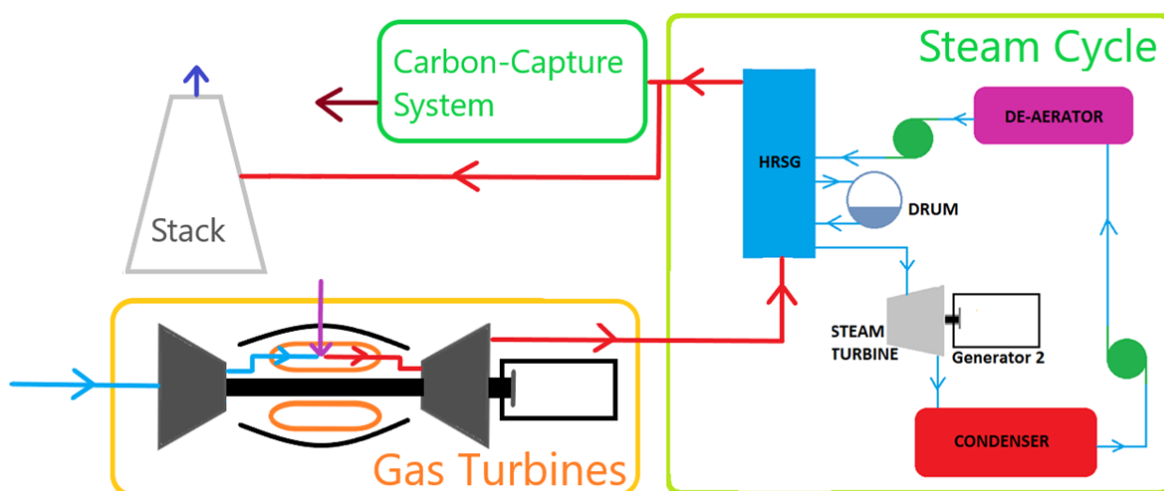


The research by Aerojet-Rocketdyne involves the RDE design, its integration to GT, and modeling of the proposed design to an NGCC plant. An Aspen Plus® (Aspen) model is used for the combined cycle simulations by using a FORTRAN code of the RDE model. This study is the only one known example of a system model of an RDE integrated gas turbine system. The model is currently being used in conjunction with the RDE design studies carried out under NETL's University Turbine Systems Research (UTSR) program. The model was used to find the best possible RDE nozzle design to improve turbine inlet flow conditions. The model is specific to Aerojet-Rocketdyne's RDE geometry and predicts 68 percent NGCC efficiency with RDE. [33]

3 DEVELOPMENT OF PGC ANALYTICAL MODELS FOR NGCC SIMULATIONS

In this study, the NGCC model developed by NETL will be used to assess the relative improvements in combined cycle (CC) efficiency from using the best promising PGC technology for an H-Class GT. Similar to Aerojet-Rocketdyne's model, the NGCC model is developed in Aspen and as a steady-state model that can be used in various thermodynamic and techno-economic analyses. The NGCC model consists of sub-systems for a GT, heat recovery steam generator (HRSG), steam turbine, stack, and carbon-capture components, illustrated in Exhibit 3-1.

Exhibit 3-1. Illustration of the NGCC model Rev.4 B31A developed at NETL



In this study, NGCC model (without carbon capturing) developed by NETL in ASPEN Plus was used, which includes gas turbine models, 3 pressure level HRSG and steam turbine models.

PGC modeling is studied broadly in the literature with various levels of details, tools, and calculation scopes. NGCC spreadsheet models in Aspen require analytical models that produce steady-state outputs. For the purpose of this study, a simple PGC analytical model with the following outputs is required:

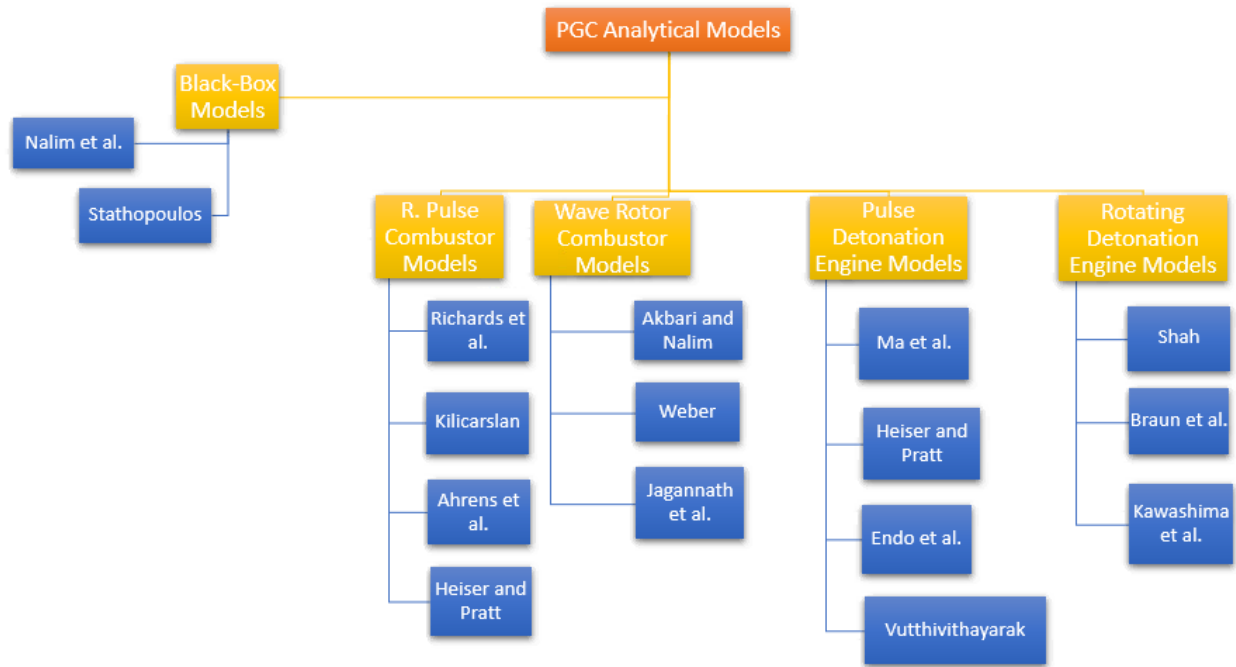
- Total pressure gain
- Fuel-to-air ratio (i.e., fuel consumption)
- Combustor exit thermodynamic states (temperature and pressure)

The simple PGC model for this study should also be able to distinguish various PGC techniques through its inputs and be able to represent the general physics of the analyzed PGC technique.

PGC analytical models that are applicable to the NGCC Aspen model from the open literature are categorized in Exhibit 3-2, based on complexity level and modeled PGC type.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 3-2. Applicable PGC analytical models to NGCC models from open literature



Black box models by Nalim et al. [28] and Stathopoulos [20] are analytical models for a generic pressure gain combustor for which the mechanism of the pressure gain is not specific; however, models specific to each PGC type need to be used in this study to compare the relative advantages and disadvantages when integrated to a GT. The detailed PGC models are compared in Exhibit 3-3.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 3-3. Comparison of applicable PGC analytical models from open literature

PGC Type	Author(s)	Fully Analytical	Time-Dependency	Validation	Primary Application	Chemical Kinetics	Model Available	Complexity Level
RPC	Richards and Gemmen [34]	No	Dynamic	Unknown	Aerospace	Modeled	Yes	Moderate
	Kilicarslan [35]	No	Dynamic	Experimental	General	Constants	Yes	Simple
	Ahrens et al. [36]	No	Dynamic	Experimental	General	Constants	Yes	Simple
	Heiser and Pratt [1]	Yes	Steady-State	Theoretical	Aerospace	Constants	Yes	Simple
WRC	Akbari et al. [29]	Yes	Steady-State	Experimental	General	Constants	Yes	Simple
	Weber [37]	Yes	Steady-State	Unknown	General	Constants	No	Moderate
	Jagannath et al. [38]	Yes	Steady-State	Experimental	Aerospace	Constants	No	Moderate
PDE	Ma et al. [39]	No	Dynamic	CFD	Aerospace	Constants	Yes	High
	Heiser and Pratt [1]	Yes	Steady-State	Theoretical	Aerospace	Constants	Yes	Simple
	Endo and Fujiwara [40]	Yes	Dynamic	Theoretical	General	Constants	Yes	Simple
	Vutthivithayarak [21]	Yes	Steady-State	Theoretical	Aerospace	Cantera	No	Moderate
RDE	Shah [4]	Yes	Steady-State	CFD	Aerospace	Constants	Yes	High
	Braun et al. [6, 7]	Yes	Dynamic	CFD	Aerospace	Cantera	No	Moderate
	Kawashima et al. [41]	No	Dynamic	CFD	Aerospace	AISTJAN	Yes	High

For the pulse combustor models, Richards and Gemmen [34], Kilicarslan [35], and Ahrens et al. [36] have similar models that incorporate the solution of a time dependent aero-thermal scheme with simple numerical solvers. Heiser and Pratt's model [1] is a simpler fully analytical model that employs a single-gamma modeling approach.

For the WRC modeling, most of the analytical models were built by the research group in Purdue University, where this PGC concept was developed. Weber [37] provides another reference model but the full model is not available in open literature. Jagannath et al. [38] uses the same model with Akbari et al. [3] but in greater detail by introducing turbomachinery related calculations for WRC channel blades.

For the PDE, Heiser and Pratt [1] have an analytical model based on the thermodynamic analysis of the ZND cycle and is a common reference, whereas Ma et al. [39] use a time dependent solution scheme. Endo and Fujiwara's [40] work is another common reference for PDE modeling, where they use a simpler time-dependent solution scheme that generates PDE outputs for each cycle frequency. Vutthivithayarak [21] uses a steady-state scheme based on Endo and Fujiwara's model [40] and Heiser and Pratt [1] but major details of the model are not available in the open literature.

For the RDE, Shah [4] has a detailed analytical model aimed toward ramjet applications of RDEs. Braun et al. [6, 7] has a simpler version of Shah's model but is very good in capturing the exit conditions of RDEs. Kawashima et al. [41] uses a time-dependent solution method in a system matrix and uses a different chemical kinetics model than other authors.

Based on the explained details and their applicability to the purpose of this study, Heiser and Pratt's models [1] are selected for RPCs, Akbari et al.'s model [3] is selected for WRCs, Heiser and Pratt's model [1] is selected for PDEs and Shah [4] and Braun et al.'s [6, 7] models are selected for the RDE.

A simplified PGC model (PGC-Sim), which uses the selected analytical modeling methodologies, is developed in MATLAB Simulink for the analysis and comparison of the PGC concepts and to be used in further analyses involving PGC-GT integration. The model includes a numerical root solver method based on the Van Wijngaarden-Dekker-Brent Method for equations that require iterative solutions.

The algorithms for the models for the RPC and PDE are used from the respective models developed by Heiser and Pratt. [1] PDE model algorithm also uses the surrogate model developed by GE Global Research [2] for fuel-to-air ratio calculations and corrections to calculated pressure gain.

The WRC model uses the algorithm by Akbari et al. [3] But an efficiency reduction term to include the effect of performance reduction from the "buffer gas" is introduced to the model to reduce the complexity of the original algorithm.

The RDE model uses the ideology from Shah [4] and Kaemming [5] and Braun et al. [6, 7] but uses Heiser and Pratt's model for detonation wave speed calculations and also include an oblique shock solver [8, 9] for the required post-shock state calculations.

3.1 DEVELOPED ALGORITHMS

3.1.1 RPC Algorithm

The RPC modeling uses the Humphrey cycle to calculate the change of thermodynamic states throughout the process described in Section 2.3.1. The Humphrey cycle is a modification of the Brayton cycle, where the constant pressure heat addition is replaced by a constant volume heat addition process. [1, 26]

The static temperature ratio across the RPC can be calculated by using Equation 3-1.

$$\frac{T_4}{T_3} = 1 + \frac{\eta_c f h_{PR}}{c_{v,3} T_3} \quad \text{Equation 3-1}$$

In Equation 3-1, f is the fuel-to-air ratio, h_{PR} is the fuel heating value for detonation, and $c_{v,3}$ is the constant volume specific heat capacity at combustor inlet station (Station 3). The static pressure ratio across the RPC is calculated with Equation 3-2, where Station 4 in the equations represents the combustor exit location.

$$\frac{P_4}{P_3} = \frac{T_4}{T_3} \quad \text{Equation 3-2}$$

The total pressure at the exit of the combustor (P_{t4}) can be found by using Equation 3-3, which is derived from the isentropic flow relations.

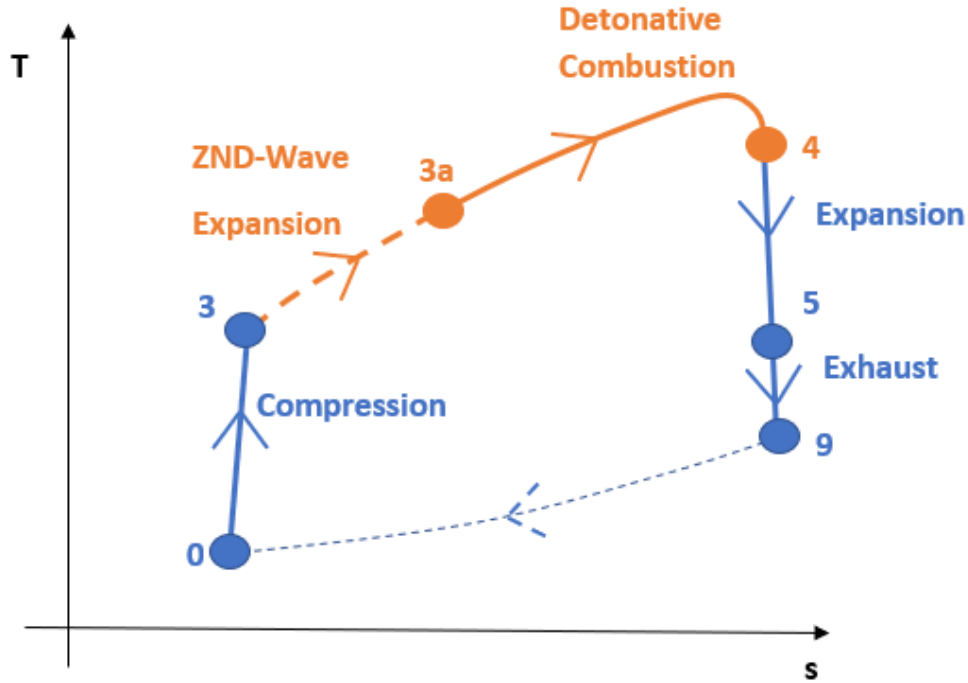
$$P_{t4} = P_4 \left(1 + \frac{\gamma_4 - 1}{2} M_4^2 \right)^{\gamma_4 / (\gamma_4 - 1)} \quad \text{Equation 3-3}$$

The combustor exit station (Station 4) properties correspond to the post-detonation properties and should be found by using a detonation property calculator, which can calculate post detonation properties by using the inflow thermodynamic states and fuel-to-air ratio. The Mach number at the combustor exit, M_4 , is governed by the Chapman-Jouget (CJ) condition. [1]

3.1.2 PDE Algorithm

Different from a Brayton cycle, in the PDE the detonation wave process is the source of the heat addition. The temperature-entropy diagram of the PDE is illustrated in Exhibit 3-4.

Exhibit 3-4. Temperature-entropy diagram of PDE



For the detonation wave process, which is the process from Station 3 to Station 4 in Exhibit 3-4, the ZND wave model is the generally accepted model for modeling the normal detonation wave in the tubes of the pulse detonation device. The detonation wave is a compound wave consisting of a normal shock wave progressing into the undisturbed fuel-air mixture, which is nearly at rest at the combustor inlet (Station 3 in Exhibit 3-4), followed by the release of heat energy in a constant area region through Rayleigh flow principles, and terminating at Station 4, which corresponds to the location of the tube exit. The strength of the leading shockwave (Mach number, temperature ratio, and pressure ratio) is uniquely determined by the inlet conditions and the amount of the heat added (i.e., fuel-to-air ratio). [1]

The entire detonation process from Station 3 to Station 4, is constrained by the CJ condition, which requires that the local Mach number at the detonator tube exit to be 1.0 (i.e., M_4 to be sonic). The heat addition region is followed by a very complex constant area region of non-steady expansion waves, which are assumed to be isentropic. The slight downturn of the T-s diagram right before Station 4 corresponds to the familiar situation near Mach 1 where heat addition causes static temperature to drop. The ZND wave structure is stationary in detonation wave coordinates from the undisturbed flow to the end of heat addition process. [1]

The Mach number of the leading shockwave is important in calculating the amount of heat release and hence, the pressure gain from the cycle. Closed-form algebraic solutions for the wave Mach number (CJ-Mach number) is calculated using Equation 3-4.

$$M_{CJ}^2 = (\gamma_3 + 1) \left[\frac{f h_{PR} \eta_b}{c_{p,3} T_3} \right] + 1 + \sqrt{\left\{ (\gamma_3 + 1) \left[\frac{f h_{PR} \eta_b}{c_{p,3} T_3} \right] + 1 \right\}^2 - 1} \quad \text{Equation 3-4}$$

The CJ-Mach number (M_{CJ}) is calculated by using the inflow stream conditions (T_3 , γ_3 , and $c_{p,3}$). The fuel-to-air ratio (f) and the fuel heating value for detonation, h_{PR} , are the other inputs. f depends on the pressure gain, and pressure gain depends on the M_{CJ} , which is a function of f . The described relation of parameters requires Equation 3-1 to be solved iteratively. [1]

The entropy rise in the detonation process is used in the estimation of the static temperature increase through a second law analysis. The entropy change is calculated using Equation 3-5.

$$\frac{s_4 - s_3}{c_{p,3}} = -\ln \left(M_{CJ}^2 \left(\frac{\gamma_3 + 1}{1 + \gamma_3 M_{CJ}^2} \right)^{\gamma_3 + 1/\gamma_3} \right) \quad \text{Equation 3-5}$$

By using the second law analysis, the static temperature change for the detonation process can be found in Equation 3-6.

$$\frac{T_4}{T_3} = e^{\frac{s_4 - s_3}{c_{p,3}}} \quad \text{Equation 3-6}$$

The static pressure gain is then calculated using Equation 3-7.

$$\frac{P_4}{P_3} = \frac{1 + \gamma_3 M_{CJ}^2}{\gamma_3 + 1} \quad \text{Equation 3-7}$$

Besides the thermodynamic model, the amount of the fuel-to-air ratio also depends on several system design parameters such as the purge fraction of the tubes. A PDE detonation chamber can be fully purged (i.e., only air flows into the detonation tube and is completely filled with air during the detonation process) or partially purged (i.e., the detonation chamber is partially filled with air and the rest is filled with hot combustion products from the previous cycle). The purge fraction plays an important role in determining the fuel-to-air ratio of the PDE cycle. Tangirala et al. [2] provides a parametric model for estimating fuel-to-air ratio and total pressure gain in practical PDEs by using experimental and computational analysis for the PDE developed by GE Global Research. The fuel-to-air ratio can be calculated by using Equation 3-8.

$$f^{-1} = \frac{h_{PR}(\gamma_3 - 1)(1 - pf)}{\gamma_3 R_3 T_{t,3} \left\{ \left(c_{p,4}/c_{p,3} \right) \left(T_{t,4}/T_{t,3} \right) - 1 \right\}} - 1 \quad \text{Equation 3-8}$$

In Equation 3-7, the constant pressure specific heat ratio at detonation tube exit, $c_{p,4}$, should be found by using a detonation property calculator. The purge fraction, pf , is calculated by using Equation 3-9 from the fraction of the time purge air is flowing through the valve (t_p) to the valve open time ($t_{vo}=t_p+t_f$), where t_f is the filling time.

$$pf = \frac{t_p}{t_{vo}} = \frac{t_p}{t_p + t_f} \quad \text{Equation 3-9}$$

From the parametric model by Tangirala et al. [2], the total pressure gain can be calculated using Equation 3-10.

$$\frac{P_{t4}}{P_{t3}} = a \left(\frac{c_{p4} T_{t4}}{c_{p3} T_{t3}} \right)^{c \gamma_3 / \gamma_3 - 1} \quad \text{Equation 3-10}$$

For specified PDE exit total temperature, T_{t4} , Equation 3-10 and Equation 3-6 are used together to obtain PDE exit Mach number, which is equal to 1 for an ideal PDE cycle but is different from 1 for real PDE cycles. The coefficients used in Equation 3-10 are given as 1.0 and 0.105 for coefficients “a” and “c,” respectively.

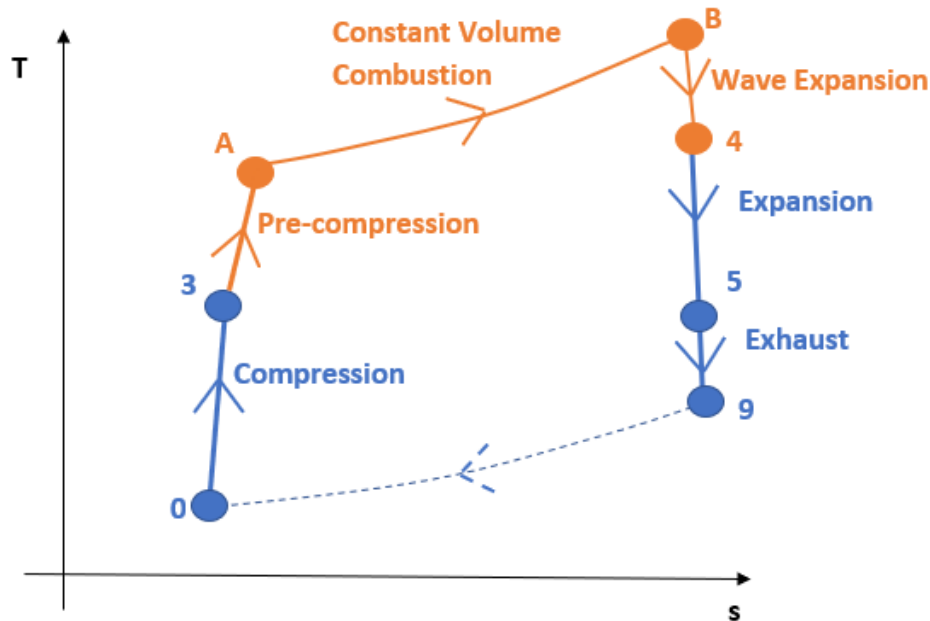
3.1.3 WRC Algorithm

The analytical model for the WRC is from the study by Akbari et al. [3], where the working fluid inside the rotor channels are assumed to be going through three main processes—filling, combustion, and purging:

1. The filling process usually occurs with pre-compression process by the hammer shock (Station 3 → State A)
2. The constant volume combustion takes place between states A and B
3. The purging process by the expansion fan and the opening the exit ports occurs between state B and Station 4

The processes are illustrated in Exhibit 3-5 on the temperature-entropy diagram of the WRC integrated Brayton Cycle.

Exhibit 3-5. Temperature-entropy diagram of WRC integrated GT



For the pre-compression region with WRC compression efficiency η_{3A} , the pressure ratio of State A static pressure to the WRC total inlet pressure can be found using Equation 3-11.

$$\frac{P_A}{P_{t3}} = \left[1 + \eta_{3A} \left(\frac{T_A}{T_{t3}} - 1 \right) \right]^{\frac{\gamma_3}{(\gamma_3 - 1)}} \quad \text{Equation 3-11}$$

Equation 3-11 calculates pressure, P_A , as a function of the compressor exit conditions and wave strengths inside the rotor channels.

Following the approach by Akbari et al. [3], the static temperature rise during the constant volume combustion process (states A $\rightarrow$ B) can be expressed by applying a total volume conservation, shown in Equation 3-12.

$$\frac{T_B}{T_A} = \mu \frac{R_3}{R_4} \left[\frac{P_B}{P_A} - (1 - \mu) \left(\frac{P_A}{P_B} \right)^{\gamma_3 - 1 / \gamma_3} \right]^{-1} \quad \text{Equation 3-12}$$

In Equation 3-12, μ is the residual buffer gas mass ratio, which is the fraction of the burned combustion gases in the active cycle (fresh mixture) to the total amount of gas present in the rotor channel. The total amount of the gas present in the rotor channel is the summation of the fresh mixture and the buffer gas remaining from the previous cycle. For perfect WRC, $\mu=1$, where the entire buffer gas is successfully exhausted to the WRC exit. As the buffer gas fraction is reduced (i.e., $\mu \rightarrow 0$), WRC performance (and pressure gain) is reduced.

In Equation 3-11 and Equation 3-12, the static temperature, T_A , is an unknown as it reflects an unknown pre-compression determined by M_4 (exit Mach number). To calculate T_A , the amount of heat release from the WRC cycle calculated.

The amount of heat release during the combustion process from states A to B is calculated by applying an energy balance of the gas trapped in the channel as a closed system, considering the fresh mixture and the buffer gas. The associated heat release per total mass can be found using Equation 3-13.

$$q_{CS} = \int_A^B c_v(T) dT \quad \text{Equation 3-13}$$

The same heat release can be expressed by applying energy balance of the overall process from stations 3 to 4, considered as an open system. The heat release for the described process per total mass can be found using Equation 3-14.

$$q_{OS} = \mu \int_{T_{t3}}^{T_{t4}} c_p(T) dT \quad \text{Equation 3-14}$$

Equation 3-13 and Equation 3-14 must yield to same heat release and thus can be set equal to find T_A . The solution approach is to guess an initial value for the pressure ratio P_A/P_B and then

use T_A calculated from Equation 3-12 to calculate q_{CS} and q_{OS} from Equation 3-13 and Equation 3-14, respectively. The iterative process repeats until the two calculated heat release values become equal.

Considering the WRC expansion adiabatic efficiency, η_{4B} , State B and Station 4 can be related to each other using Equation 3-15.

$$\frac{P_{t4}}{P_B} = \left(1 - \frac{1 - (T_{t4}/T_B)}{\eta_{4B}} \right)^{\gamma_4/\gamma_4-1} \quad \text{Equation 3-15}$$

Assuming an ideal isentropic expansion wave, the method of characteristics can be used to find the flow properties across the expansion wave (i.e., T_4/T_B). The isentropic wave assumption can be reconciled with a non-ideal overall expansion by assuming that losses are associated with the high-speed flow after the wave acceleration of the gas, rather than in the wave itself. [3] Then, using the relations derived across a C-Characteristic line (right running wave) in the axial plane, the equation for the static temperature ratio T_4/T_B can be found using Equation 3-16.

$$\frac{T_4}{T_B} = \left(1 + \frac{\gamma_4 - 1}{2} M_4^2 \right)^{-2} \quad \text{Equation 3-16}$$

The total temperature at the WRC exit, T_{t4} , is dependent on the static temperature, T_4 , and the speed of the exit flow, M_4 . Therefore, Equation 3-15 and Equation 3-16 are solved together to obtain the total pressure gain from the WRC.

3.1.4 RDE Algorithm

The flow field in an RDE consists of a compound wave structure, which is formed by a detonation wave, attached oblique shock, and weak expansion waves in the mixing region, which requires detailed modeling of the flow field, even for simplified models. An analytical RDE model has been developed for rocket applications by AFRL [4, 6] and Innovative Scientific Solutions. [25, 5] Some parts of this algorithm have been changed in this study for GT applications and an oblique shock solver has been added.

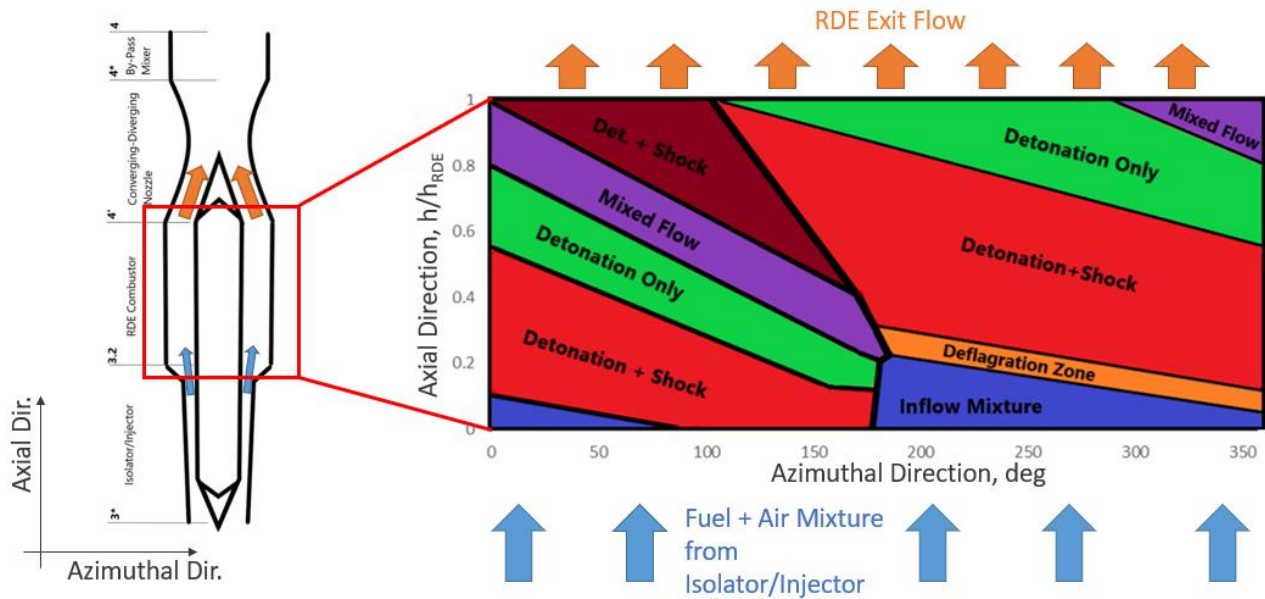
The RDE model assumptions are listed as follows:

- Only one detonation wave exists in the detonation chamber
- Detonation height is an input parameter
- Deflagration flow mixes with the detonation flow only at the oblique shock interface
- Flow streamlines do not pass through neighboring flow regions; they pass only through the detonation wave and the oblique shock
- Expansion waves behind the oblique shock are negligible (i.e., weak)
- RDE exit and mixing flow region average properties can be found by mass averaging of relative streams

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Based on the listed assumptions, the flow field of the RDE can be divided into five distinct regions as shown in Exhibit 3-6. The shown flow scheme applies to the unwrapped cylindrical combustion chamber of the RDE.

Exhibit 3-6. RDE flow scheme assumption for analytical model development



The detonation properties are a key part of any type of RDE analytical model, as they provide thermodynamic property information such as specific heats (c_p), specific heat ratio (γ), gas constant (R), and compressibility factor (Z). Two sets of gamma values are used for the reactants and detonation products, which are known as the “2- γ Model.” For the pre-detonation thermodynamic properties, the mass average of the reactants (natural gas and air) is used. Post-detonation thermodynamic properties are obtained by using GASEQ Software [42] for different fuel-to-air ratios (f). GASEQ Software was used to generate curve-fits for c_p , γ , and R for fuel-to-air ratio range of 0–0.075.

Each flow path from the assumed flow scheme of Exhibit 3-6 has different sets of equations and modeling details. The flow fractions that go into each flow path are determined from the computational fluid dynamics (CFD) study by Kaemming and Paxson [25] for different detonation heights. The fractioning is calculated with correlations obtained for single wave detonation height to RDE combustion chamber height ratio (h_{det}/h_{RDE}). The flow partitioning and basic explanation of each flow path is given as follows:

- Path a is the portion of the flow that passes through the detonation wave only and moves to the exit without any other interference.
- Path b is the portion of the flow that passes through the detonation wave and then passes through the oblique shock. A portion of this flow mixes with other flows and a bigger portion of this flow moves to the exit without any other interference.

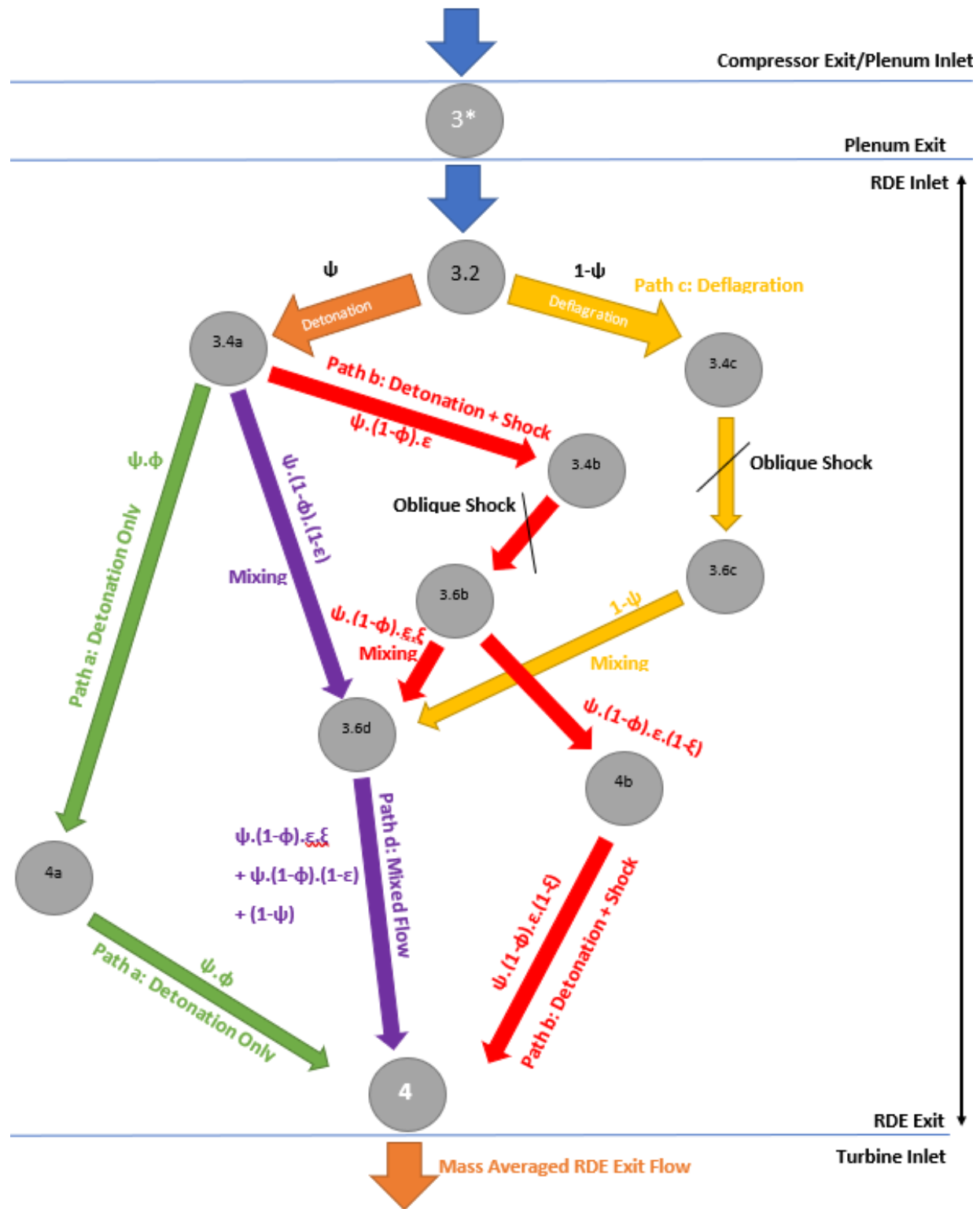
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- Path c is the portion of the flow that experience the deflagration, where the non-detonation or conventional burning of the inlet mixture occur. This flow passes through the oblique shock and mixes with the detonation flows afterwards.
- Path d flow starts from the oblique shock and is a mixture of the flows coming from paths a, b, and c. Path d flow moves to the RDE exit without any other interference.

The flowchart of the analysis paths is shown together with RDE station numbering in Exhibit 3-7.

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Exhibit 3-7. RDE analysis flow chart for analytical modeling



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The flow proportions to each path are calculated using Equation 3-17 through Equation 3-20. [4, 6] The equations for parameters x , y and z are from linear regression curve-fits to the plots presented in the AFRL study. [4, 6]

$$x = -0.7007 * \left(\frac{h_{det}}{h_{RDE}} \right) + 0.7203$$

$$y = -0.3805 * \left(\frac{h_{det}}{h_{RDE}} \right) + 0.3999$$

$$z = 0.1504 \left(\frac{h_{det}}{h_{RDE}} \right) + 0.0497$$

$$\phi = z - zx$$

Equation 3-17

$$\varepsilon = \frac{1}{2} \left(1 + \frac{z - \phi}{1 - \phi} \right)$$

Equation 3-18

$$\xi = \frac{1 - \varepsilon}{\varepsilon}$$

Equation 3-19

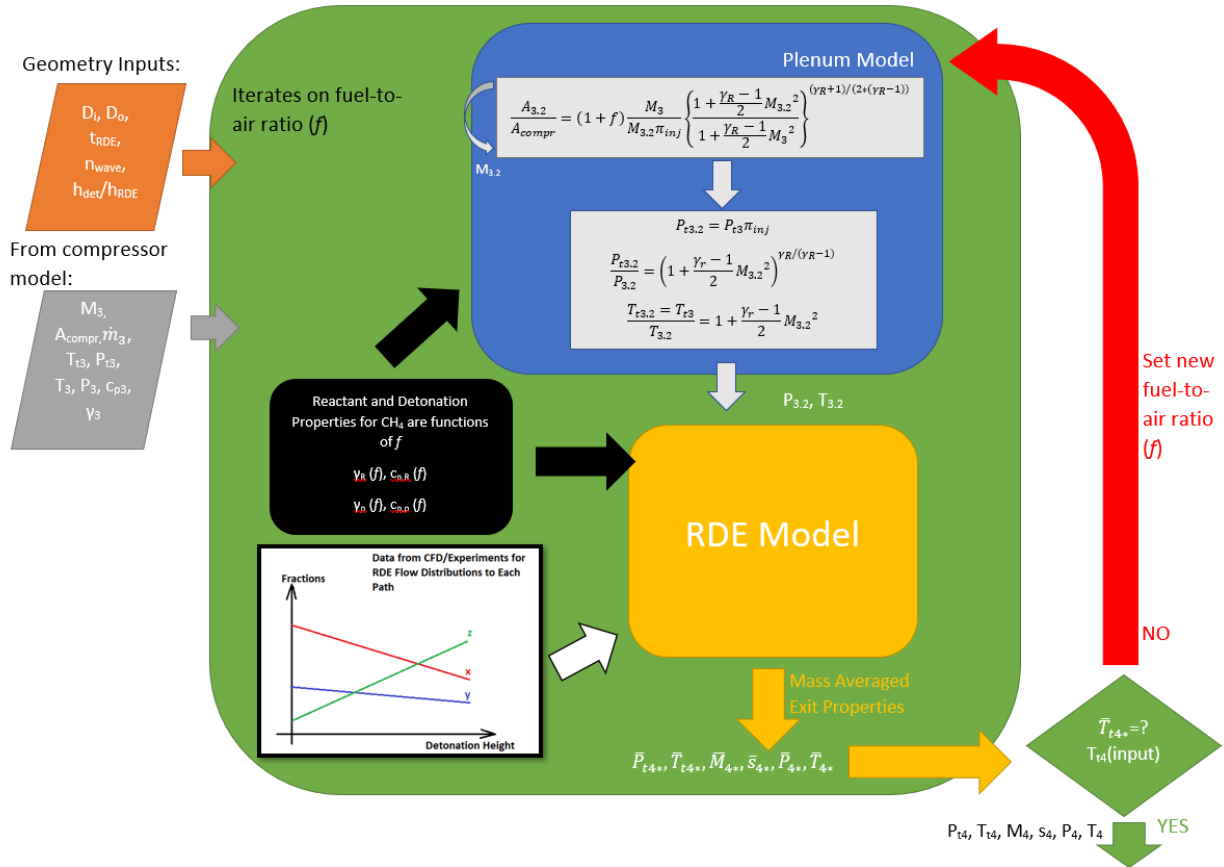
$$\psi = \frac{y}{y + 2(1 - \phi)(1 - \varepsilon)}$$

Equation 3-20

The fuel is proportioned between the deflagration and detonation paths with ψ . The algorithm from AFRL [4] is slightly modified here by removing the rocket nozzle related calculations and several injector calculations. The model makes an iteration on fuel-to-air ratio until the mass averaged RDE exit flow temperature is equal to the set RDE exit temperature by the user. This general algorithm design is similar to the algorithms used to calculate fuel consumption in conventional combustors. The plenum is modeled separately with the equations provided in Appendix B: Plenum Model Equations and provides input to the RDE model. The path flow fractions and detonation properties are updated at each iteration. The simplified flowchart of the algorithm is shown in Exhibit 3-8.

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Exhibit 3-8. RDE analytical model algorithm flowchart



The equations used in the RDE model are provided in Appendix C: RDE Flow Path Equations. The RDE model execution sequence starts with Path a and ends with the calculations for the exit mixing. The general information on the RDE model calculation scheme is provided as follows:

- Path a calculation includes detonation calculations to find post-detonation properties by using Heiser and Pratt's method. [1] Flow speeds are then calculated by using methods similar to Braun et al. [6, 7], where the speeds are calculated for the wave frame and then translated to static frame of reference to obtain total properties. Entropy change is then calculated by using second law analysis.
- Path b post-detonation properties are the same with Path a, therefore, some of the results from Path a are directly used here for pre-shock states. The oblique shock solver (Appendix D: 2-Dimensional Oblique Shock Solver Equations) used and post-shock properties as well as the shock angle are calculated. The change in entropy is calculated using second law analysis.
- Path c thermodynamic states before the shock are found differently depending on the relative amounts of the deflagration to detonation fuel consumption. Similar to Path b, the oblique shock solver is used here with the calculated shock angle from Path b to find properties before the mixing.

- Properties from paths a, b, and c are used to find the mixed flow's thermodynamic properties, which is denoted as Path d. A mass averaging is made to find average quantities. Second law analysis for mixing flows is used to find the pressure of the exiting flow.
- Finally, another mixing analysis is made to obtain the average thermodynamic properties at the RDE exit. Mass averaging is applied to obtain the total and static temperatures, specific heats, and the gas constant and second law analysis is used to find the average exit pressures (both static and total).

The validations of the developed model are provided in Section 3.2.4.

3.1.5 Numerical Root Solver Algorithm

The numerical root solver function is required for the iterative solutions used for

- Fuel-to-air ratio for RPC and PDE
- Peak pressure ratios (P_a/P_b) in WRC
- Oblique shock and CJ-Mach number solutions in RDE

The root solution method developed by Van Wijngaarden, Dekker, and Brent, is used in the PGC-Sim where the solution scheme requires an iterative solution. The Brent method combines the bisection method, the secant method, and inverse quadratic interpolation. The resulting algorithm proves faster than the three algorithms on which it is based. In this method, the reliability of the bisection method is retained, while the root finding speed can be as fast as less reliable methods. The algorithm initially tries the potentially fast converging secant method or the inverse quadratic interpolation if possible and uses the bisection method if the other two methods fail to converge. [43]

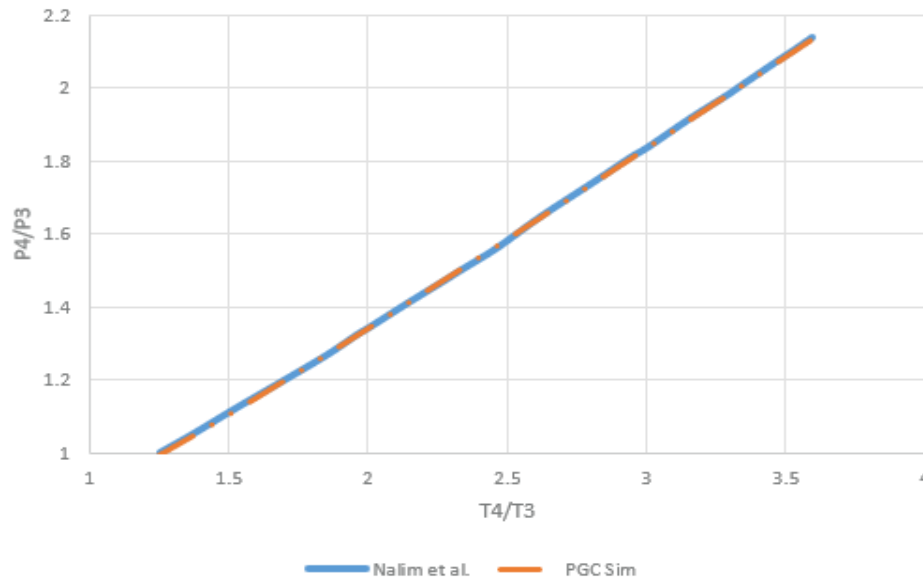
The algorithm used in the PGC-Sim is presented in Appendix A: Brent Method.

3.2 COMPARISONS AND CALIBRATIONS

3.2.1 Numerical Root Solver Algorithm

The root solver algorithm function results are compared with the results from the black-box PGC model by Nalim et al. [28] with static pressure gain calculations and is shown in Exhibit 3-9. The comparison for the root solver showed good agreement for a generic PGC scenario and used in the several parts of the PGC-Sim algorithm.

Exhibit 3-9. Comparison made with static pressure gain (P_4/P_3) with respect to different values of PGC temperature ratio values (T_4/T_3) for generic PGC model by Nalim et al. [28]

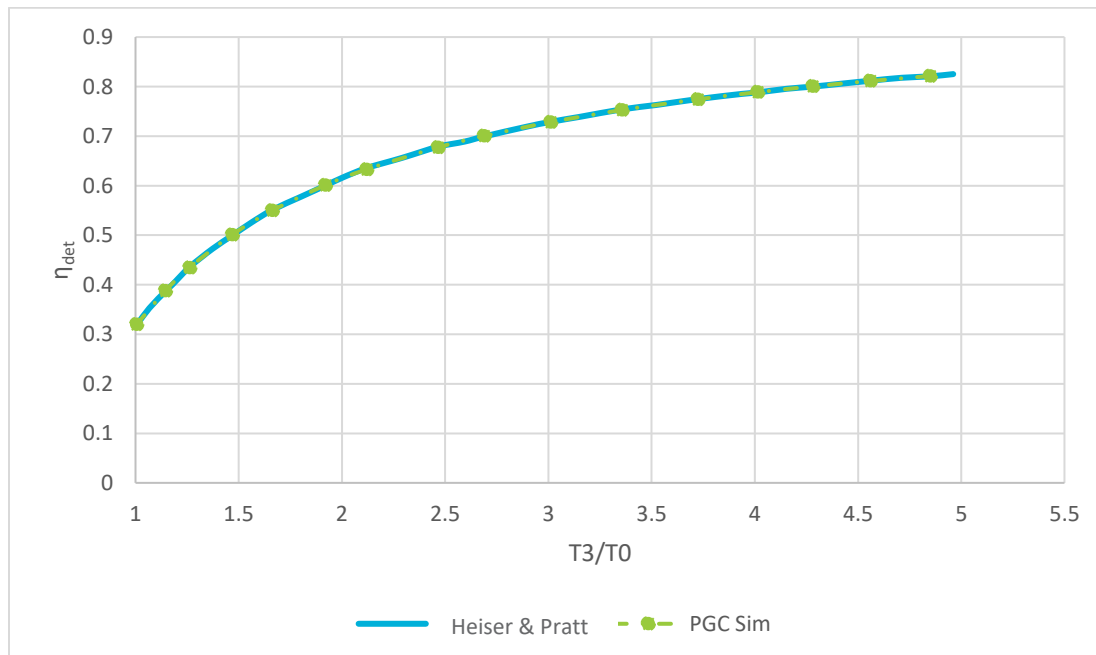


3.2.2 RPC and PDE Algorithms

The calculations in PGC-Sim for the RPC and PDE are compared by using the data from Heiser and Pratt [1] and GE Global Research [2] for PDE cases. A model-to-model comparison is made by using the detonation efficiency and static pressure gain parameters.

For the RPC model, the calculated change in the detonation efficiency with combustor inlet temperature is compared with the model results of Heiser and Pratt [1] in Exhibit 3-10.

Exhibit 3-10. Comparison made for the change in detonator efficiency with combustor inlet temperature (RPC)

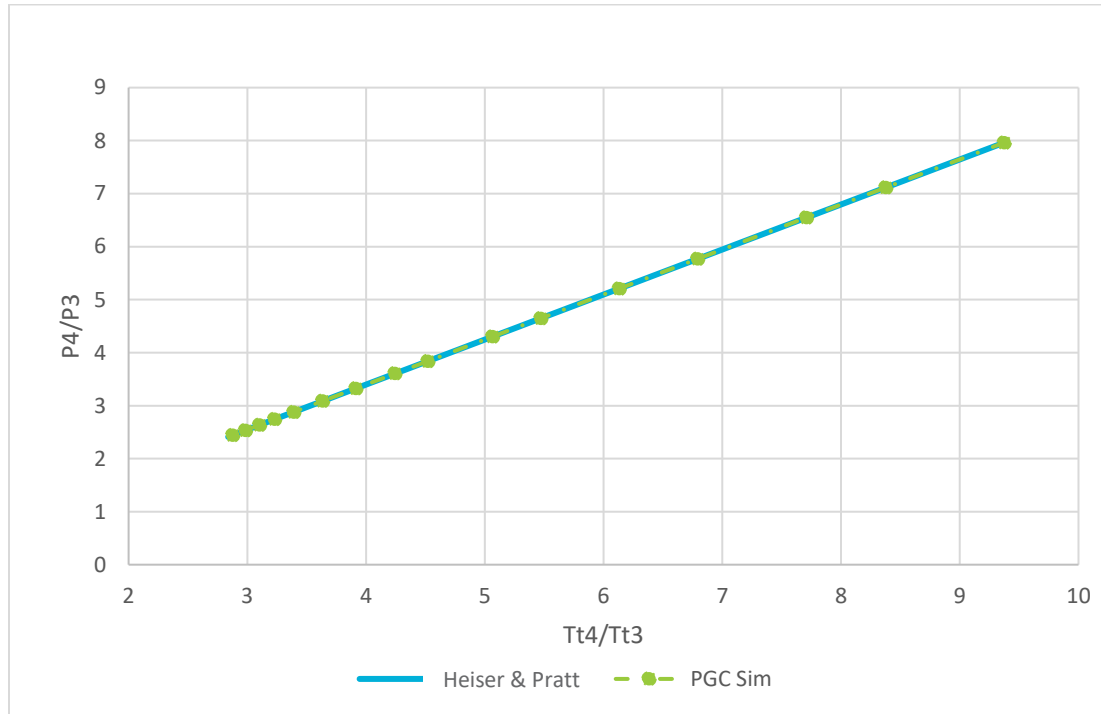


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It should be noted that PGC-Sim primarily calculates total pressure gain, however for the comparison purposes calculated total pressure gain is converted to static pressure gain because the compared data from Heiser and Pratt [1] was given only for static pressure gain.

Another comparison with Heiser and Pratt's model is made for calculated static pressure gain (P_4/P_3) for different values of RPC exit to inlet total temperature ratios (T_{t4}/T_{t3}) and shown in Exhibit 3-11.

Exhibit 3-11. Comparison made for the change in static pressure gain with combustor total temperature ratio (RPC)

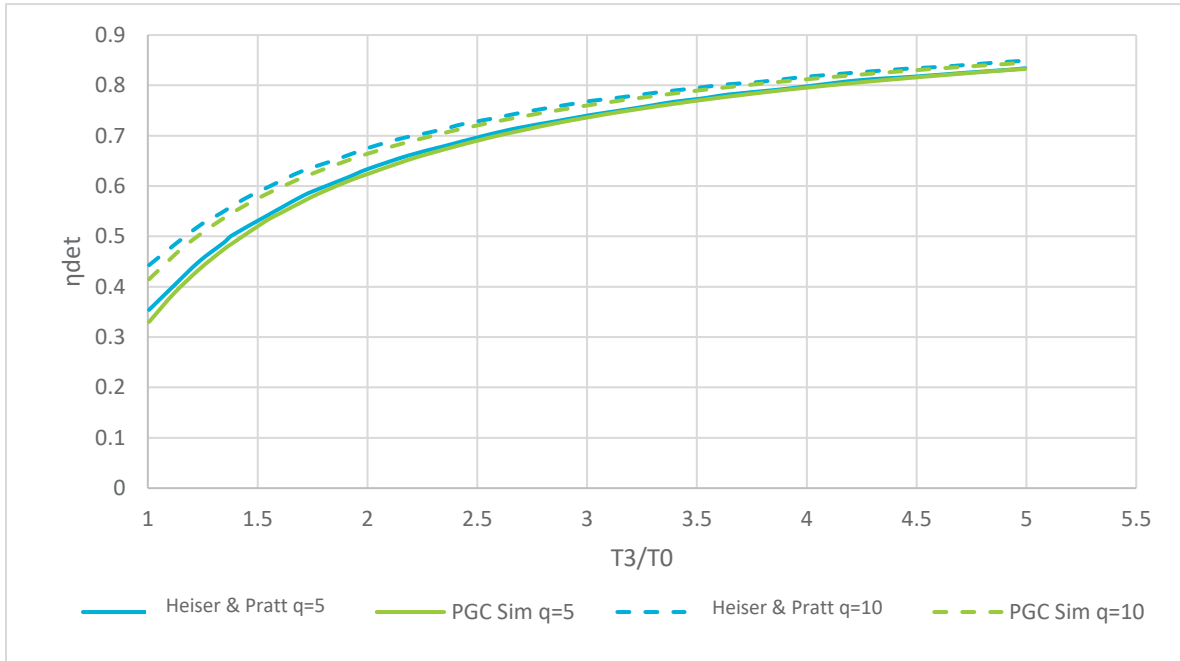


For both comparison cases, the difference of PGC-Sim results to reference model results is less than 0.5 percent.

For the PDE model, the calculated change in the detonation efficiency with combustor inlet temperature is compared with the model results of Heiser and Pratt [1] for two different fuel heating levels in Exhibit 3-12.

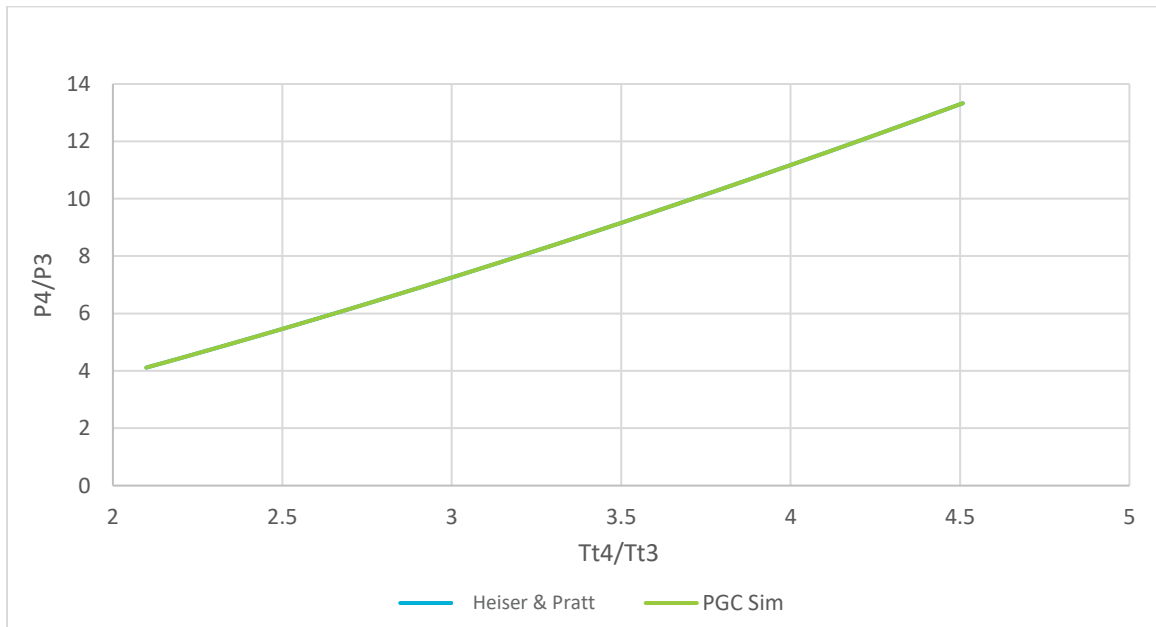
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Exhibit 3-12. Comparison made for the change in detonation efficiency with combustor inlet temperature for two different fuel heating values (PDE)



Another comparison with Heiser and Pratt's model was made for calculated static pressure gain (P_4/P_3) for different values of RPC exit to inlet total temperature ratios (T_{t4}/T_{t3}) and is shown in Exhibit 3-13.

Exhibit 3-13. Comparison made for the change in static pressure gain with combustor total temperature ratio (PDE)



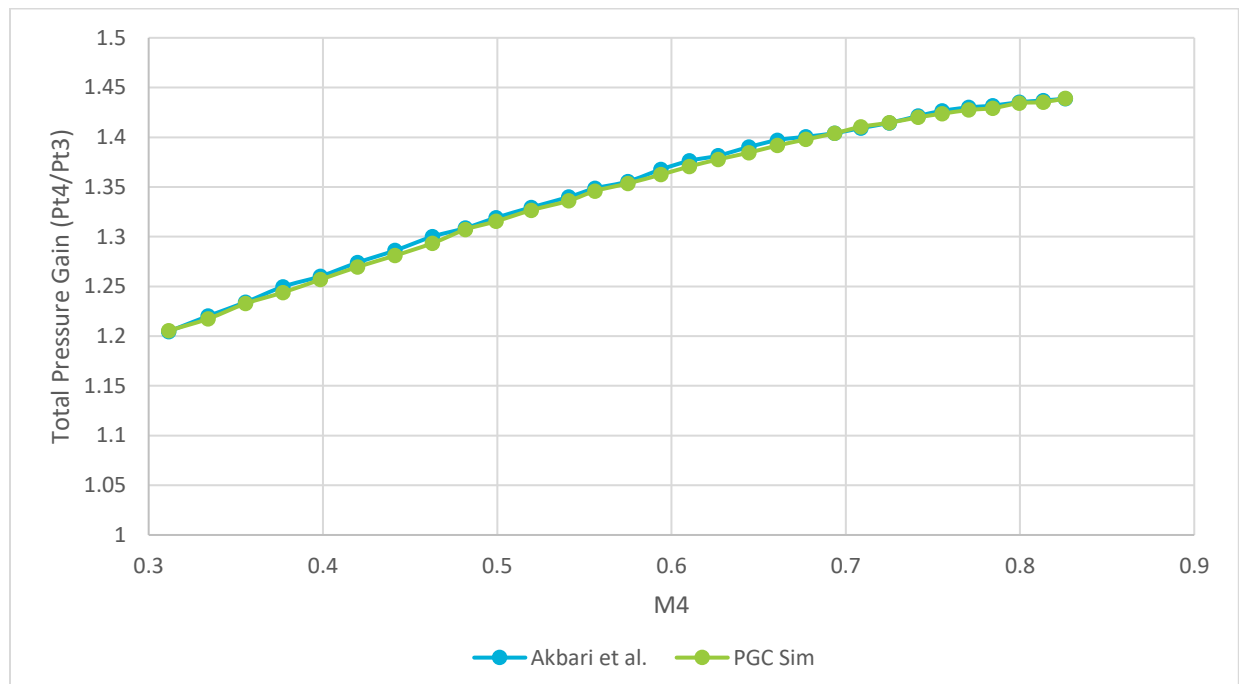
For both comparison cases, the difference of PGC-Sim results to reference model results is less than 0.5 percent.

3.2.3 WRC Algorithm

The calculations in PGC-Sim for the WRC were validated by using the data provided by Akbari et al. [3] The only difference of PGC-Sim in the calculation methodology from Akbari et al. [3] is the way of including the effect of the buffer gas on WRC performance parameters, where an efficiency parameter is used in PGC-Sim to include buffer gas effects as the combustor temperature ratio increases. The buffer gas efficiency reduction parameter is obtained by correlating several temperature ratio and inlet condition data from Heiser and Pratt. [1]

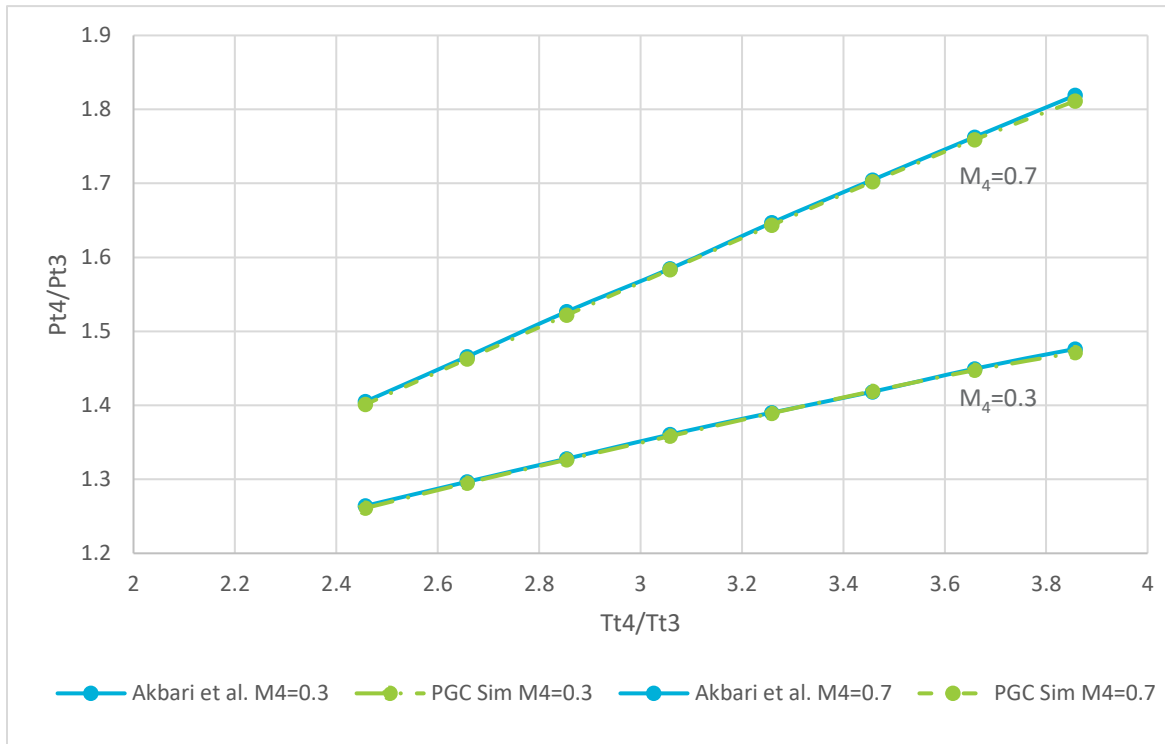
A comparison is made with the reference model for the changes in the total pressure gain from WRC for different combustor exit Mach numbers, presented in Exhibit 3-14.

Exhibit 3-14. Comparison made for the change in total pressure gain for different combustor exit Mach numbers of WRC



Another comparison is made for the changes in the total pressure gain with different values of WRC exit to inlet total temperature ratio, presented in Exhibit 3-15.

Exhibit 3-15. Comparison made for the change in total pressure gain for different combustor exit to inlet total temperature ratios (WRC)

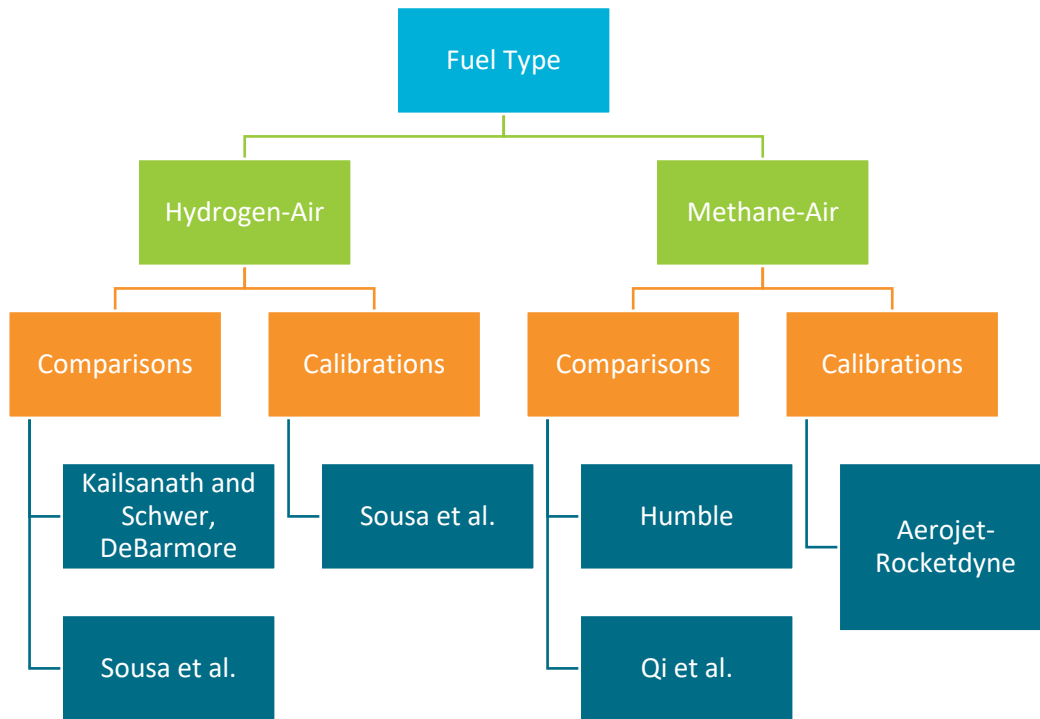


For both comparison cases, the difference between PGC-Sim results and the reference model results is less than 0.5 percent.

3.2.4 RDE Algorithm

After developing the model, it was compared and then calibrated for the purpose of H-Class GT integration. Several literature resources are used to compare and calibrate the RDE model. The resources used in comparisons and calibrations of the model outputs are shown in Exhibit 3-16.

Exhibit 3-16. Comparison and calibration resources used in RDE model development



The literature was selected based on the availability of the following information:

- Pressure and temperature profiles in axial direction at specified RDE height
- Exit Mach number
- Obtained pressure gain under the given inlet conditions
- Detonation height
- Used fuel-to-air or equivalence ratio
- Inlet flow information and RDE geometry

Because PGC-Sim is a system level model, one-to-one match with the compared CFD and experimental studies are not the aim; the validation tolerance for temperature and pressure profiles is set to 15 percent. The validations are made both for hydrogen and methane fuels and presented in the subsequent sections.

3.2.4.1 Hydrogen Fuel Cases

Most RDE literature that has both temperature and pressure profiles is for hydrogen-air detonations. Shown validations in Exhibit 3-15 and Exhibit 3-16 are made with the results of CFD analyses made by Kailsanath and Schwer [44] and DeBarmore [45] for stoichiometric detonation conditions. The analysis conditions are listed in Exhibit 3-17.

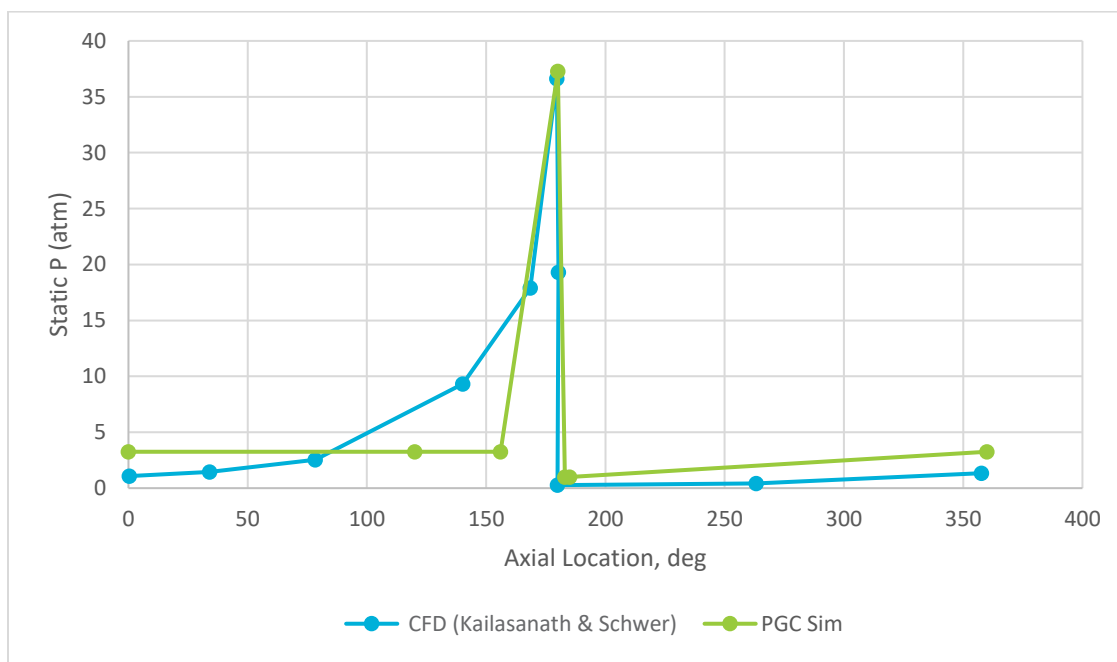
COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 3-17. CFD simulation conditions used by Kailsanath and Schwer [44] and DeBarmore [45]

Parameter	Value (Unit)
Fuel-to-Air Ratio	0.0292
RDE Inflow Pressure	147 psia
RDE Inflow Temperature	540 °R
Detonation Height/RDE Height	0.2

Static temperature and pressure profiles at the detonation height are used for validation of the model. The static pressure profile from the study by Kailsanath and Schwer [44] and DeBarmore [45] at detonation height is compared with PGC-Sim results in Exhibit 3-18.

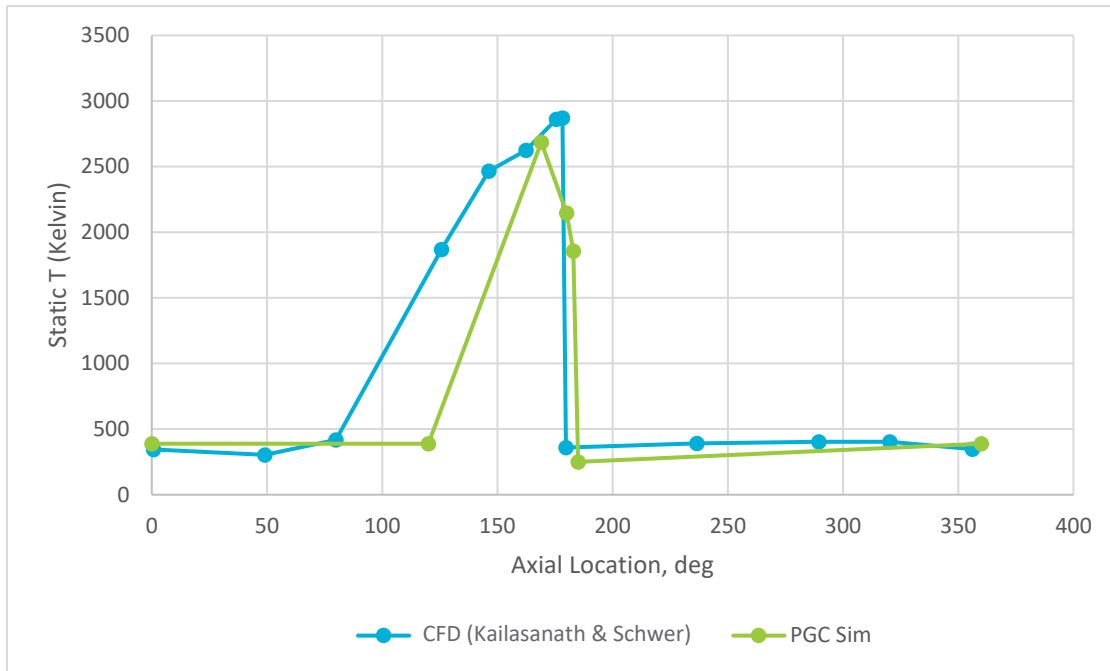
Exhibit 3-18. Static pressure profile at detonation height from CFD analysis [44, 45] compared with PGC-Sim results



The static temperature profile at detonation height from the study by Kailsanath and Schwer [44] and DeBarmore [45] is compared with PGC-Sim results in Exhibit 3-19.

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Exhibit 3-19. Static temperature profile at detonation height from CFD analysis [44, 45] compared with PGC-Sim results



The temperature and pressure profiles at the detonation height obtained by PGC-Sim are within acceptable limits for an analytical model prediction of a CFD model. The points shown for the PGC-Sim curve are the values obtained at various flow path stations that exist at the detonation height, which are from the following regions:

- Detonation + Shock
- Detonation Only
- Mixed Flow
- Deflagration Zone

Sousa et al. [46] developed an RDE simulation model that has a 1D detonation solver with a 2D flow solver by using their CFD results with hydrogen fuel at stoichiometric conditions. The analysis conditions are listed in Exhibit 3-20.

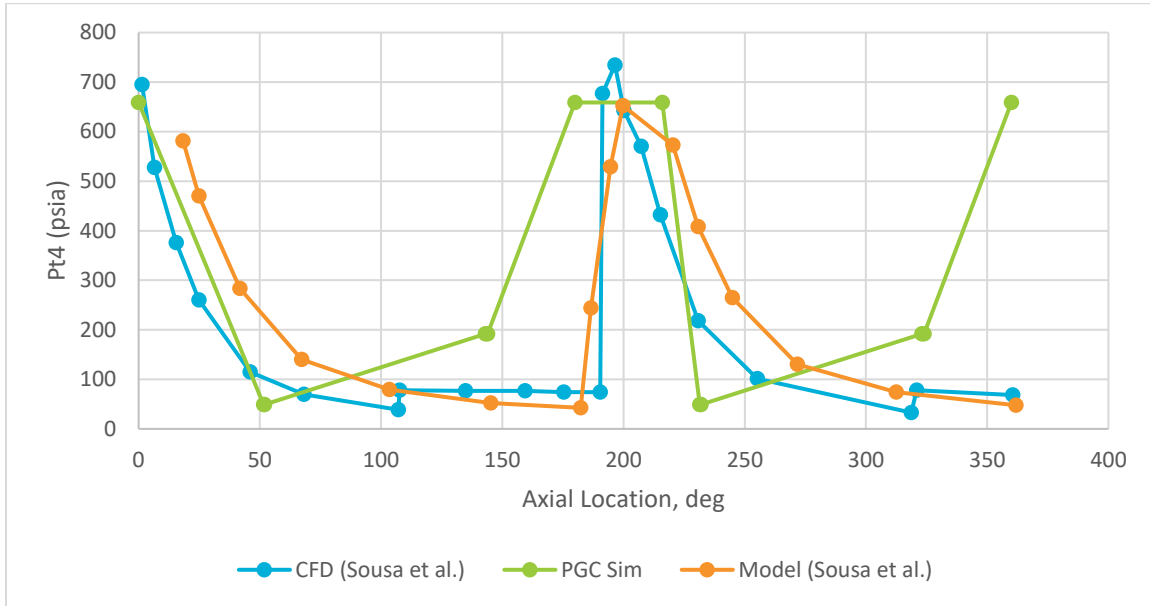
Exhibit 3-20. CFD simulation conditions used by Sousa et al. [46]

Parameter	Value (Unit)
Fuel-to-Air Ratio	0.0292
RDE Inflow Pressure	116 psia
RDE Inflow Temperature	594 °R
Detonation Height/RDE Height	0.46

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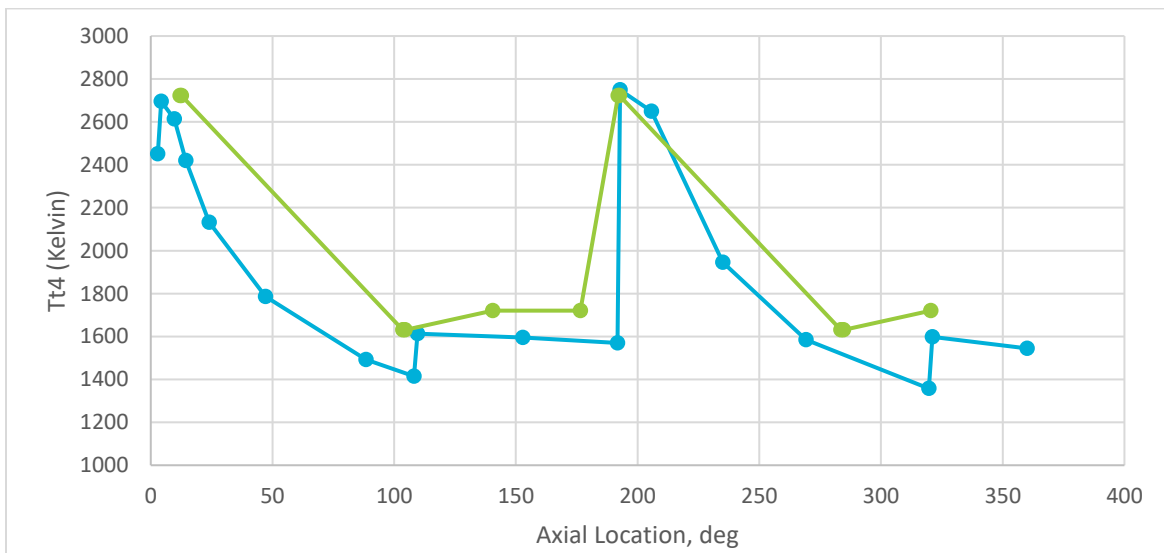
The total pressure profile from the CFD study and the analytical model by Sousa et al. [46] at RDE exit flow plane is compared with PGC-Sim results in Exhibit 3-21.

Exhibit 3-21. Total pressure profile at RDE exit plane from CFD analysis and analytical model [46] compared with PGC-Sim results



The total temperature profile from the CFD study and the analytical model by Sousa et al. [46] at RDE exit flow plane is compared with PGC-Sim results in Exhibit 3-22.

Exhibit 3-22. Total temperature profile at RDE exit plane from CFD analysis and analytical model [46] compared with PGC-Sim results



PGC-Sim has a considerably lower level of spatial discretization, due to the analytical equations used. However, the overall temperature and pressure scheme is captured successfully and was

enough for a system level simulation—within 15 percent for both pressure and temperature profiles.

3.2.4.2 Methane Fuel Cases

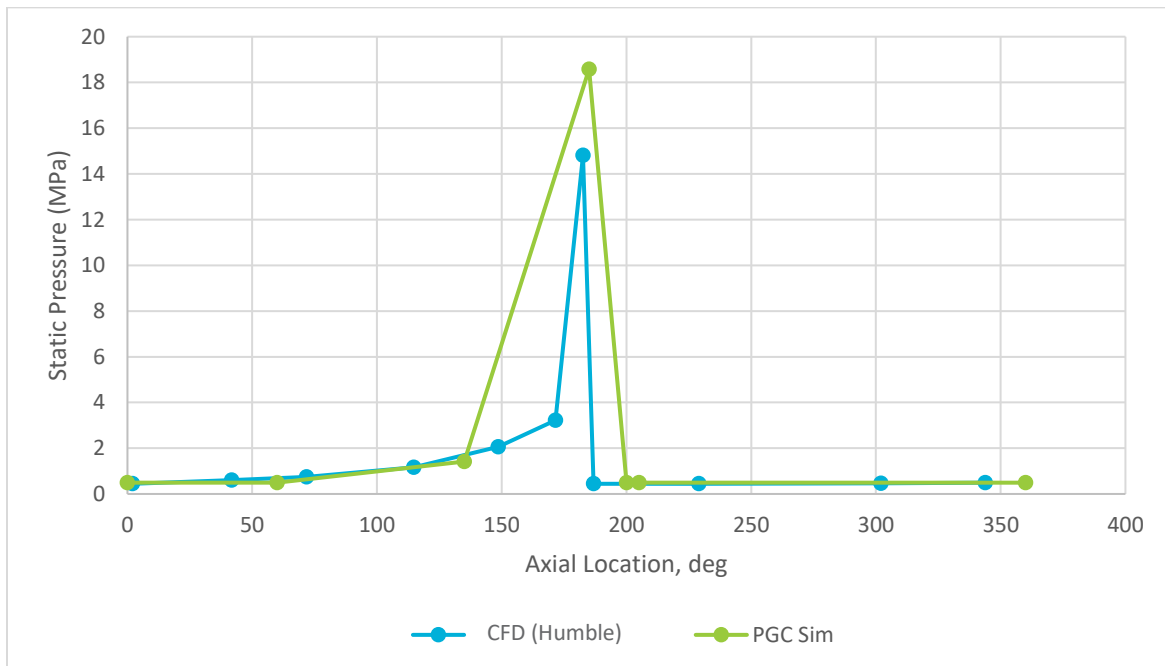
For the same reason GT with natural gas fuels will be considered in the PGC system integrations, it is important to compare the developed model's performance with methane-air detonation cases. A study by Humble [47] about reduced order RDE numerical modeling is used to compare static pressure and temperature profiles at detonation height for methane fuel cases. The modeling approach used by Humble [47] is coupled CFD and lumped parameter modeling to develop a reduced order RDE model for methane fuel detonation. The model is validated with experimental RDE data from Purdue University. The analysis conditions are listed in Exhibit 3-23.

Exhibit 3-23. Analysis conditions used by Humble [47]

Parameter	Value (Unit)
Fuel-to-Air Ratio	0.03
RDE Inflow Pressure	72.5 psia
RDE Inflow Temperature	540 °R
Detonation Height/RDE Height	0.1

Static temperature and pressure profiles at the detonation height are used for comparing the model outputs. The static pressure profile from the study by Humble [47] is compared with PGC-Sim results in Exhibit 3-24.

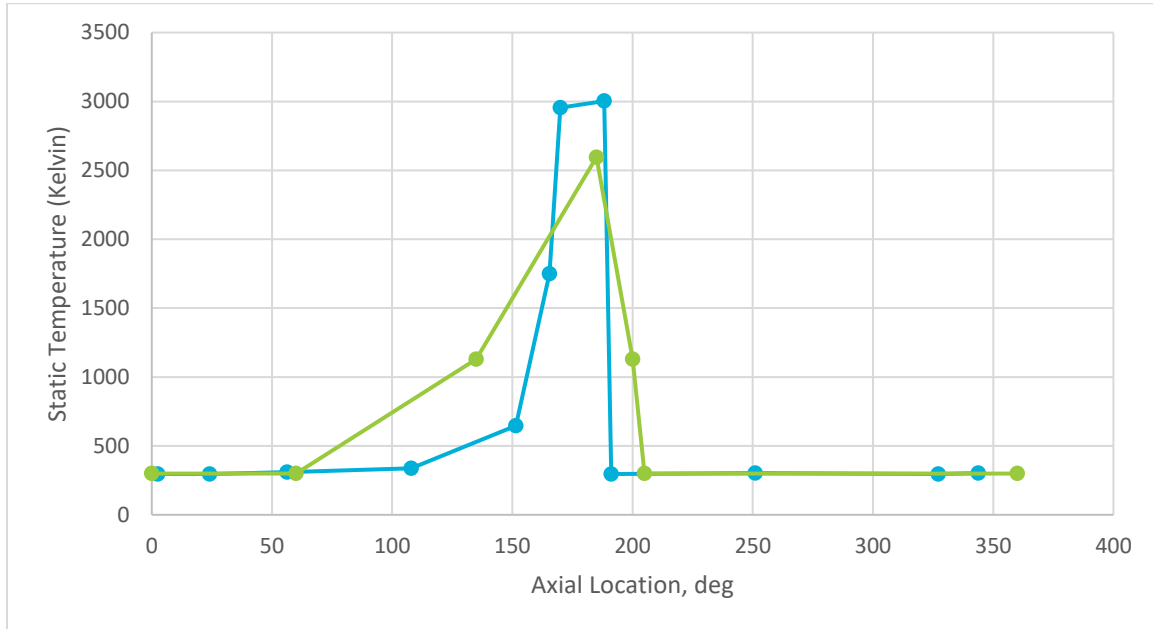
Exhibit 3-24. Static pressure profile at detonation height from Humble's model [47] compared with PGC-Sim results



COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

The static temperature profile at detonation height from Humble's model [47] is compared with PGC-Sim results in Exhibit 3-25.

Exhibit 3-25. Static temperature profile at detonation height from Humble's model [47] compared with PGC-Sim results



The differences of PGC-Sim predictions from the shown comparisons in Exhibit 3-24 and Exhibit 3-25 are within acceptable limits for an analytical model prediction of a CFD model and captures the overall physics adequately for system-level modeling purposes.

Qi et al. [48] performed a systems-level analysis for an RDE-GT hybrid engine running on natural gas fuel, where the variation of total pressure gain and fuel consumption of RDE are studied for various compressor pressure ratios. The analysis tool in the study is a 2D CFD simulation with simple compressor and turbine models to calculate GT performance parameters. The analysis conditions are listed in Exhibit 3-26.

Exhibit 3-26. Analysis conditions used by Qi et al. [48]

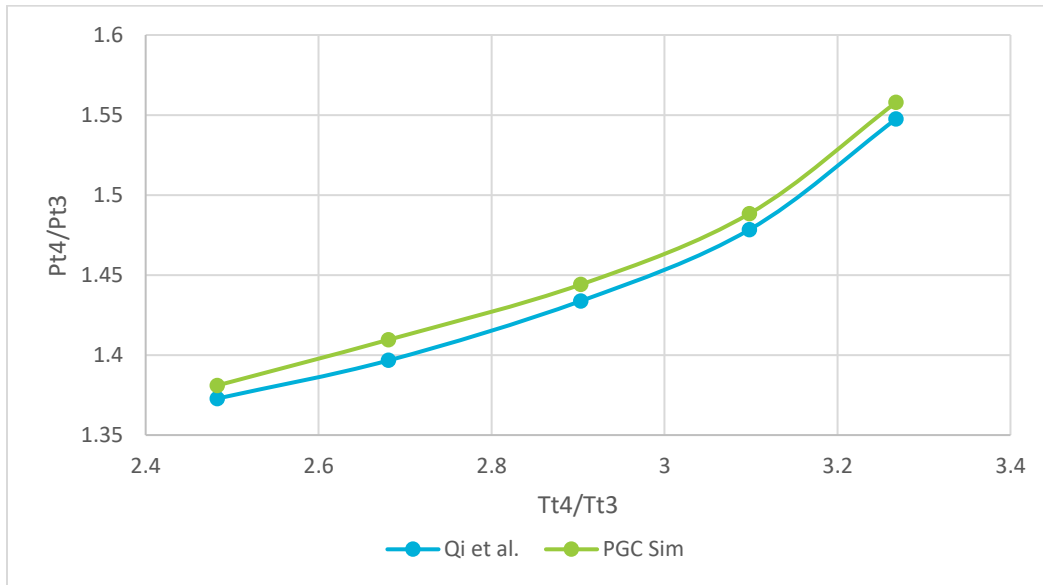
Parameter	Value (Unit)
Fuel-to-Air Ratio	varied
RDE Inflow Pressure	197 psia
RDE Inflow Temperature	1239 °R
RDE Inflow Mach Number	0.38
Detonation Height/RDE Height	0.5

The variation of the total pressure gain from RDE and fuel-to-air ratio with the change of RDE inlet to exit temperature ratio is used in validating the RDE model for various RDE inlet

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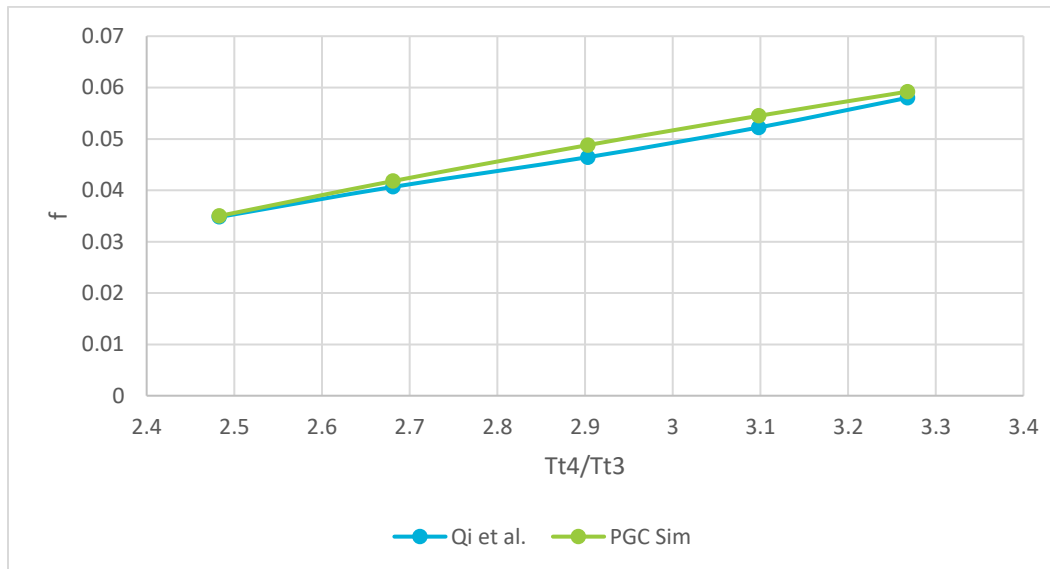
conditions. The change in the total pressure gain from RDE for various RDE exit temperatures (RDE inlet temperature kept constant) is compared with Qi et al. [48] in Exhibit 3-27.

Exhibit 3-27. RDE total pressure gain with respect to RDE exit temperature compared with Qi et al. [48]



The variation of the fuel-to-air ratio with RDE exit temperature calculated by PGC-Sim is compared with the results from the study by Qi et al. [48] in Exhibit 3-28.

Exhibit 3-28. RDE fuel-to-air ratio change with respect to RDE exit temperature change compared with Qi et al. [48]



Similar to conventional combustors, higher fuel consumption is expected as the RDE exit temperature is increased. This is because of the fact that the detonation is dependent on the existence of deflagration, which produces higher heat flux when the amount of the fuel is

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increased. For higher RDE exit temperatures, higher pressure gain is expected due to increased detonation wave speed. The compared trends for the total pressure gain and fuel-to-air ratio are within the acceptable difference limits.

The calibration of the model is then made with the data from the UTSR study by Aerojet-Rocketdyne [33, 49], where an RDE system is developed for H-Class GT integration. The RDE design by Aerojet-Rocketdyne for natural gas detonation is used in the calibrations, where the RDE diameter is 9.4 inches and RDE height is 13.4 inches. [49] Other calibration conditions are listed in Exhibit 3-29.

Exhibit 3-29. Model calibration conditions with Aerojet-Rocketdyne study [33, 49]

Parameter	Value (Unit)
Fuel-to-Air Ratio	0.0278
RDE Inflow Pressure	180 psia
RDE Inflow Temperature	1143 °R
RDE Inflow Mach Number	0.38
Detonation Height/RDE Height	0.2

The calibration condition for the RDE model was with single wave operation and no by-pass air. Some of the PGC-Sim parameters are compared with published data by Aerojet-Rocketdyne [49], listed in Exhibit 3-30.

Exhibit 3-30. PGC-Sim results with Aerojet-Rocketdyne configuration [33, 49]

Parameter	Published Value (Unit)	PGC-Sim (Unit)
Avg. RDE Exit Pressure (total)	261 psia	263 psia
Fuel-to-Air Ratio	0.0278	0.0276
Avg. RDE Exit Temperature (total)	3329 °R	3329 °R
RDE Exit Flow Mach Number	1.0	1.13
CJ Detonation Speed	1200–1800 ft/s	1600 ft/s

The results from the PGC-Sim for single wave operation engine with no by-pass cooling and given geometrical properties produced very close results, which is important for the following steps of the study. The CJ detonation speed's exact value is not published due to being proprietary to Aerojet-Rocketdyne company but PGC-Sim's estimation is within the expected range.

4 PGC-GT INTEGRATION

4.1 DEVELOPMENT OF A PGC-GT MODEL

After completing the validations and calibration of the PGC-Sim, the model was integrated into an H-Class GT model developed in MATLAB/Simulink as its combustor section. The GT model for PGC integration analysis is developed from the uncooled on-design section of the Cooled Gas Turbine Model (CGTM), which was previously developed for analyzing the effects of turbine cooling on H-Class GT performance. [10, 11] The reasons for using CGTM for developing a Pressure Gain-Gas Turbine Model (PGGTM) are listed as follows:

- CGTM is already validated and calibrated for current H-Class GTs
- The turbine cooling analysis features of the model could be used in future studies concerning turbine cooling for pressure gain GTs
- The turbomachinery analysis section of the model could be used in future studies concerning turbomachinery design changes to turbines used in pressure gain GTs

The turbine cooling is also included in the developed PGGTM through user input coolant fractions.

PGGTM uses the PGC-Sim analytical model (Section 3) as its combustor/detonation section calculations. A user input specifies the type of the PGC used in the analysis. The list of PGGTM inputs and their values are listed in Exhibit 4-1.

Exhibit 4-1. PGGTM input list shown for the stock H-Class gas turbine data

Parameter	Value	Unit
Cycle Inputs		
Ambient Pressure	14.7	psia
Ambient Temperature	530 (70)	°R (°F)
Fuel Heating Value	21397	Btu/lbm
Compressor Bleed Air	1%	% (of mainstream)
Turbine Cooling Fraction (stators, total)	9%	% (of mainstream)
Turbine Cooling Fraction (rotors, total)	9%	% (of mainstream)
By-Pass (transition) Cooling Fraction	varied	% (of mainstream)
Compressor Polytropic Efficiency	89%	%
Turbine Polytropic Efficiency	varied	%
Combustor Pressure Loss (for conventional combustor options)	3%	%
Diffuser Pressure Ratio	0.99	-
Exhaust Nozzle Pressure Ratio	0.95	-

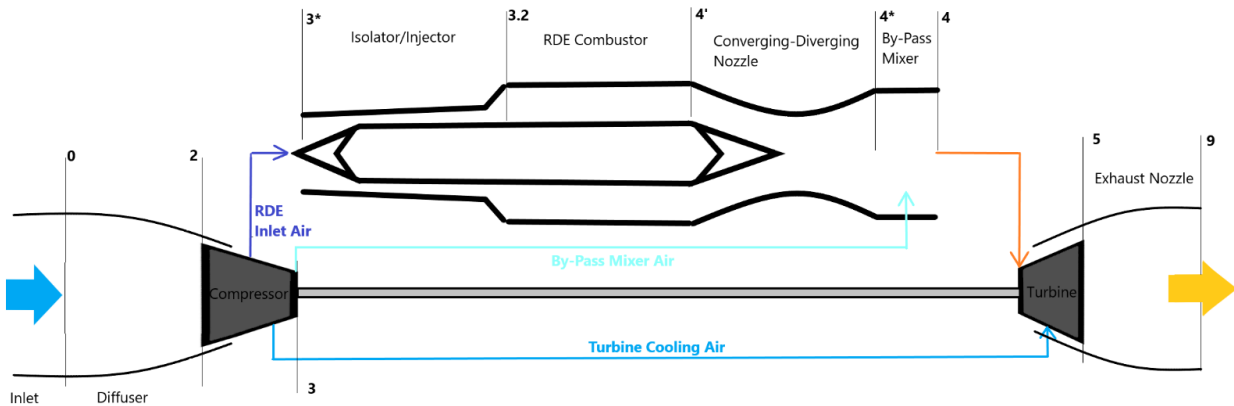
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Parameter	Value	Unit
Compressor Pressure Ratio	23.1	-
Turbine Inlet Temperature	3260	°R (°F)
By-Pass (transition) Cooling Temperature Difference	200	°R (°F)
Engine Inlet Mass Flowrate	1520	lbm/s
Engine Back Pressure Ratio	1.04	-
PGC Inputs		
PGC Type	0-4	-
Compressor Exit Flow Mach Number	0.3	-
Detonation Efficiency	97%	%
RPC and PDE Inputs		
Purge Fraction	varied	-
WRC Inputs		
Pre-compression Pressure Ratio	2.36	-
Pre-compression Efficiency	83%	%
Combustor Gas Expansion Efficiency	83%	%
RDE Inputs		
Compressor Exit Throughflow Area	0.79	ft ²
Mean RDE Throughflow Diameter	0.39	ft
RDE Flow Passage Length	0.045	ft
Detonation Height to RDE Height Ratio (non-dimensional wave height)	Varied (0.1–0.5)	-
Injector Pressure Loss	Varied (0.0–15%)	%
Number of Waves	1	-

The inputs specific to a particular PGC type are the inputs the analytical PGC model used within PGC-Sim. PGGTM station numbering, air flows, and included components are shown in Exhibit 4-2 for the RDE option. If conventional combustion option is selected from the inputs, PGGTM produces typical H-Class GT performance results.

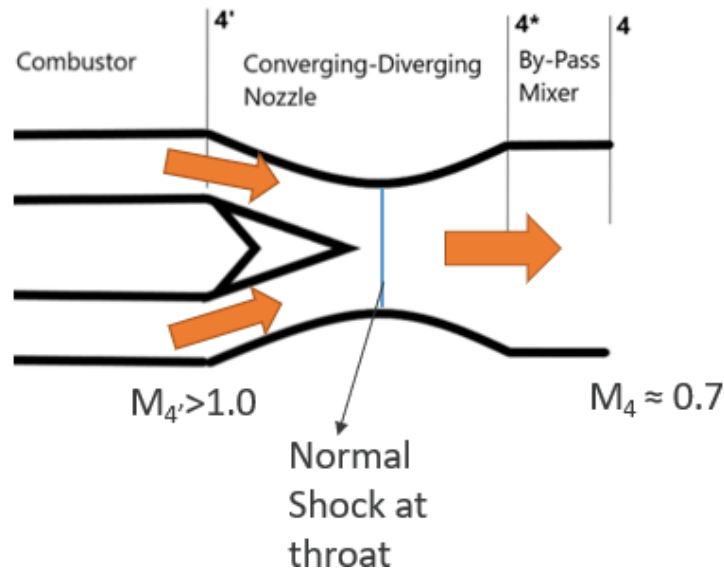
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Exhibit 4-2. PGGTM engine components and engine station numbering shown for RDE option



PGC exit flow is oftentimes supersonic, which is much higher than the typical turbine inlet flow speed conditions of conventional engines. Moreover, in the case of pulsating engines and RDEs, the flow has high swirl velocity, which needs to be dampened out prior to entering the turbine. Recent studies by Aerojet-Rocketdyne provided various solutions to the turbine transition problem for RDEs and found that a converging-diverging nozzle could minimize the pressure loss and increase flow stability for turbine integration applications. [49] In PGGTM, a convergent-divergent nozzle model is used to include the transition loss effects. Choked flow is assumed at the transition piece and nozzle provides subsonic turbine inlet flow speed, if the PGC exit flow is supersonic. An illustration of the nozzle model used in PGGTM is presented in Exhibit 4-3.

Exhibit 4-3. An illustration of the convergent-divergent nozzle model used in PGGTM



For an adiabatic nozzle, the total temperature at the turbine inlet is found using Equation 4-1. [8]

$$T_{t4} = T_{t4'} \quad \text{Equation 4-1}$$

The total temperature is preserved across a normal shock, which is the condition for the choked flow in the convergent-divergent nozzle. The total pressure loss for the nozzle is calculated using Equation 4-2. [8]

$$\frac{P_{t4}}{P_{t4'}} = \left(\frac{\frac{\gamma_{4'} + 1}{2} M_{4'}^2}{1 + \frac{\gamma_{4'} + 1}{2} M_{4'}^2} \right)^{\gamma_{4'}/\gamma_{4'} - 1} \left(\frac{2\gamma_{4'}}{\gamma_{4'} + 1} M_{4'}^2 - \frac{\gamma_{4'} - 1}{\gamma_{4'} + 1} \right)^{-1/\gamma_{4'} - 1} \quad \text{Equation 4-2}$$

4.2 ANALYSIS OF DIFFERENT PGC-GT INTEGRATION CONCEPTS

A typical H-Class GT performance is used in this analysis to compare the GT performance gains with various PGC types of this study. Currently, almost all institutions working on PGC-GT integration concepts keep the engine frame the same with conventional engine in order to minimize development efforts for turbine cooling and steam cycle components when the PGC-GT hybrid system is integrated into an NGCC power plant.

Therefore, for the analysis of PGC-GT hybrid systems performance comparisons, the turbine section inlet and exit conditions are kept the same with the typical H-Class GT values, which are listed in Exhibit 4-4 together with other H-Class GT parameters. [15] The only possible necessary change to the turbine under these operating conditions could be to add another stage to account for the higher inlet pressure and to reach the same exit conditions with the typical H-Class GT, which is not an input parameter for the system-level analysis performed in this section.

Exhibit 4-4. Baseline H-Class GT parameters used in analysis

Parameter	Value (Unit)
Combustor Pressure Loss	3%
Combustor Efficiency	99%
Turbine Inlet Temperature	3260 °R
Turbine Exit Temperature	1622 °R
Turbine Exit Pressure	15.23 psia
Shaft Power Output	340238 kW
Thermal Efficiency	42.5%
Heat Rate	8034 Btu/lbm.hr

In order to have constant inlet and exit conditions at the turbine, the compressor pressure ratio is different for each PGC-GT configuration. For the PGC integrated systems, the turbine isentropic efficiency is used within 70–80 percent [12, 13], which is lower than the typical

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values for conventional gas turbines due to the flow irregularity and flow swirl introduced by PGCs. [13]

Some of the key system parameters of the studied PGC-GT systems are listed in Exhibit 4-5. The pulsating engine configurations have slightly lower turbine efficiency than RDE, because of the higher instabilities in the flow expected in those configurations. The RPC-GT configuration required the same compression value as the conventional baseline engine in order to have the H-Class GT conditions, which is because of the level of pressure gain and the reduced turbine efficiency. WRC exit flow is similar to having another turbine prior to the actual turbine; therefore, the reduction in turbine efficiency is not expected to be high. Turbine cooling fraction is used from CGTM results, which was run separately for the same input conditions. The PGC total pressure gain calculated by the PGC-Sim to be the highest for PDE, followed by RDE, RPC, and WRC. The compressor pressure ratios listed in Exhibit 4-5 are determined based on the specified turbine inlet and exit temperatures and the “achievable” pressure gain and is therefore different for each PGC-GT system.

Exhibit 4-5. PGC-GT system specifications used in the analysis

Parameter	Conventional GT (Baseline)	RPC-GT	PDE-GT	WRC-GT	RDE-GT
Compressor Pressure Ratio	23.1	23.1	5.2	19.9	11.4
Compressor Polytrropic Efficiency	90%				
Compressor Exit Temperature	1401 °R	1401 °R	893 °R	1341 °R	1136 °R
PGC/Combustor Total Pressure Ratio	0.97	2.348	11.73	1.627	4.508
Combined Pressure Ratio	23.1	54.2	61.0	32.3	51.4
Combustor Exit Mach Number	0.3	1.0	1.0	0.7	1.22
Fuel-to-Air Ratio	0.03088	0.03054	0.04958	0.03319	0.03873
Turbine Polytrropic Efficiency	91%	69%	69%	81%	71%
Turbine Inlet Temperature	3260 °R				
Turbine Exit Temperature	1622 °R				
Turbine Cooling Fraction	18.96%				

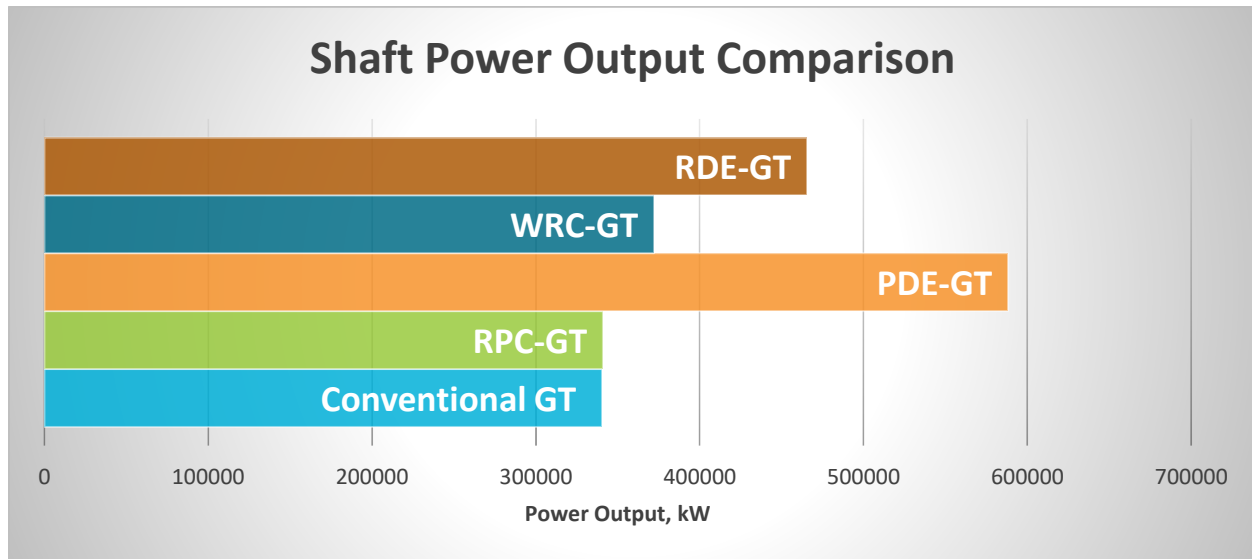
RDE pressure gain depends on the inlet conditions from the compressor. However, in this , the turbine exhaust conditions are set to be the same with the baseline conventional GT for minimizing the changes on the steam cycle of NGCC. In order to have similar exhaust conditions with a conventional H-Class gas turbine, compressor parameters and PGC performance are determined in an iterative fashion. The only change to turbine section in this study is possibly

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adding several more stages to the end to compensate for the increased inlet pressure. There is a pressure loss in the convergent-divergent nozzle, and it is calculated by using Equation 4-2.

With the presented system parameters in Exhibit 4-5, the calculated shaft power outputs are compared for each PGC-GT hybrid system in Exhibit 4-6.

Exhibit 4-6. PGC-GT system shaft power output comparison

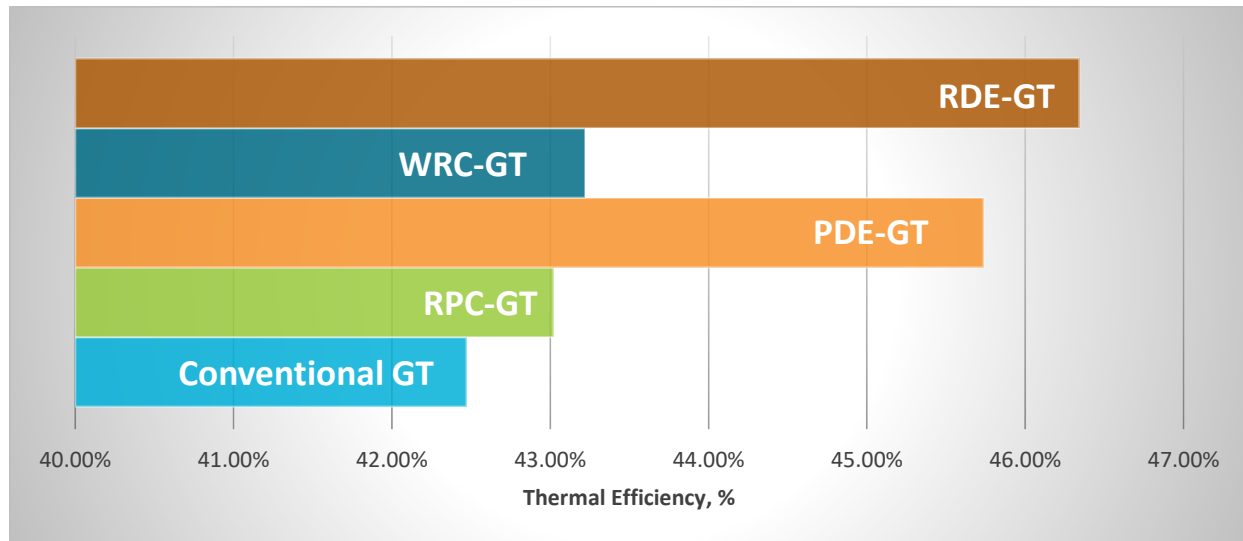


Shaft power output is directly related to the maximum pressure gain from the cycle and the turbine efficiency. PDE produced the highest output, followed by RDE, WRC, and RPC. WRC produced more output than RPC, which produces higher pressure gain than WRC. The ranking between RPC and WRC indicates the importance of the turbine integration losses, which is lower in WRC.

The thermal efficiency ranking of the systems is a result of how much power is generated in expense of the fuel consumption. The calculated GT thermal efficiency values are compared for each PGC-GT hybrid system in Exhibit 4-7.

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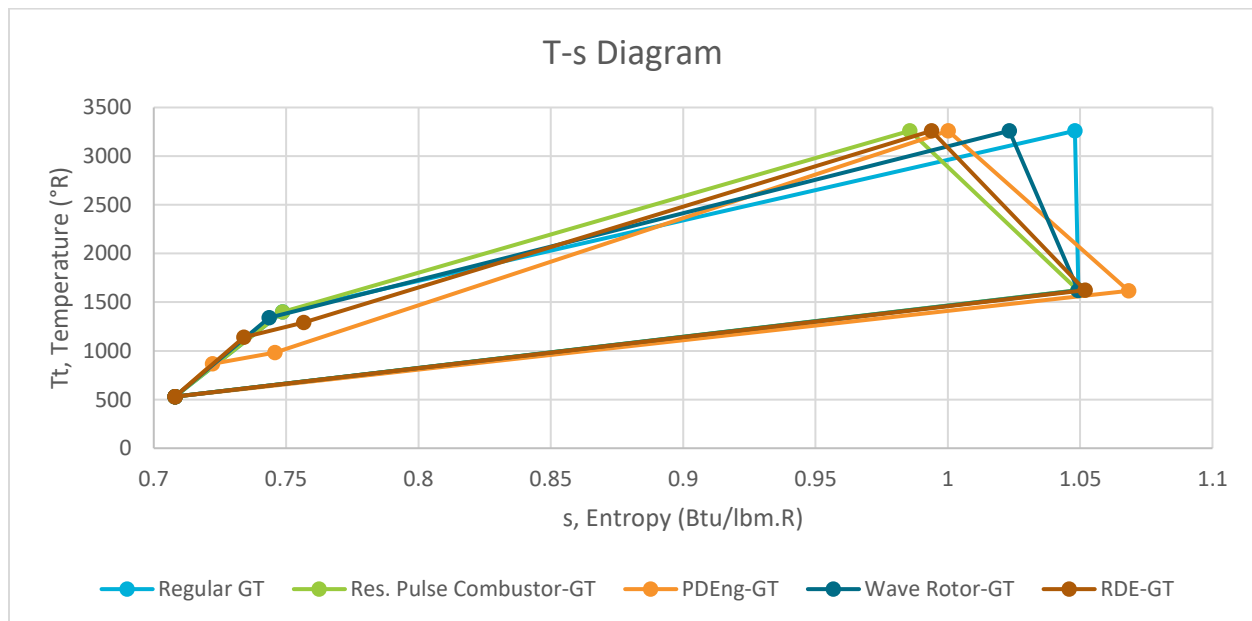
Exhibit 4-7. PGC-GT system thermal efficiency comparison



The system with RDE has much higher thermal efficiency than PDE, which puts it to first place in the efficiency rank. RDE generates second highest power output with much less fuel consumption than PDE and, therefore, has higher efficiency. WRC and RPC rank the third and fourth, respectively.

The performance rankings of the analyzed systems can be further understood by comparing their T-s and pressure-specific volume (P-v) diagrams. The T-s diagram gives information about the required heat input to the cycle, and it is compared for the PGC-GT configurations in Exhibit 4-8.

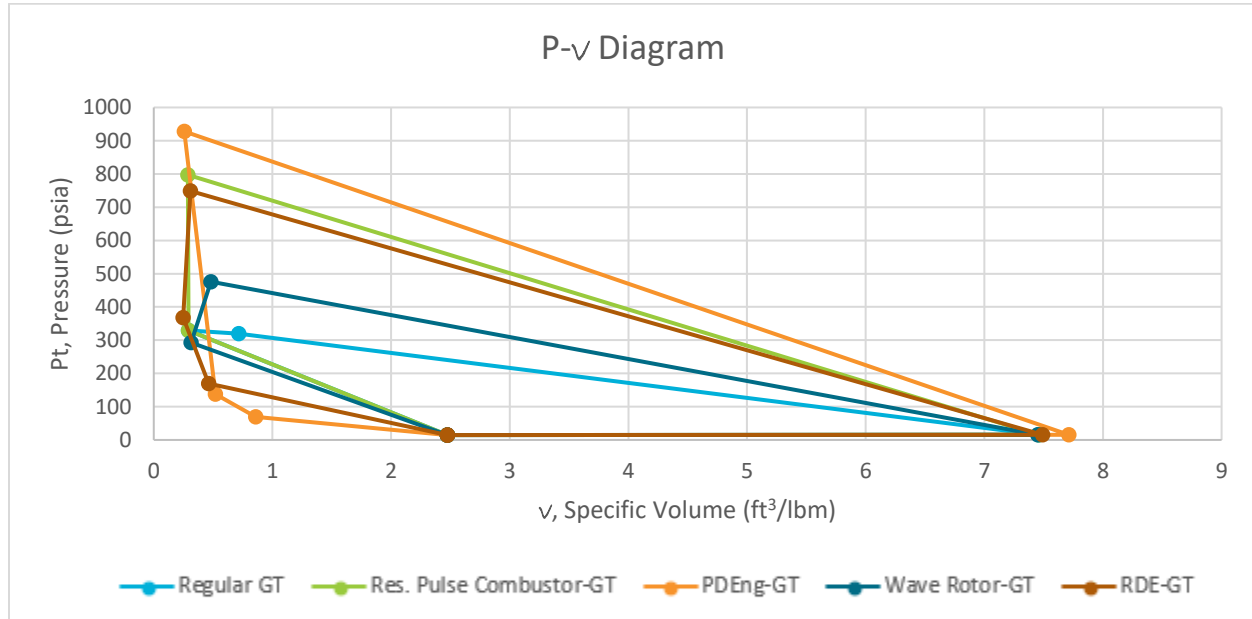
Exhibit 4-8. PGC-GT system T-s change comparison



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Area enclosed under the P-v diagram is related to the work output from the thermodynamic cycle. P-v diagrams of each PGC-GT configuration are compared in Exhibit 4-9. The ranks of the enclosed area for each curve directly follow the power output ranks of Exhibit 4-6.

Exhibit 4-9. PGC-GT system P-v change comparison



4.3 SENSITIVITY ANALYSIS OF PERFORMANCE PARAMETERS FOR PGC-GT SYSTEMS

A sensitivity analysis is performed for each concept to find what parameters could be changed to improve each system performance and understand which parameters are most important for each system. The studied parameters are listed as follows:

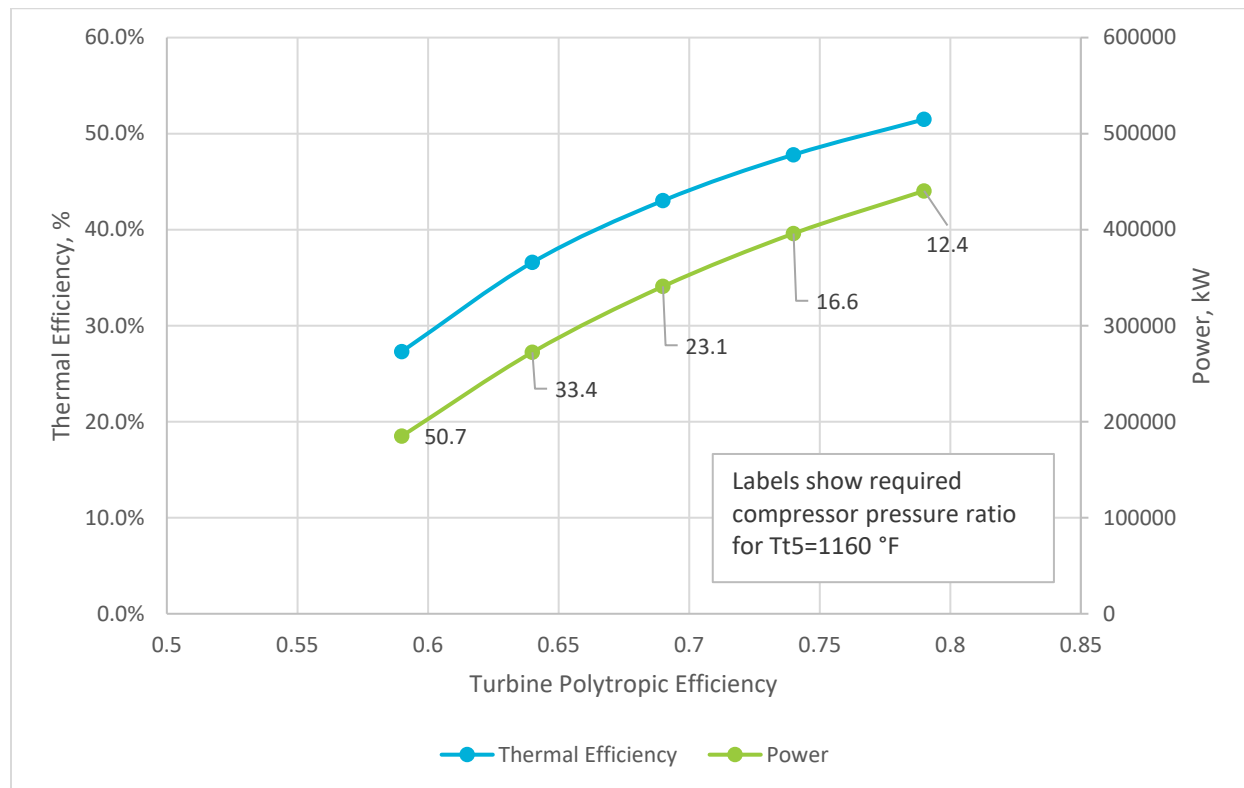
- Turbine polytropic (and isentropic) efficiency
- Detonation efficiency (current results were with 99 percent)
- PGC exit temperature (with by-pass cooling to 3260 °R at turbine inlet)
- Effect of PGC specific parameters (purge fraction (PDE), WRC expansion efficiency, detonation height (RDE), and injector pressure loss (RDE))

In all systems considered, the compressor pressure ratio is reduced to have the same turbine exhaust conditions with the conventional gas turbine case as the pressure gain from the pressure gain combustor is increased. In general, because the compressor uses power from the turbine to generate compression, whereas the PGC does not use turbine power to generate the pressure gain; increased net power output from the GT from using the PGC increases the efficiency.

4.3.1 RPC-GT System

For the RPC-GT system, the highest impact to performance came from the turbine polytropic efficiency, followed by the PGC exit temperature increase. The highest possible GT efficiency is obtained when the turbine polytropic efficiency is increased to 80 percent from 70 percent (baseline value), shown in Exhibit 4-10. The thermal efficiency of the system increases when most of the compression comes from the PGC and not from the compressor as can be seen in the trends shown in Exhibit 4-10.

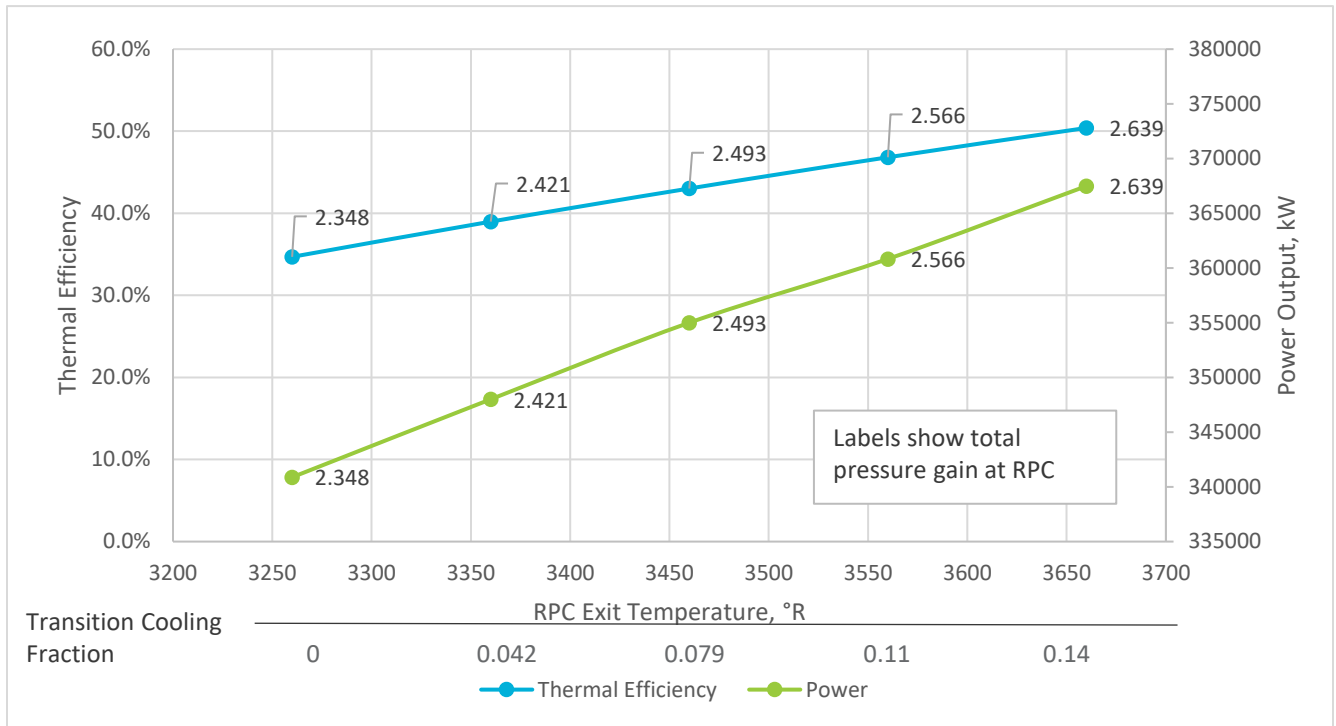
Exhibit 4-10. Sensitivity of RPC-GT system performance to turbine polytropic efficiency for fixed turbine inlet and exit temperature



Increasing RPC exit temperature provides the second highest improvement to the RPC-GT system performance parameters. The transition cooling is needed to be applied to bring the turbine inlet temperature back to the baseline values. Exhibit 4-11 shows the sensitivity of thermal efficiency and power output from increasing RPC exit temperature and the required transition cooling flow fraction.

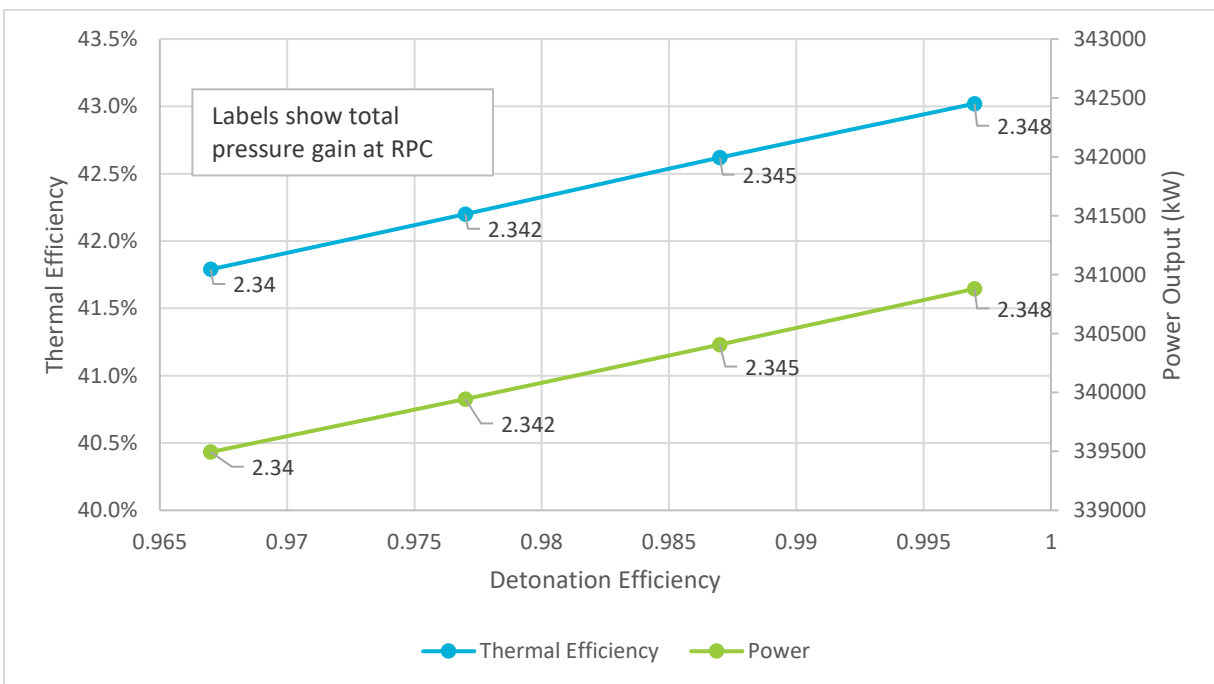
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Exhibit 4-11. Sensitivity of RPC-GT system performance to RPC exit temperature where turbine inlet temperature is fixed with transition cooling



The sensitivity of RPC-GT performance to the detonation efficiency is also studied. The impact to performance parameters is shown in Exhibit 4-12.

Exhibit 4-12. Sensitivity of RPC-GT system performance to RPC detonation efficiency

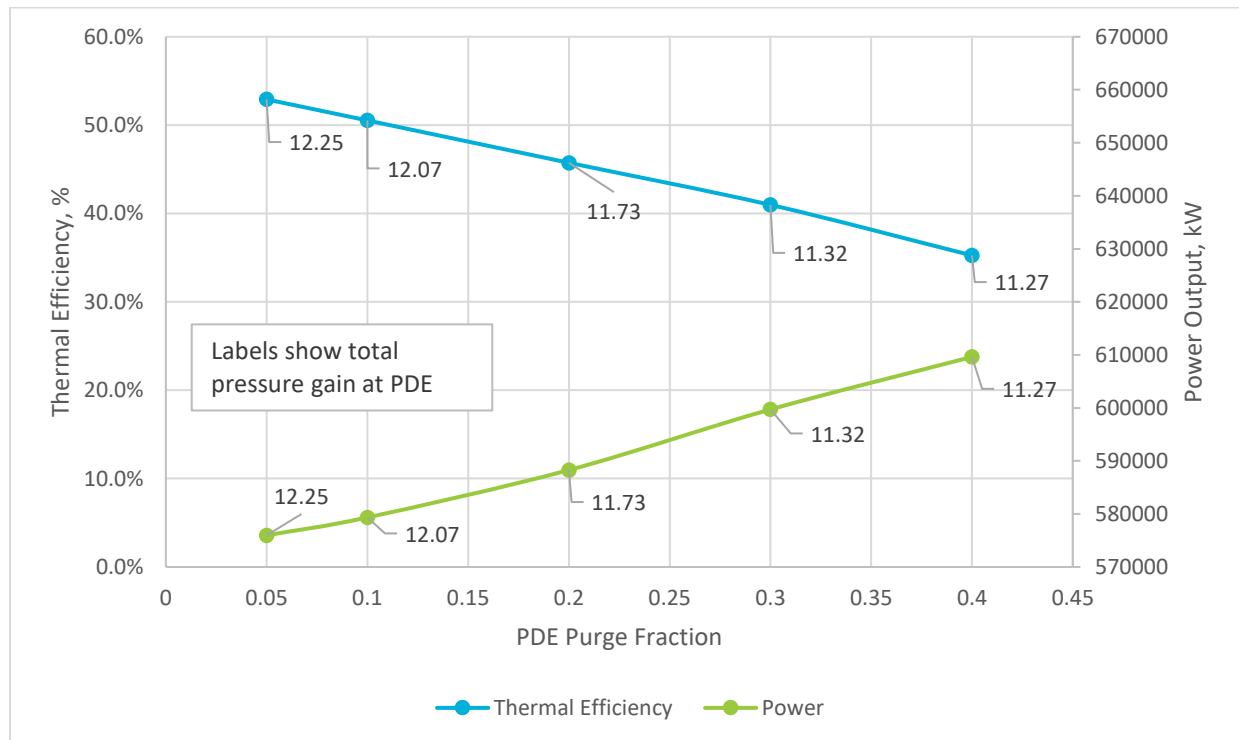


Turbine efficiency is a result of integration losses and it could be harder to attain higher values than the predicted baseline values. Increasing the RPC exit temperature through a transition cooling back to design turbine inlet temperature might be the best solution for this system to improve its performance from the baseline values.

4.3.2 PDE-GT System

For the PDE-GT system, the GT efficiency is increased when the purge fraction of the engine is reduced to 0.05 from 0.2. Purge fraction is the fraction of time needed for the purge air used in detonation tubes to fill the tube to the valve open time; lower values of this fraction are hard to implement with current technology. [2] The impact of the purge fraction to PDE-GT system performance parameters is shown in Exhibit 4-13.

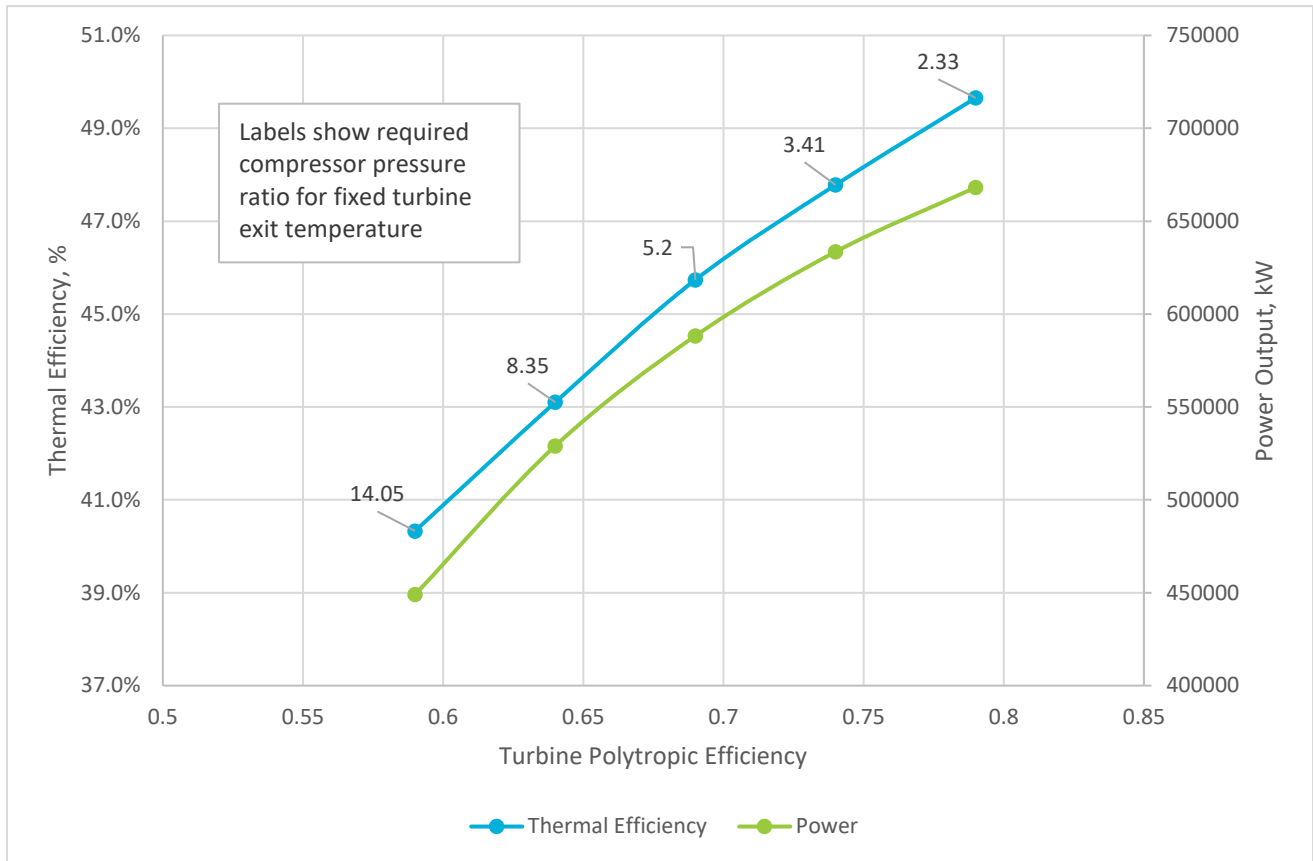
Exhibit 4-13. Sensitivity of PDE-GT system performance to PDE purge fraction for fixed turbine inlet and exit temperature conditions



Increasing the turbine polytropic efficiency, which is dependent on the level of turbine-PDE integration success level, provides the second highest performance improvement from baseline values. The impact to performance parameters from increasing turbine polytropic efficiency is shown in Exhibit 4-14.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

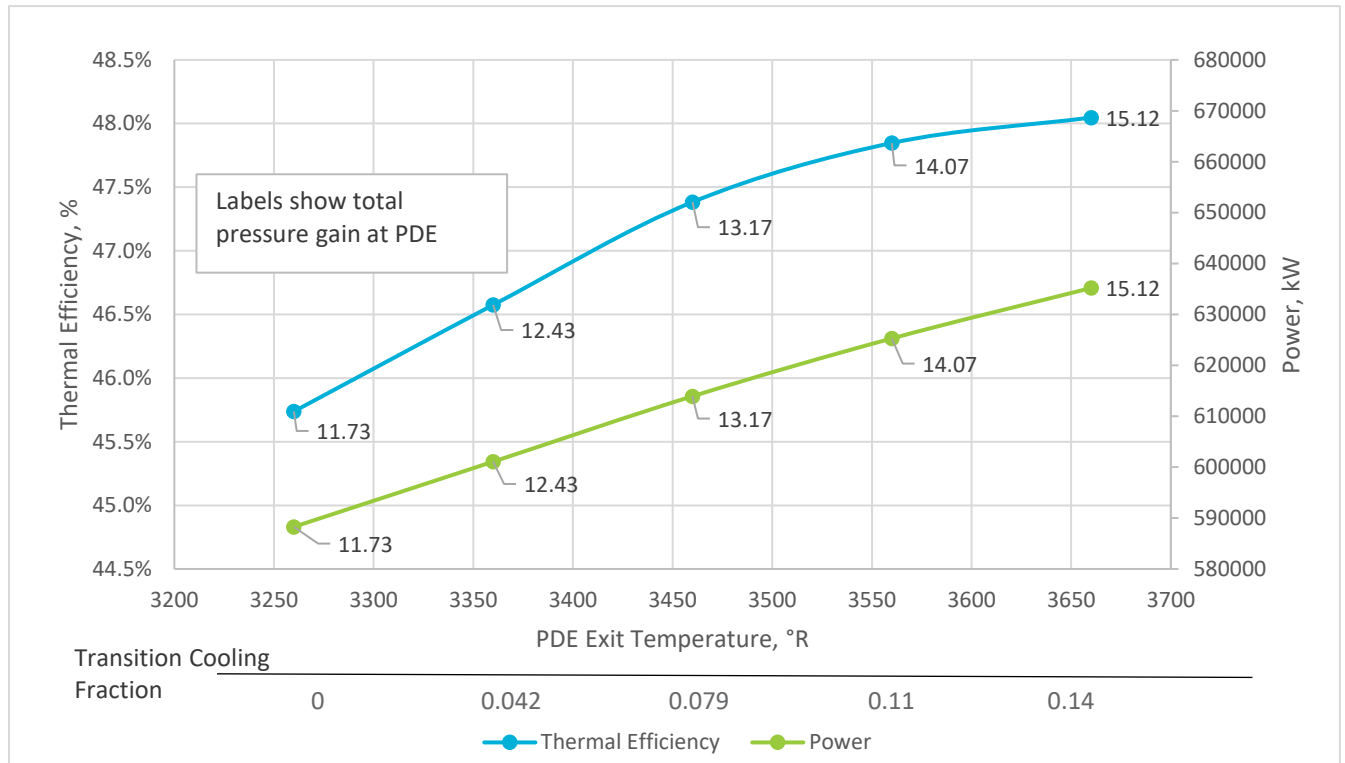
Exhibit 4-14. Sensitivity of PDE-GT system performance to turbine polytropic efficiency for fixed turbine inlet and exit temperature conditions



The effect of increasing the PDE exit temperature on performance was also studied. Transition cooling is applied to bring the PDE exit flow temperature back to baseline turbine inlet temperature in order to have same amount of turbine cooling fractions to be used to cool the turbine and, hence, eliminate the impact of coolant extraction on the compressor and changes in the cooling losses in the turbine. This improvement provides the third highest impact to performance increase from the baseline values, shown in Exhibit 4-15.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 4-15. Sensitivity of PDE-GT system performance to PDE exit temperature where turbine inlet temperature is fixed with transition cooling

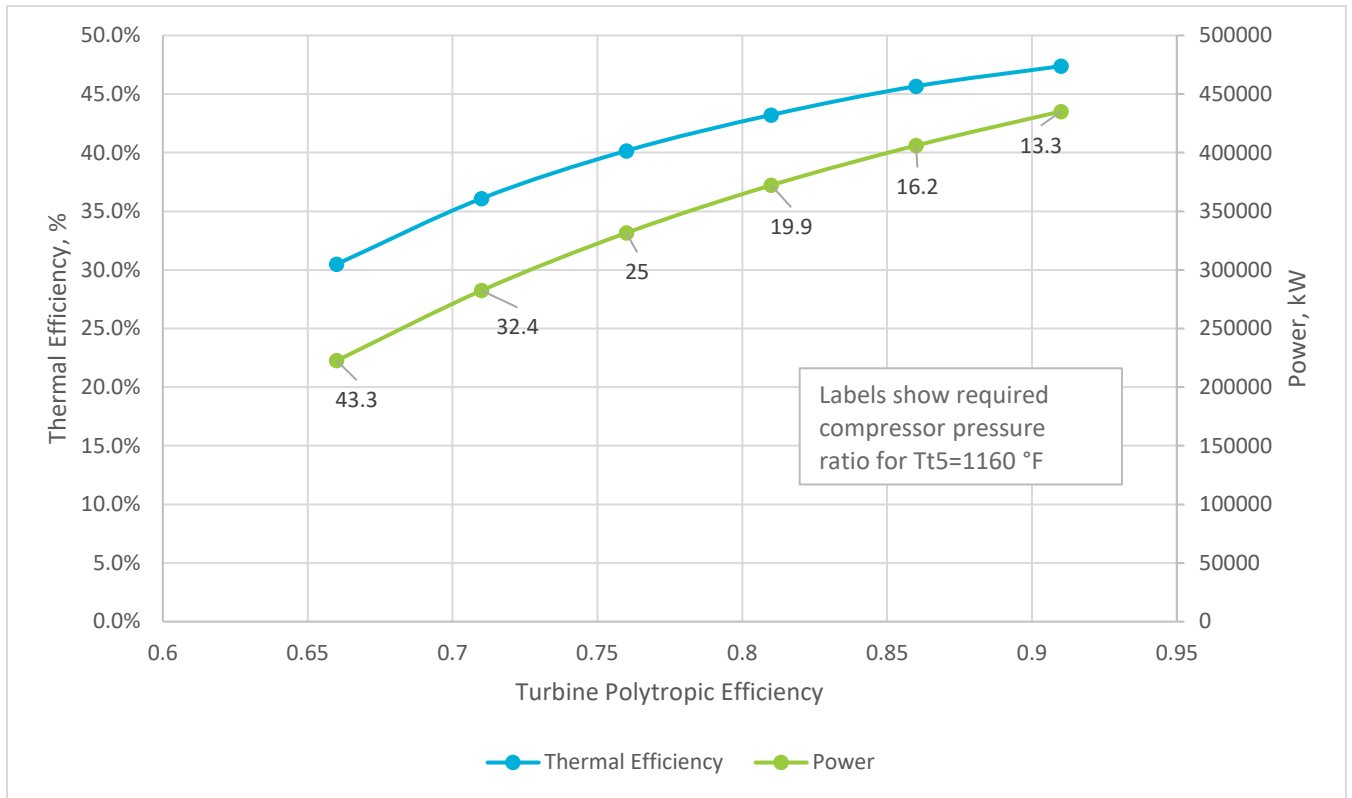


4.3.3 WRC-GT System

For the WRC-GT system, the highest performance improvement is obtained when the turbine polytropic efficiency is increased from 80 percent to 90 percent, which is the level of the conventional GT systems' turbine efficiency. This would mean eliminating all turbine integration losses induced from WRC exit flow. The impact of the turbine polytropic efficiency to WRC-GT system performance parameters is shown in Exhibit 4-16. As the compressor pressure ratio is decreased, and most of the cycle compression comes from the PGC the overall cycle efficiency increases because of lower power demand from the turbine to run the compressor.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

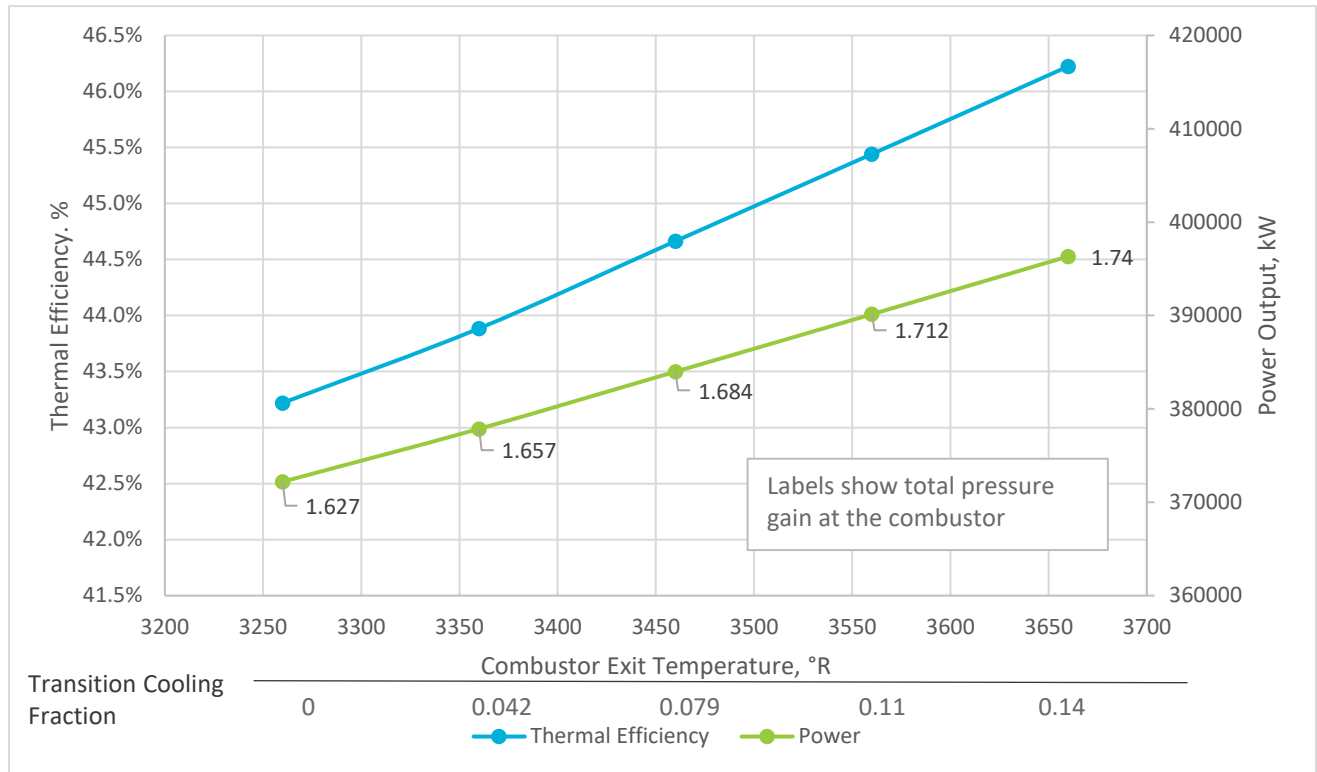
Exhibit 4-16. Sensitivity of WRC-GT system performance to turbine polytropic efficiency for fixed turbine inlet and exit temperature conditions



Second highest performance improvement is obtained by increasing the WRC exit temperature by 400 Rankine ($^{\circ}\text{R}$) from the baseline value of 3260 $^{\circ}\text{R}$. Similar to the previous PGC cases, transition cooling is applied to bring the WRC exit flow temperature back to baseline turbine inlet temperature to avoid design changes to the turbine. The applied transition cooling fractions and the changes in shaft power output and thermal efficiency is shown in Exhibit 4-17.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

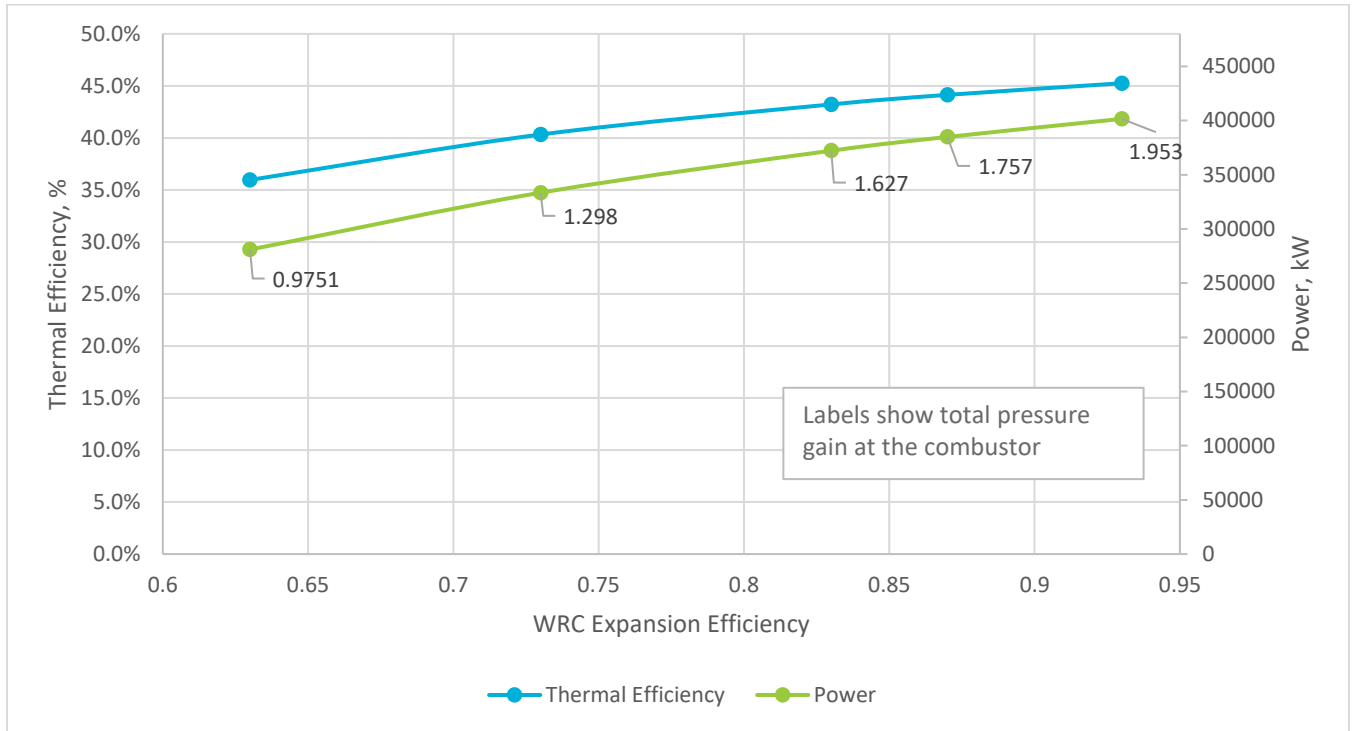
Exhibit 4-17. Sensitivity of WRC-GT system performance to WRC exit temperature where the turbine inlet temperature is fixed with transition cooling



For WRC, another important system design parameter is the WRC compression/expansion efficiency, which is the efficiency of the WRC system to pre-compress the flow and expand to the combustor exit station. Baseline efficiency value for this parameter is used as 0.83, which is provided by Nalim et al. [28] Akbari et al. [29] The impact from changing this parameter to the WRC-GT system performance was lower than the previous two parameters analyzed. The corresponding change in the WRC-GT system performance is shown in Exhibit 4-18.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 4-18. Sensitivity of WRC-GT system performance to WRC compression/expansion efficiency

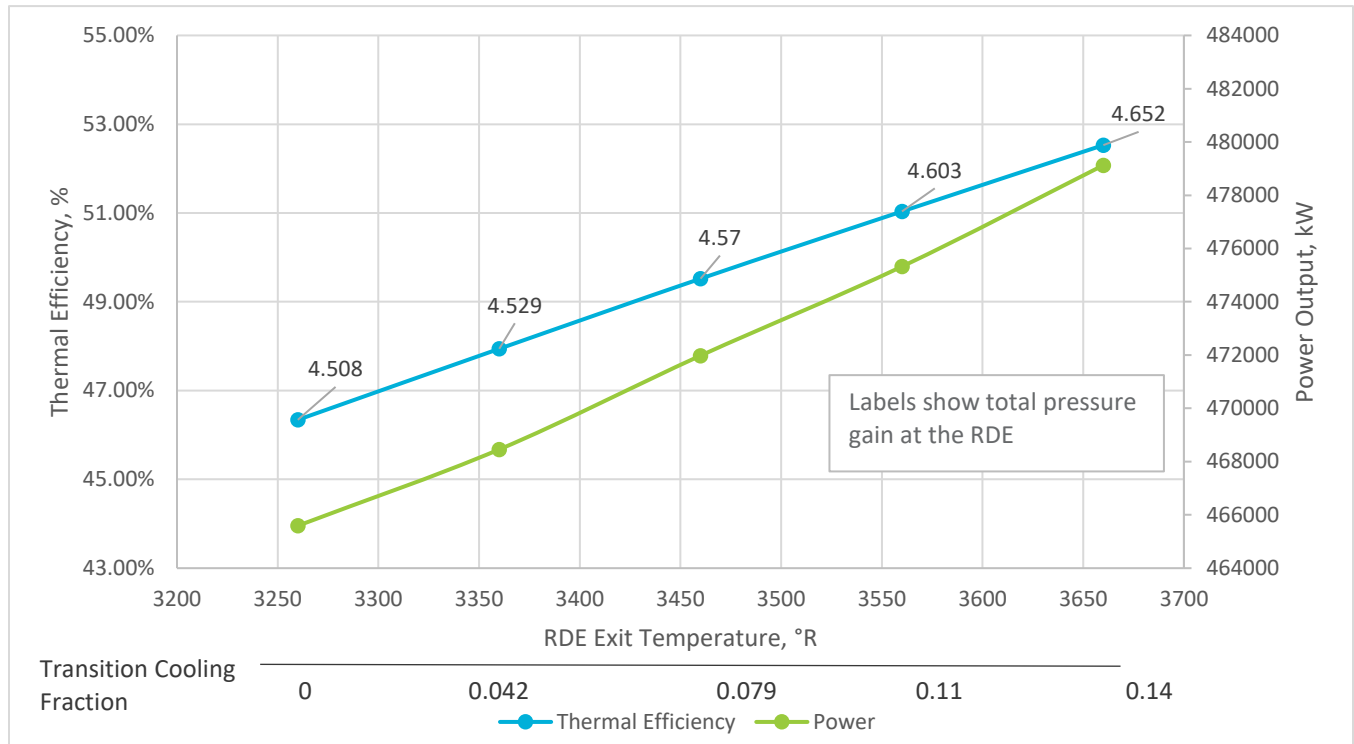


4.3.4 RDE-GT System

For the RDE-GT system, increasing the RDE exit temperature from 3260 to 3660 °R provides the highest possible improvement to system performance parameters. As the exit temperature is increased, the wave height is reduced which also reduced the fuel consumption. Transition cooling is applied at the by-pass region to cool the RDE exhaust flow temperature down to the baseline turbine inlet temperature. The applied transition cooling fractions and the changes in shaft power output and thermal efficiency are shown in Exhibit 4-19.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

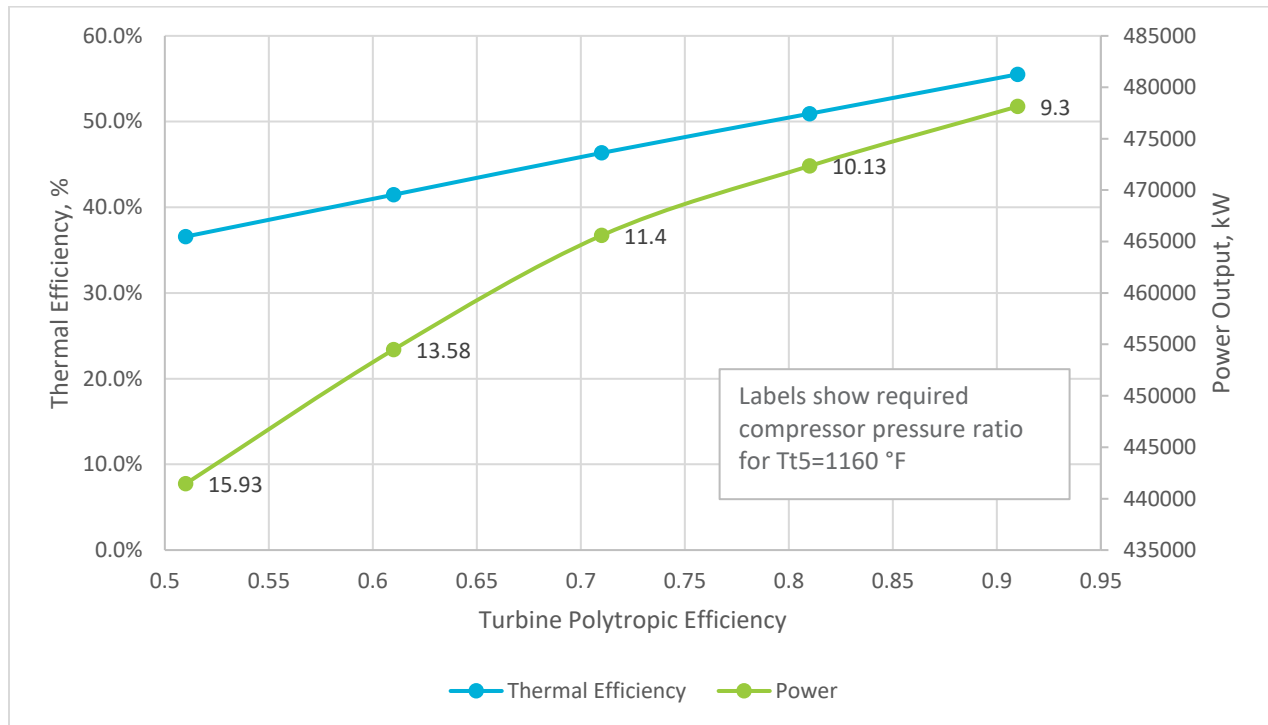
Exhibit 4-19. Sensitivity of RDE-GT system performance to RDE exit temperature where the turbine inlet temperature is fixed with transition cooling



Increasing the turbine polytropic efficiency from 70 to 90 percent provides the second highest improvement to RDE-GT performance parameters. This improvement is highly dependent on the level of success in the integration of the turbine section to the RDE, which is related to the efficiency of the convergent-divergent nozzle design. The changes in performance parameters from this parameter are shown in Exhibit 4-20. For the higher turbine efficiency cases, the contribution to the cycle compression from the RDE is increased, which eventually increased the gas turbine thermal efficiency as less amount of shaft power is needed to be used for the compressor.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

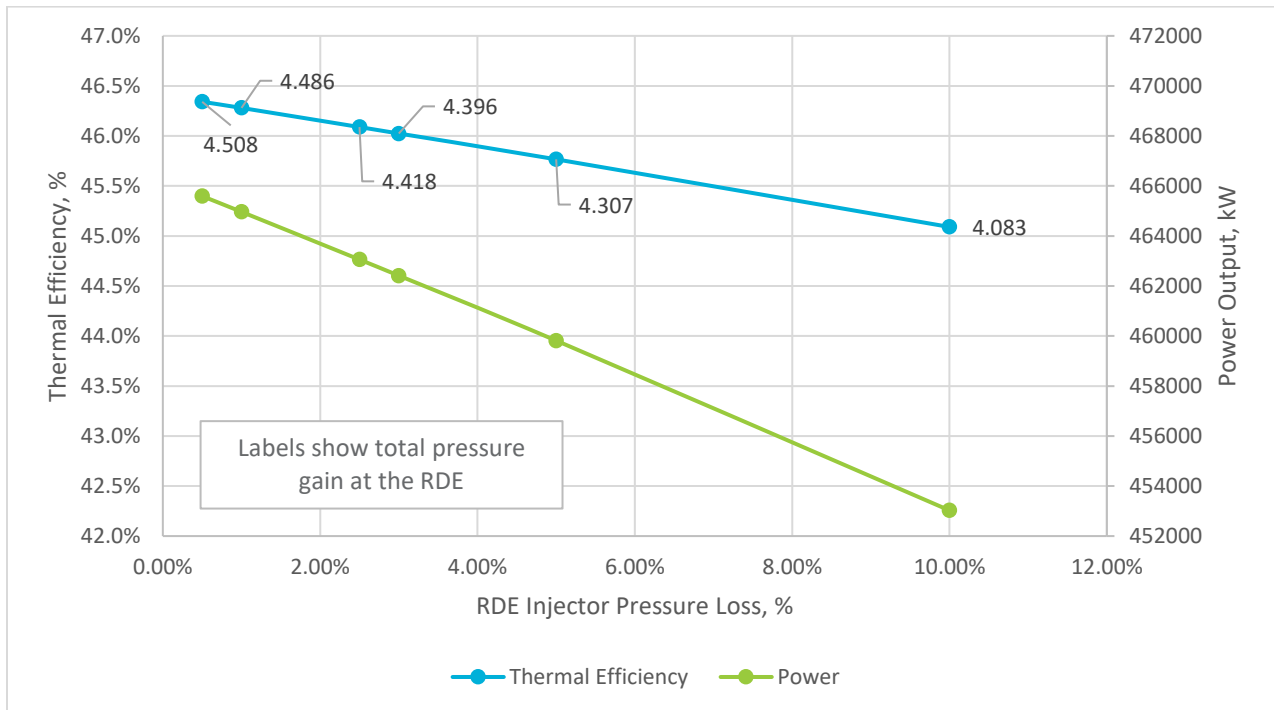
Exhibit 4-20. Sensitivity of RDE-GT system performance to turbine polytropic efficiency



RDE injector or plenum pressure loss is one of the biggest challenges in RDE design. The impact of this parameter to RDE-GT performance parameters is analyzed by changing the inlet pressure loss from 0 to 10 percent. The impact from the plenum/injector pressure loss to RDE-GT performance is shown in Exhibit 4-21.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

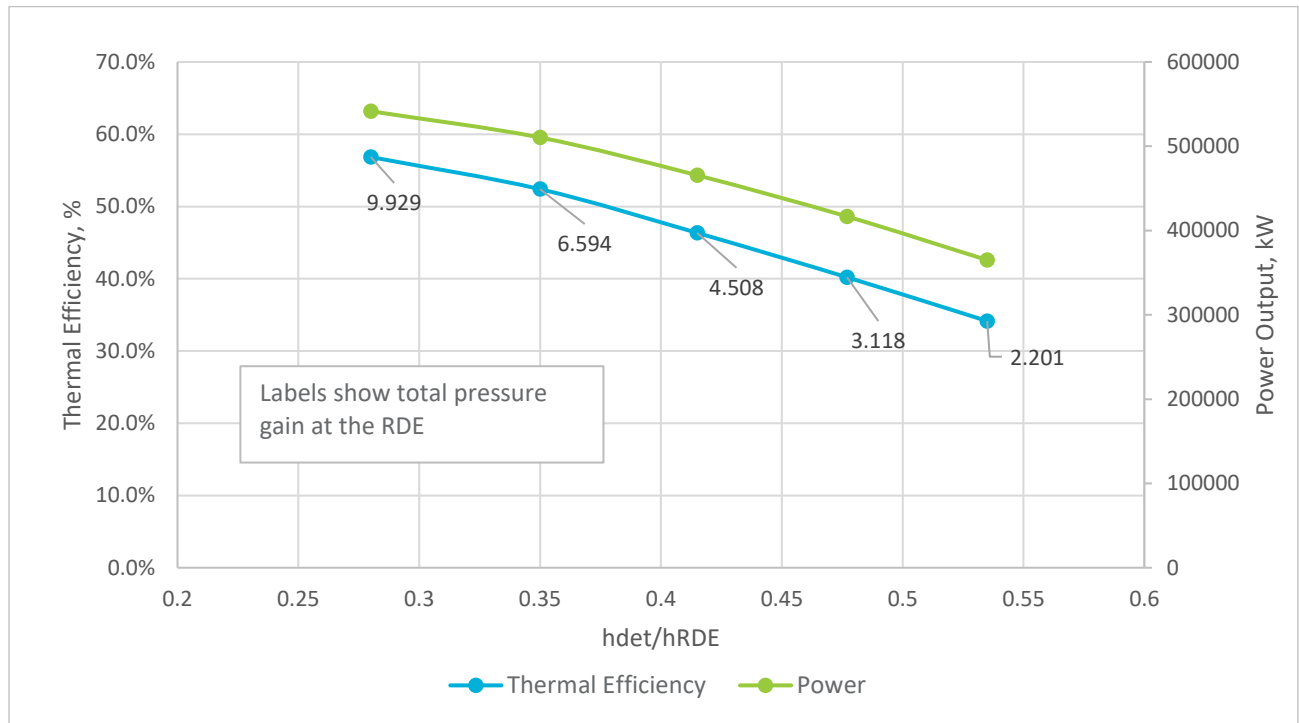
Exhibit 4-21. Sensitivity of RDE-GT system performance to RDE inlet pressure loss



Although not directly controllable or adjustable during the operation of the RDE, the detonation wave height is a very important parameter for RDE pressure gain performance. The wave height depends on several parameters such as RDE inlet conditions (air temperature, pressure, flowspeed and flowrate), RDE geometry and fuel-air mixing ratio. The impact of different detonation wave heights to RDE-GT system performance is studied by changing the relative detonation height to RDE length from 0.25 to 0.55. The impact to system performance from detonation height is shown in Exhibit 4-22.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 4-22. Sensitivity of RDE-GT system performance to normalized detonation wave height

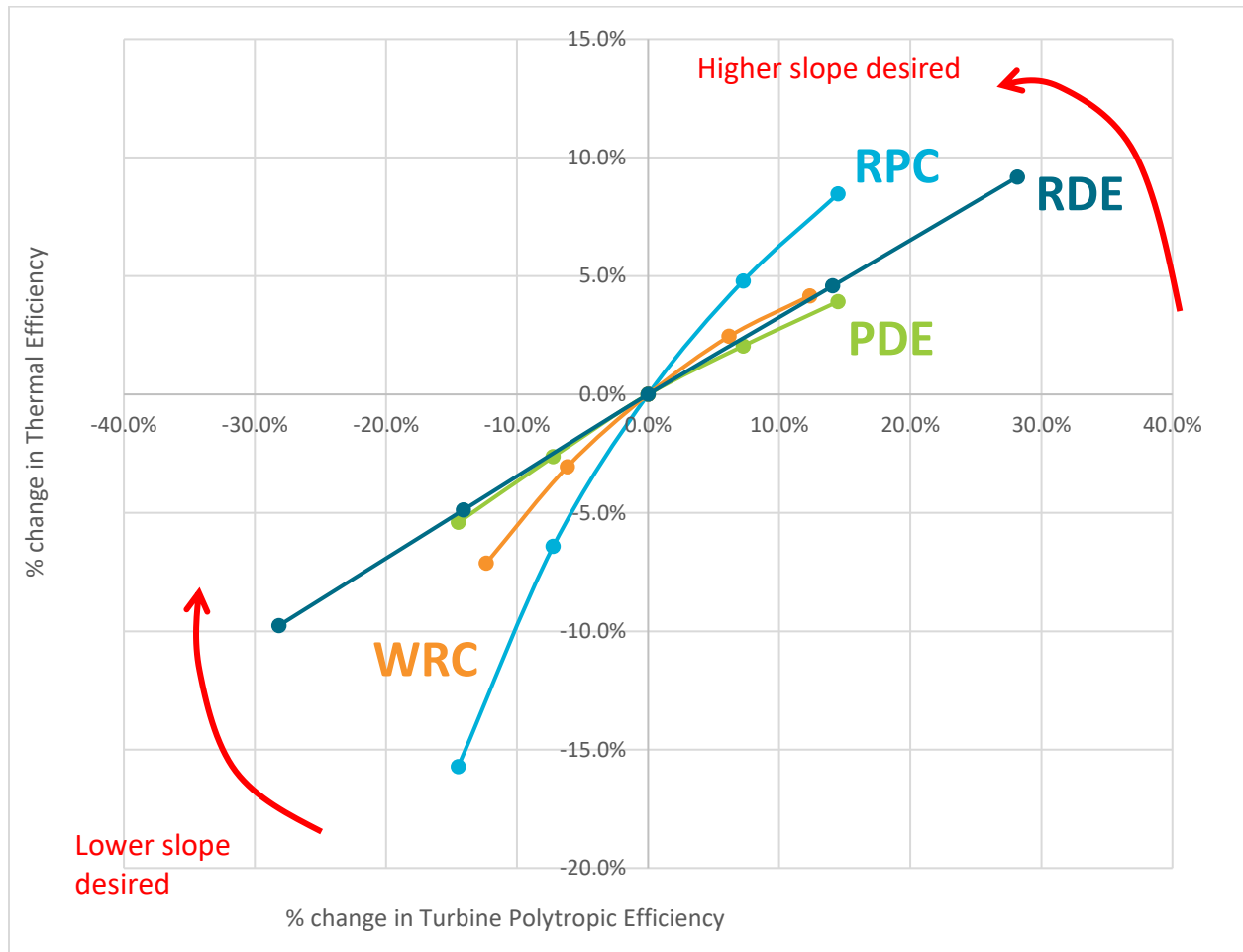


4.4 RESPONSE LEVELS OF DIFFERENT PGC-GT SYSTEMS TO SYSTEM PERFORMANCE IMPROVEMENTS

In almost all systems considered in this study, the effect of the turbine polytropic efficiency is very high in improving the GT thermal efficiency. In Exhibit 4-23, the response of each PGC system to the same amount of increase or decrease in the turbine efficiency is presented.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 4-23. Comparison of PGC-GT systems sensitivity to turbine polytropic efficiency change



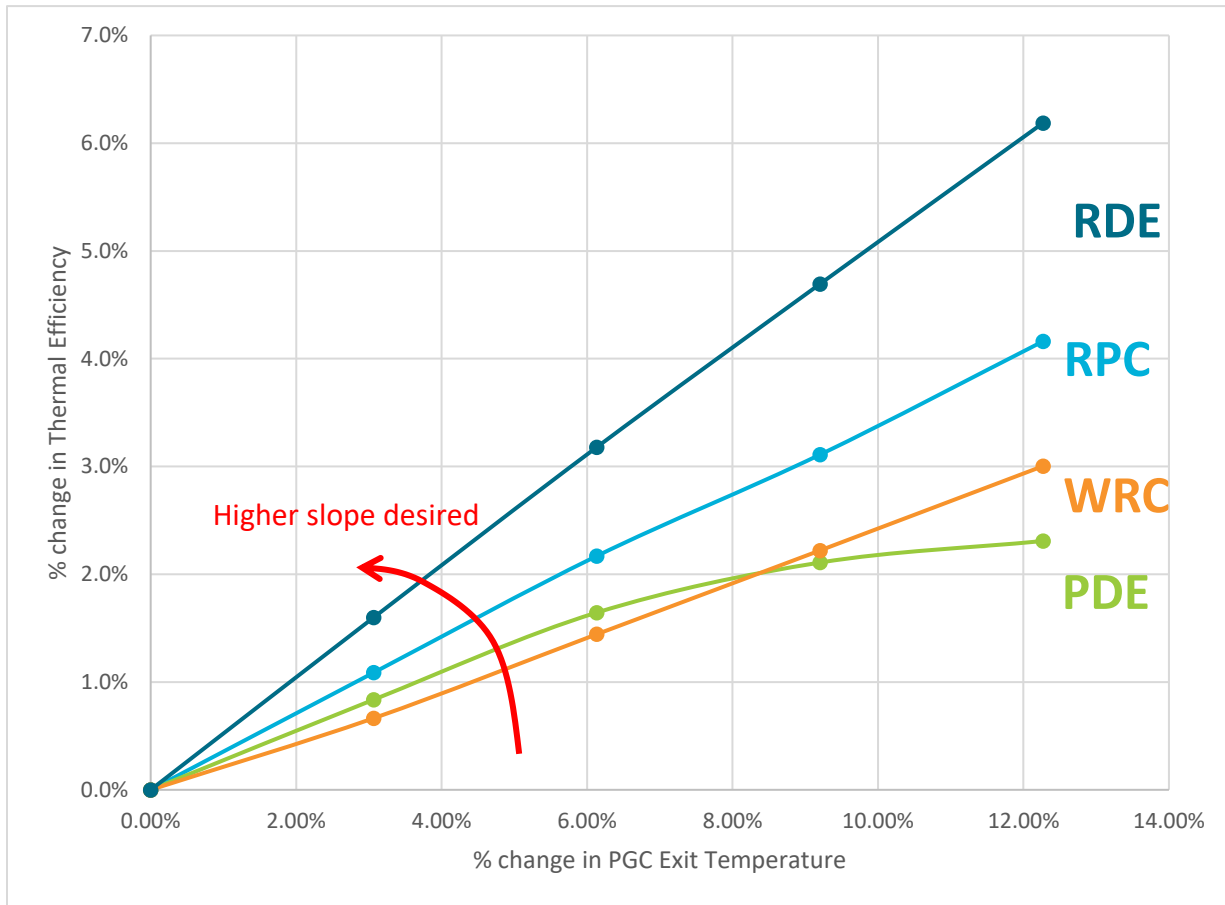
If the turbine integration losses could be reduced, higher response would be desired. The ranking for increasing the turbine polytropic efficiency impact to improve efficiency is highest for the RPC, RDE, WRC, and PDE.

Currently, most of the PGC-GT integration literature is from early-stage experiments and numerical model predictions and there is a probability of having much lower turbine efficiencies than 70 percent in actual systems. Therefore, the left portion of the chart in Exhibit 4-23 is also important in ranking the systems. Lower response to a decrease in turbine efficiency is desired and is indicated by lower slopes in the chart. The RDE-GT system is the least sensitive to the turbine efficiency reduction, followed by the PDE, WRC, and RPC.

The second most impactful improvement is to increase the PGC exit temperature by applying a transition cooling before the turbine. Higher response could be good if the by-pass cooling system could be designed with minimum losses. The comparison of the thermal efficiency improvement by increasing the PGC exit temperature the same amount is compared for each system in Exhibit 4-24.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 4-24. Comparison of PGC-GT systems sensitivity to turbine polytropic efficiency change where the turbine inlet temperature is fixed with by-pass cooling



From the slopes in Exhibit 4-24, the highest impact to GT thermal efficiency from increasing the PGC exit temperature is obtained for RDE, followed by RPC, WRC, and PDE. PDE systems are prone to have much higher fuel consumption when the exit temperature is further increased and, therefore, this engine did not benefit much from this improvement.

A comparison of the analyzed systems is made in Exhibit 4-25 with the PGC-GT system shaft power output, thermal efficiency, heat rate, sensitivity to decrease in turbine efficiency, sensitivity to increase in PGC exit temperature, and ease of improving the current (baseline) performance.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM
PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 4-25. PGC-GT system specifications used in the analysis

Parameter	RPC-GT	PDE-GT	WRC-GT	RDE-GT
Power Output (MW)	341	588	372	466
Thermal Efficiency	43.02%	45.74%	43.22%	46.34%
Heat Rate (Btu/kWh)	7931	7460	7894	7363
Compressor Pressure Ratio	23.1	5.2	19.9	11.4
PGC Pressure Ratio	2.348	11.73	1.627	4.508
Sensitivity to Decrease in Turbine Efficiency	1.09	0.37	0.69	0.35
Sensitivity to Increase in PGC Exit Temperature	0.34	0.19	0.25	0.5
Best Way to Improve Current Performance	Increase turbine efficiency by reducing PGC exit flow unsteadiness	Reduce purge fraction	Increase turbine efficiency by reducing PGC exit flow unsteadiness	Higher RDE exit temperatures

Based on thermal efficiency, sensitivity to decrease in turbine efficiency and ease of improving current performance, the RDE-GT system is the most promising for power applications. The PDE-GT system is the second-best configuration with highest power output potential but reducing the fuel consumption requires using very low purge fractions (which is difficult to implement [2]).

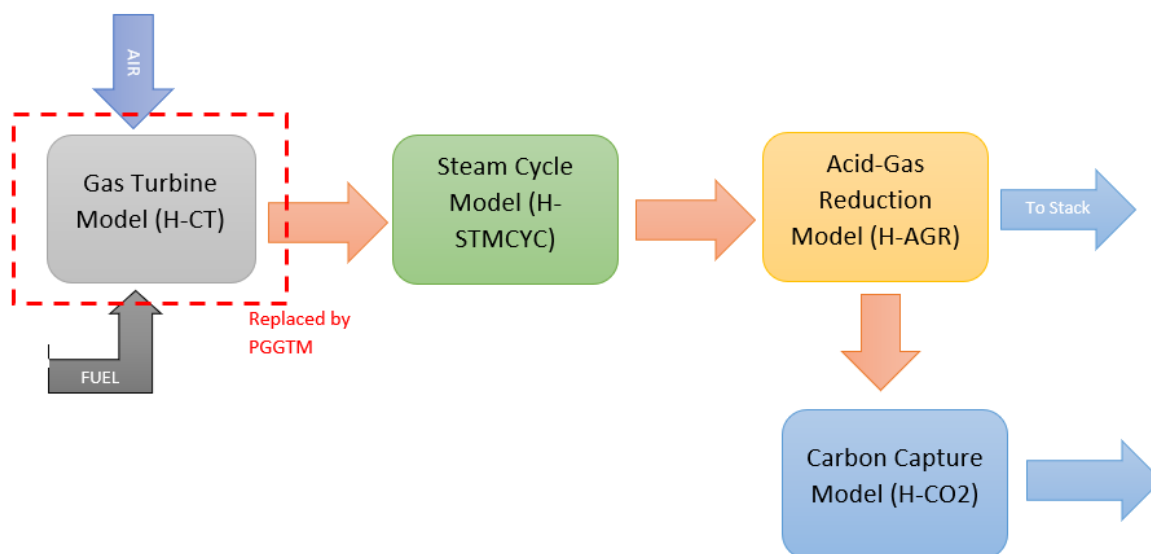
5 PGC-GT SYSTEM TO NGCC INTEGRATION

Among the PGC types considered in this study, RDE and PDE hybrid GTs give the highest potential to increase the GT efficiency and power output. When the ease of improving the presented performance levels is considered, the RDE system provides an advantage over the PDE system and, therefore, it is selected to be the configuration that will be studied for NGCC integration.

5.1 DEVELOPMENT OF A PGC-GT INTEGRATED NGCC SYSTEM SIMULATION

The NGCC steady-state plant simulation model used in this study is called NGCC-Sim and is based on the NETL Bituminous Baseline Rev.4 Case B31A NGCC Aspen model previously developed at NETL for F-Class GT coupled systems. [14] An overview of the major NGCC simulation subcomponents is shown in Exhibit 5-1.

Exhibit 5-1. NGCC-Sim main flowsheet showing the major system components



In this part of the study, several NGCC system components are modified to provide typical H-Class GT integrated NGCC performance (2X1 configuration). For the RDE modeling in GT, a surrogate model is developed using the PGC-Sim, which is developed previously (Section 3). A user input is defined to specify the combustor type: conventional or RDE.

5.1.1 Changes Made in the NGCC Simulation Models

5.1.1.1 Changes Made in the GT Hierarchy (H-CT)

The following changes have been made in the GT hierarchy system to model H-Class GT performance:

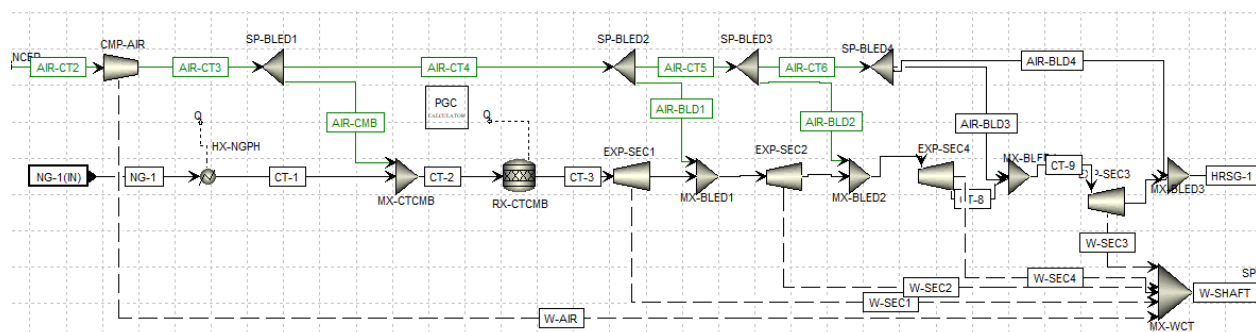
- Compressor efficiency and pressure ratio changed to typical H-Class values (90% and 23.0)

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

- Combustor exit temperature changed to typical H-Class GT values (~ 3260 °R)
- Number of turbine stages increased to 4
- Turbine efficiency and pressure ratio changed to typical H-Class values (93% and 21.15) [15]

The indicated changes are made in accordance with a previous study about the impacts of turbine cooling improvements on H-Class GT integrated combined cycle performance. [15] The new flowsheet for the GT hierarchy is shown in Exhibit 5-2.

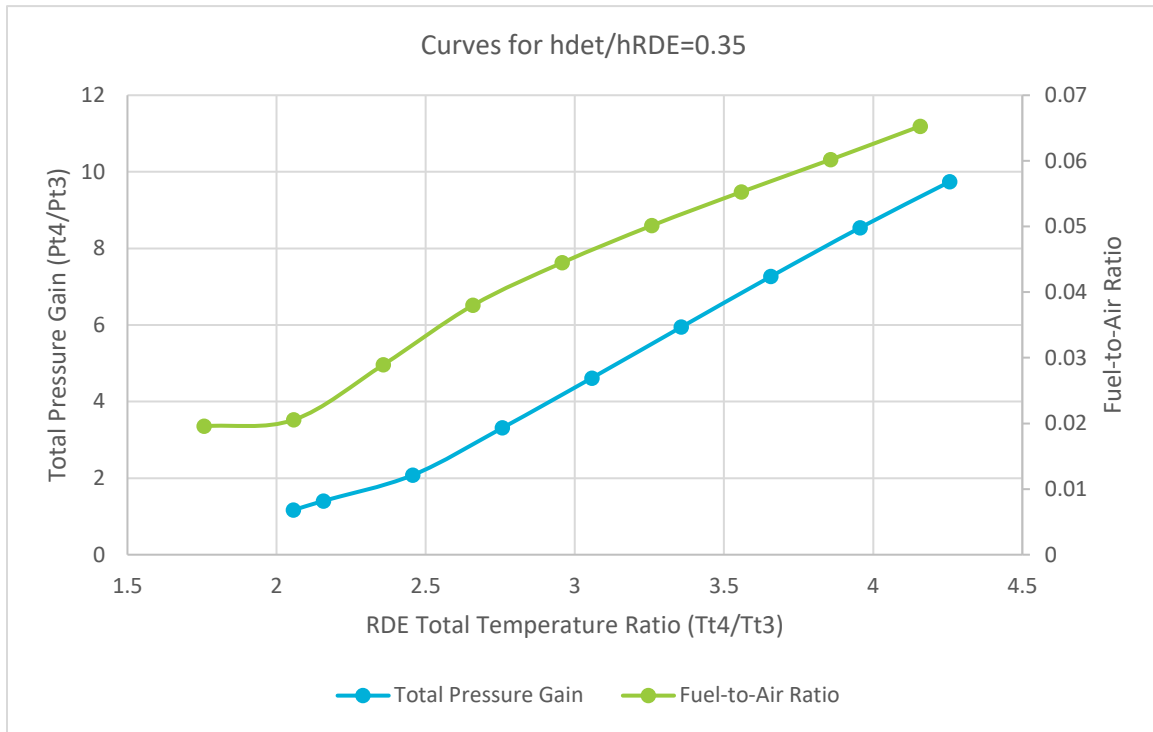
Exhibit 5-2. H-CT flowsheet showing the updated GT model components



PGC (PGC Block in Exhibit 5-2) is modeled as an Aspen calculator block that modifies the combustor parameters of the combustor block (RX-CTCMB). The modified parameters of the combustor block by PGC are the exit pressure, temperature, and fuel flowrate. Currently, no default Aspen property set exists for the natural gas detonation with air; therefore, standard combustion properties are retained in the model. However, comparison of GASEQ Software results for detonation for key thermodynamic properties (heat capacity, enthalpy, etc.) for the GT temperature ranges shows around a 4–5 percent difference from the conventional combustion values, which is adequate for the current levels of modeling purposes.

The surrogate model for RDE is developed by using curve-fits from running the PGC-Sim with various detonation heights and inlet to exit temperature and pressure conditions. Example model curves for total pressure gain and fuel-to-air ratio of RDE for 0.35 relative detonation height is provided in Exhibit 5-3.

Exhibit 5-3. An example of RDE performance curves used in the development of RDE surrogate model given for normalized wave height ratio (h_{det}/h_{RDE}) of 0.35



For all detonation height scenarios, third and fourth order curve fit polynomials are used to obtain surrogate model equations for the pressure gain and fuel consumption. The surrogate model calculates the RDE total pressure gain and fuel consumption values based on the changes in the inlet and exit flow conditions and modifies the combustor block parameters accordingly.

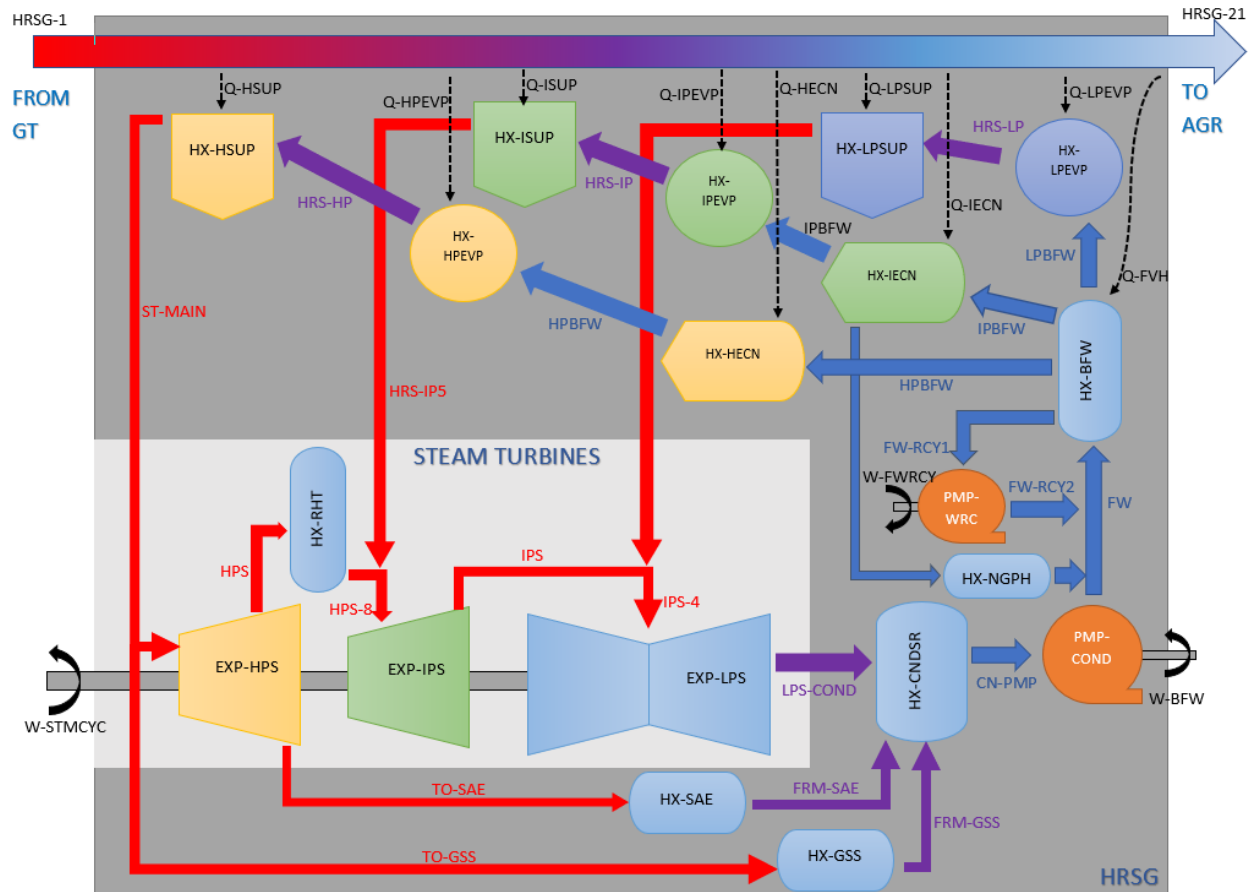
For the turbine cooling system of the GT hierarchy, the cooling system is adapted to include four stages as shown in Exhibit 4-24. Turbine efficiencies and pressure ratio are changed to typical H-Class values, which are obtained from the previous NGCC study with H-Class GTs. [15] Turbine cooling analysis or cooled turbine model is not integrated, but the model uses user-input turbine cooling fractions.

5.1.1.2 Changes made in the Steam Cycle Hierarchy (H-STM CYC)

The steam cycle hierarchy in NGCC-Sim contains the models for the three-pressure level HRSG and the steam turbines. A simplified flowchart for major streams and components of the system is presented in Exhibit 5-4.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 5-4. Simplified flowchart for the steam cycle hierarchy



In the full model flowsheet, heat exchangers, economizers, evaporators, and superheaters have multiple stages. The steam cycle runs in a convergence loop that satisfies the constraints put on pinch point temperatures, combined condensate steam temperature and natural gas pre-heat (NGPH) heat transfer rate for non-carbon capture cases by varying the feedwater flow rate, feedwater recycle fraction, and the fraction of feedwater to the NGPH heat exchanger.

5.1.1.2.1 Parameter Changes in the HRSG Model

When the GT performance conditions are changed from F-Class to the H-Class levels, the GT exhaust flow conditions (or HRSG inlet conditions) change due to following [15]:

- Higher GT air intake mass flow rate
- Higher turbine inlet temperature
- Higher compressor pressure ratio (i.e., compression ratio)

The increase in the GT intake mass flow rate from F-Class values would increase the GT exhaust mass flow rate, which requires higher feedwater mass flow rates to the HRSG to account for the difference introduced to the heat transfer rate from the gas flow.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

As the temperature and pressure of the GT exhaust gases are changed due to increased turbine inlet temperature and compression ratios, the values of the constant pressure specific heat and the temperature differences also changes. Assuming no significant changes to the pinch point temperature constraints from the F-Class engine coupled HRSG to H-Class engine coupled HRSG, corresponding increase in the heat flux from the GT exhaust flow can only be balanced by increasing the feedwater rates in the HRSG. The corresponding changes made in the HRSG parameters are shown in Exhibit 5-5.

Exhibit 5-5. Parameter changes in the HRSG model

Parameter	F-Class GT coupled HRSG [14]	H-Class GT coupled HRSG
High Pressure Feedwater		
Mass Flowrate	301.6 lbm/s	385.9 lbm/s
Pinch Point Approach Temperature	46.7 °F	45.0 °F
Intermediate Pressure Feedwater		
Mass Flowrate	78.5 lbm/s	117.7 lbm/s
Pinch Point Approach Temperature	45.8 °F	39.7 °F
Low Pressure Feedwater		
Mass Flowrate	44.5 lbm/s	31 lbm/s
Pinch Point Approach Temperature	40 °F	40 °F

5.1.1.2.2 Parameter Changes in the Steam Turbine Model

For the steam turbines, the changes are made in the efficiency, inlet and exit pressures, and temperatures, based on the current steam turbines coupled with H-Class engines and steam turbine improvement paths obtained from the open literature. High- and low-pressure steam turbine inlet pressures are increased in recent turbines, which corresponds to increases in the efficiency levels. Intermediate pressure turbine inlet pressure and temperature is reduced but advanced component design is assumed to provide higher efficiency. Parameter changes related to the HRSG exit streams presented in Exhibit 5-5 are made in accordance with the steam turbine performance increase. The changes made in the steam turbine model parameters to calibrate NGCC-Sim to the H-Class GT coupled plant performance are listed in Exhibit 5-6.

Exhibit 5-6. Parameter changes in the steam turbine models

Parameter	F-Class GT coupled ST [14]	H-Class GT coupled ST
High Pressure Steam Turbine		
Efficiency	91%	94%
Inlet Pressure	2400 psia	2683 psia
Exit Pressure	542 psia	525 psia
Intermediate Pressure Feedwater		
Efficiency	93%	94%

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Parameter	F-Class GT coupled ST [14]	H-Class GT coupled ST
Inlet Pressure	509 psia	480 psia
Inlet Temperature	1084 °F	1044 °F
Low Pressure Feedwater		
Efficiency	92%	94%
Inlet Pressure	74 psia	84 psia
Inlet Temperature	581 °F	584 °F

5.1.2 Comparison of the Modified GT Model with Previous Study

The validation of the modified GT hierarchy for the GT is made by comparing its results to PGGTM that was developed in Simulink (Section 4). The input conditions used in the validation are from Exhibit 4-5. The key GT performance parameters from the modified H-CT hierarchy are compared with the results from PGGTM for conventional combustor case in Exhibit 5-7.

Exhibit 5-7. Performance parameters comparison for conventional GT

Performance Parameter	H-CT in NGCC-Sim	PGGTM (Simulink)
Fuel-to-Air Ratio	0.03048	0.03048
Turbine Exit Temperature (°F)	1155	1160
Turbine Pressure Ratio	0.047	0.048
Power (MW)	342	341
Heat Rate (Btu/kWh)	8086	8056
Thermal Efficiency	42.2%	42.4%

The key GT performance parameters from the modified H-CT hierarchy are compared with the results from PGGTM for RDE case in Exhibit 5-8.

Exhibit 5-8. Performance parameters comparison for RDE-GT

Performance Parameter	H-CT in NGCC-Sim	PGGTM (Simulink)
Fuel-to-Air Ratio	0.0388	0.0389
Turbine Exit Temperature (°F)	1150	1155
Turbine Pressure Ratio	0.017	0.018
Power (MW)	463	465
Heat Rate (Btu/kWh)	7291	7391
Thermal Efficiency	46.8%	46.2%

The comparison for the conventional GT and RDE coupled GT models shows reasonable and acceptable differences, which can be explained with the difference between stock compressor

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

and turbine models of Aspen with the PGGTM models and flow property calculations in Aspen. Particularly for the RDE coupled GT validations, the differences also include the difference in estimating RDE performance with a curve-fit with respect to estimating it with the analytical model used in Simulink.

5.2 NGCC PERFORMANCE WITH RDE-GT SYSTEM

For the baseline RDE-GT system, which has the system design parameters listed in Exhibit 4-5, the NGCC performance parameters are obtained as presented in Exhibit 5-9. The first column shows the NGCC performance with a conventional H-Class GT, which is identical with the values from previous NGCC analysis for turbine cooling. [15] The second column shows the corresponding NGCC performance parameter changes when the RDE coupled H-Class GT is used in the same NGCC power plant.

Exhibit 5-9. Performance parameters comparison for RDE-GT integrated NGCC with conventional GT integrated NGCC (Cycle: 2 GT x 2 HRSG x 1 ST)

Parameter	NGCC with H-Class GT (Conventional)	NGCC with H-Class RDE-GT Hybrid	Change (from Conventional GT)
Combustion Turbine Power (MW)	685	926	+35.2%
Steam Turbine Power (MW)	336	337	+0.3%
Total Gross Power (MW)	1020	1263	+23.8%
Balance of Plant (kW)	17,483	18,264	+4.5%
Net Power (MW)	1003	1244	+24.0%
LHV Net Plant Efficiency	61.7%	63.5%	+1.8% (absolute)
LHV Net Plant Heat Rate (Btu/kWh)	5531	5373	-2.9%
LHV GT Efficiency	42.1%	47.0%	+4.9% (absolute)
Steam Turbine Efficiency	40.5%	40.4%	-0.1% (absolute)
Steam Turbine Heat Rate (Btu/kWh)	8405	8436	+0.4%
Condenser Duty (MMBtu/hr)	1603	1609	+0.4%
Natural Gas Feed flow (lbm/hr)	273343	331182	+21.2%

The biggest change from conventional GT integrated NGCC is the increase in the combustion turbine power with RDE-GT system, which is around 35 percent, and is directly reflected to the increase in the net power output. The plant efficiency is increased by 1.8 percent and heat rate reduced by 3 percent. Balance of plant is increased by 4.5 percent, which is due to the higher net power output obtained with the RDE-GT coupled NGCC system.

The results obtained for the NGCC performance with RDE-GT system assumes turbine polytropic efficiency of 70 percent, which will be increased at later development stages of RDE-GT coupled systems. In addition, the increase in the fuel consumption in RDE coupled system is balanced out with the significant increase in the power output. Steam turbine performance is basically not affected because the gas turbine exhaust temperature is kept the same with the conventional configuration.

5.3 NGCC PERFORMANCE SENSITIVITY TO RDE-GT PARAMETERS

To understand which GT and RDE parameters have the most potential to increase the NGCC efficiency, a sensitivity analysis is performed with the following parameters:

- Turbine efficiency
- RDE exit temperature
- RDE inlet pressure loss
- Compressor efficiency

The studied parameters are determined based on the sensitivity analysis made for the RDE-GT system in Section 4.3.

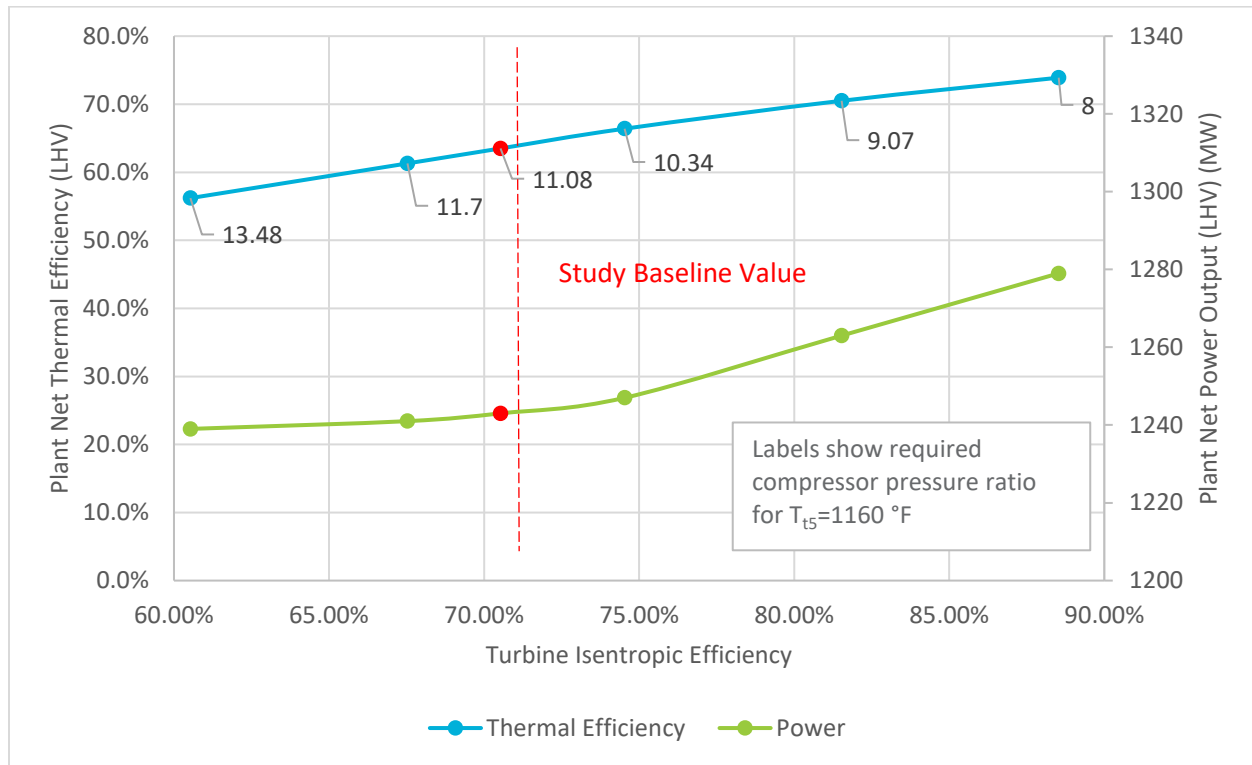
5.3.1 Impact of Turbine Efficiency on NGCC Performance

According to published results from current RDE experimental rigs with axial turbine coupling, the turbine efficiency, either isentropic or polytropic, is highly impacted from the RDE exit flow instability. The isentropic turbine efficiency values of 90–92 percent for conventional gas turbines could be as low as 70 percent when the RDE exit flow is untreated. Two possible approaches used by RDE researchers to improve the turbine efficiency exist:

- Using an efficient convergent-divergent nozzle design [49]
- Designing a supersonic turbine that may or may not require the convergent-divergent nozzle section [13]

In either case, more than 80 percent turbine efficiency is expected. The sensitivity of power plant net thermal efficiency and net power output to turbine isentropic efficiency is shown in Exhibit 5-10.

Exhibit 5-10. NGCC LHV thermal efficiency and net power output sensitivity to turbine isentropic efficiency



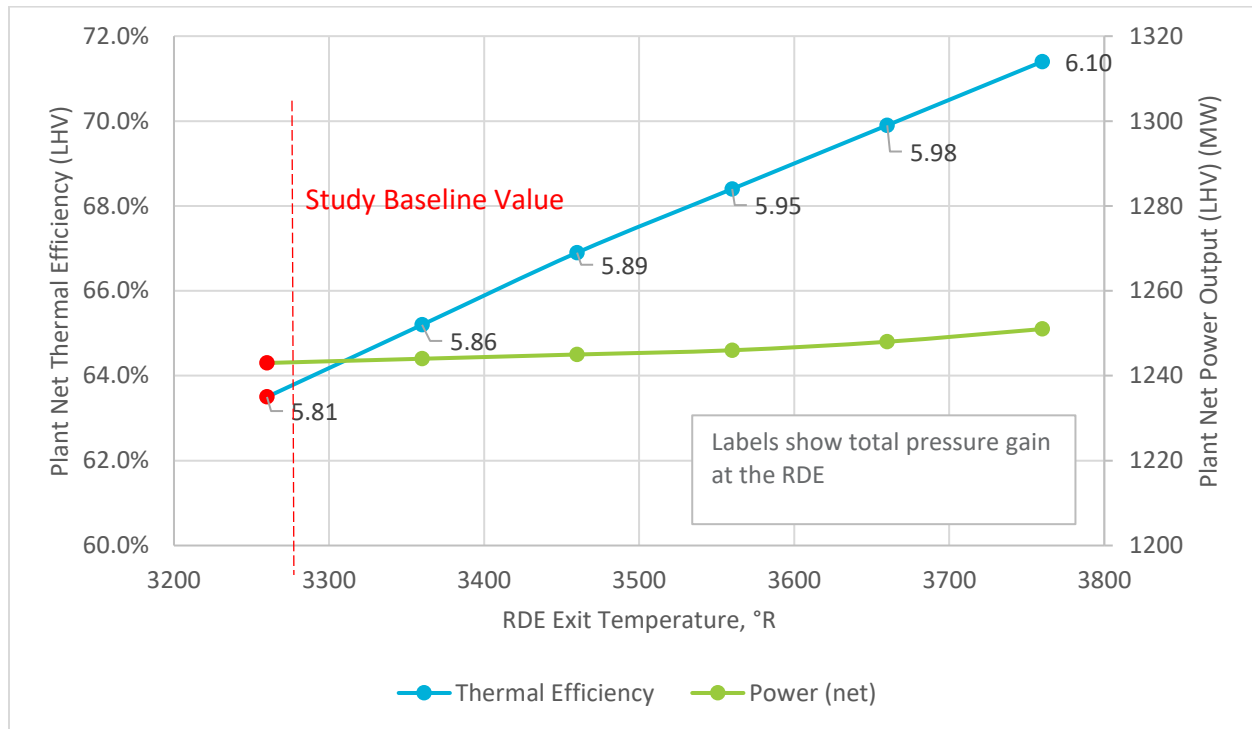
When the turbine isentropic efficiency is increased from 70 to 90 percent, the NGCC efficiency is increased from 63.5 to 73.7 percent. NGCC efficiency of 70 percent is reached with 82 percent turbine efficiency, which is the expected level of turbine efficiency with recent developments in RDE integrated turbines in the open literature. The reduction from the baseline turbine efficiency by 3 percent would give current NGCC efficiency levels with conventional gas turbines; but even in this case, the high values of net power output would provide important gains in the cost of electricity (COE).

5.3.2 Impact of RDE Exit Temperature on NGCC Performance

The RDE exit temperature is an important parameter for the total pressure gain from the RDE. Similar to conventional combustion, having higher exit temperature means higher fuel consumption but overall efficiency increases if the pressure gain is high. The impact is due to increased CJ velocity in the RDE flow. In this part of the study, it is assumed that the by-pass cooling or transition cooling section between the RDE nozzle and the turbine is efficient enough to reduce the RDE exhaust temperature back to 3260 °R. The required transition cooling fractions are calculated with a similar method used in CGTM. [10]

The sensitivity of plant net thermal efficiency and net power output to RDE exit temperature is shown in Exhibit 5-11.

Exhibit 5-11. NGCC LHV thermal efficiency and net power output sensitivity to RDE exit temperature



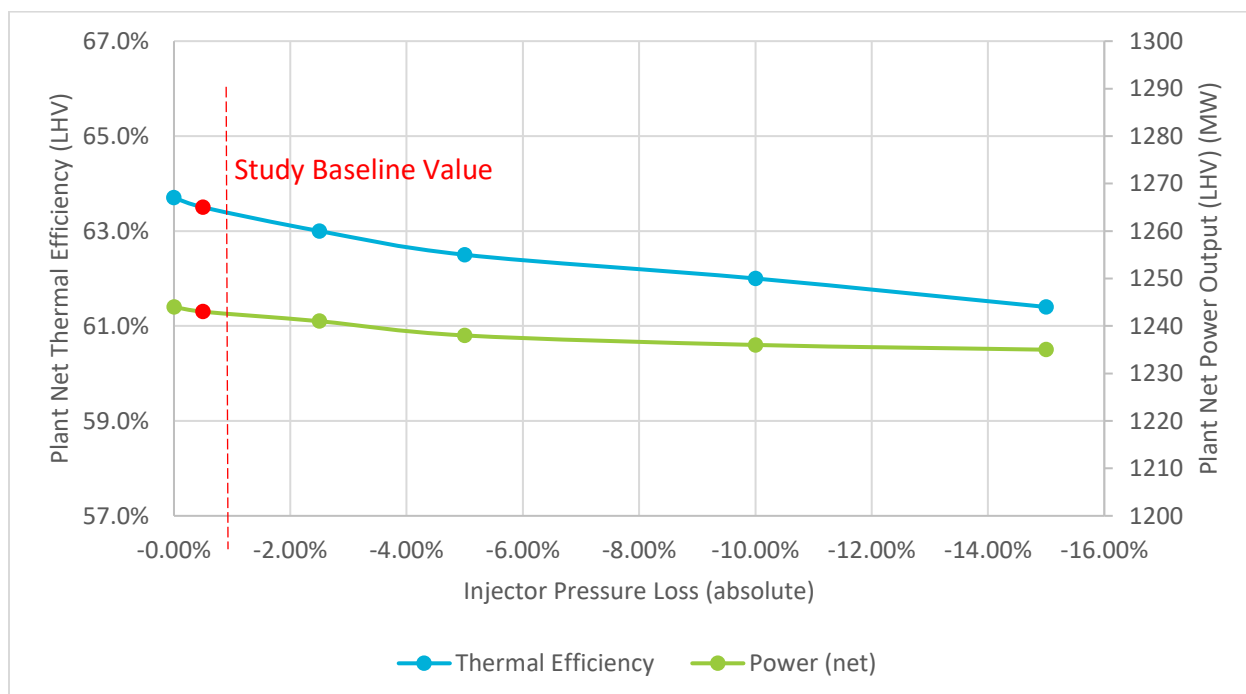
When the RDE exit temperature is increased from the baseline value by 500 °R, the NGCC efficiency is increased from 64 to 72 percent, which is the steepest increase provided in efficiency among the entire analysis parameters of the study. The current combustor liner materials induce a limit on the RDE exit temperature and, therefore, increasing the exit temperature beyond 3600 °R might not be feasible. A combination of higher RDE exit temperature with higher turbine efficiency is a more practical improvement path.

5.3.3 Impact of RDE Injector Pressure Loss on NGCC Performance

RDE injector and plenum losses cause pressure gain reduction and increase in the fuel consumption, which is considered one of the most important RDE losses. This loss is usually due to fuel-air mixing inefficiency, injector performance, and flow losses. Injector pressure losses are included in PGC-Sim as a total pressure loss term at the RDE inlet. Studied sensitivity analysis range for this parameter was selected to be 0–15 percent.

The sensitivity of plant net thermal efficiency and net power output to RDE injector pressure loss is shown in Exhibit 5-12.

Exhibit 5-12. NGCC LHV thermal efficiency and net power output sensitivity to injector pressure loss



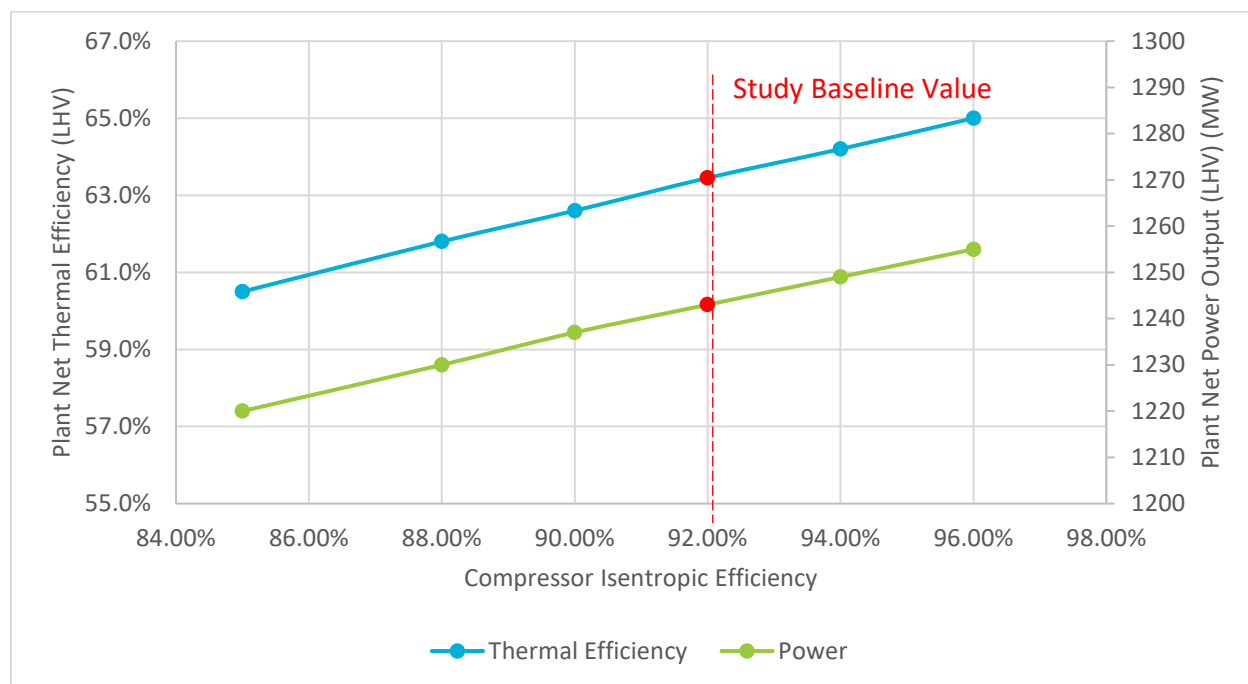
The reduction in the NGCC thermal efficiency and power output increases as the amount of the injector and plenum losses is increased. For the studied region, 2.3 percent absolute reduction in the thermal efficiency is calculated from the perfect plenum case. In the RDE-GT system considered for this study, the plenum losses can be compensated to an extent by using a compressor with higher pressure ratio.

5.3.4 Impact of Compressor Isentropic Efficiency on NGCC Performance

The compressor is required to maintain proper inlet conditions to the RDE. For the RDE-GT systems, the compressor pressure ratio is much lower than the pressure ratio used in conventional GTs. The smaller capacity requirement from compressors of RDE-GT systems is due to having the RDE as the secondary pressure generation source for the Brayton Cycle. Current compressors used in GTs typically have 89–92 percent efficiency and major loss resources for compressors are coolant extractions, blade fouling, and blade end-wall interactions. Smaller capacity compressors might have lower efficiencies due to several design challenges such as increased end-wall losses; therefore, the sensitivity analysis range for compressor efficiency is 85–96 percent. Advances in compressor design would enable 94–95 percent efficiency in the near future.

The sensitivity of plant net thermal efficiency and net power output to compressor isentropic efficiency is shown in Exhibit 5-13.

Exhibit 5-13. NGCC LHV thermal efficiency and net power output sensitivity to compressor isentropic efficiency



The compressor isentropic efficiency has almost a linear impact on both NGCC efficiency and power output. The study range starts at 85 percent, which is an efficiency level that is at the lower end of the current compressor technology and reaches 96 percent efficiency. The thermal efficiency is increased by 5 percent (absolute) from the lowest end of the compressor efficiency to the advanced compressor values.

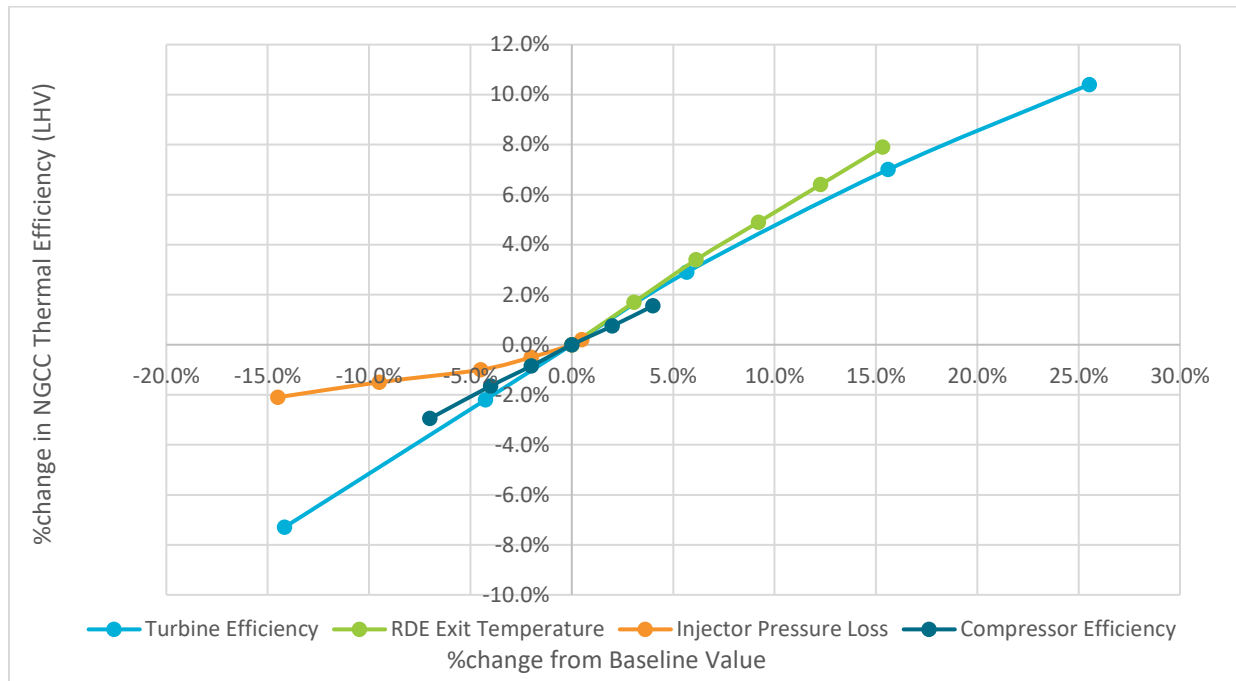
5.3.5 Comparison of the Impact Strength of Sensitivity Parameters

The relative strengths of each sensitivity parameter on the NGCC thermal efficiency are compared in this section. The comparison charts are obtained by plotting the relative increase and decrease in the selected NGCC performance parameter with respect to the changes in the sensitivity parameters. Higher slopes on comparison graphs mean higher dependency on a particular sensitivity parameter.

The impact strengths of the studied sensitivity parameters on LHV NGCC thermal efficiency are compared in Exhibit 5-14.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 5-14. NGCC LHV thermal efficiency sensitivity to analysis parameters

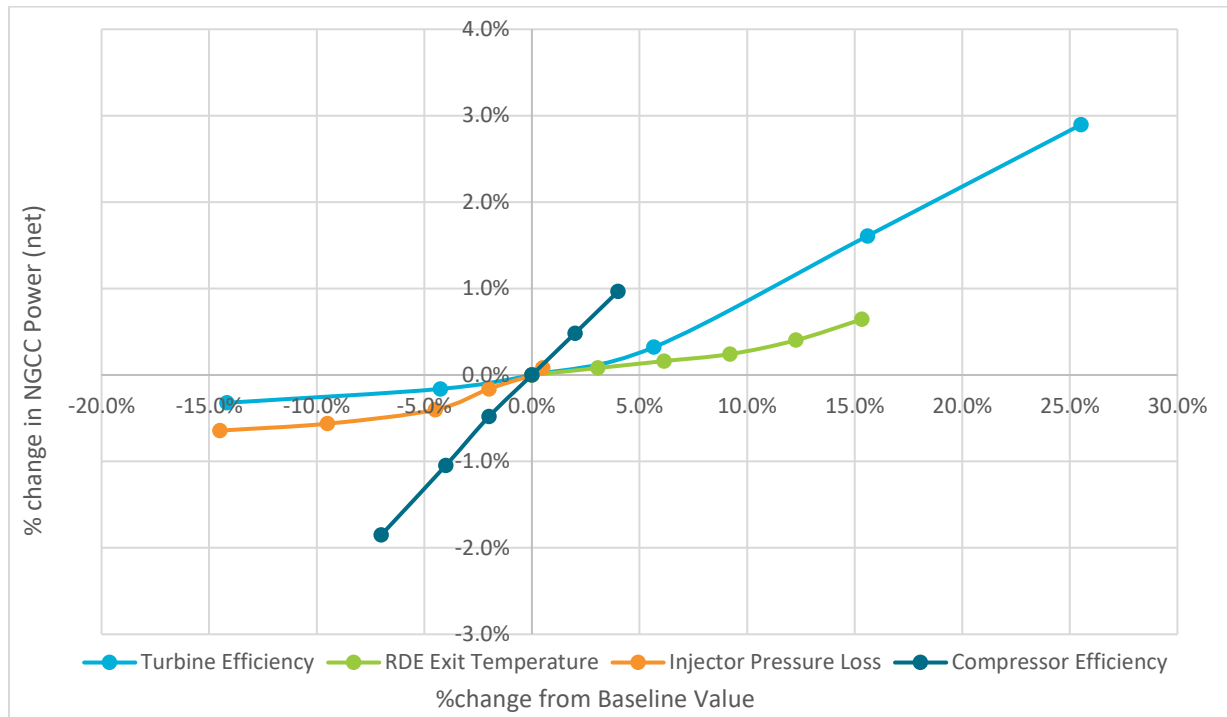


According to the results for thermal efficiency, the highest impact on increased NGCC efficiency comes from higher RDE exit temperatures, followed by increasing the turbine efficiency. Injector pressure loss and compressor efficiency have third and fourth place, respectively. The highest negative impact to NGCC efficiency comes from lower turbine efficiency, low compressor efficiency, and high injector pressure losses.

For the power output, compressor efficiency has the highest impact, followed by the injector pressure loss, turbine efficiency, and RDE exit temperature. The impact strengths of the studied sensitivity parameters on NGCC net power output are compared in Exhibit 5-15.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 5-15. NGCC net power output sensitivity to analysis parameters

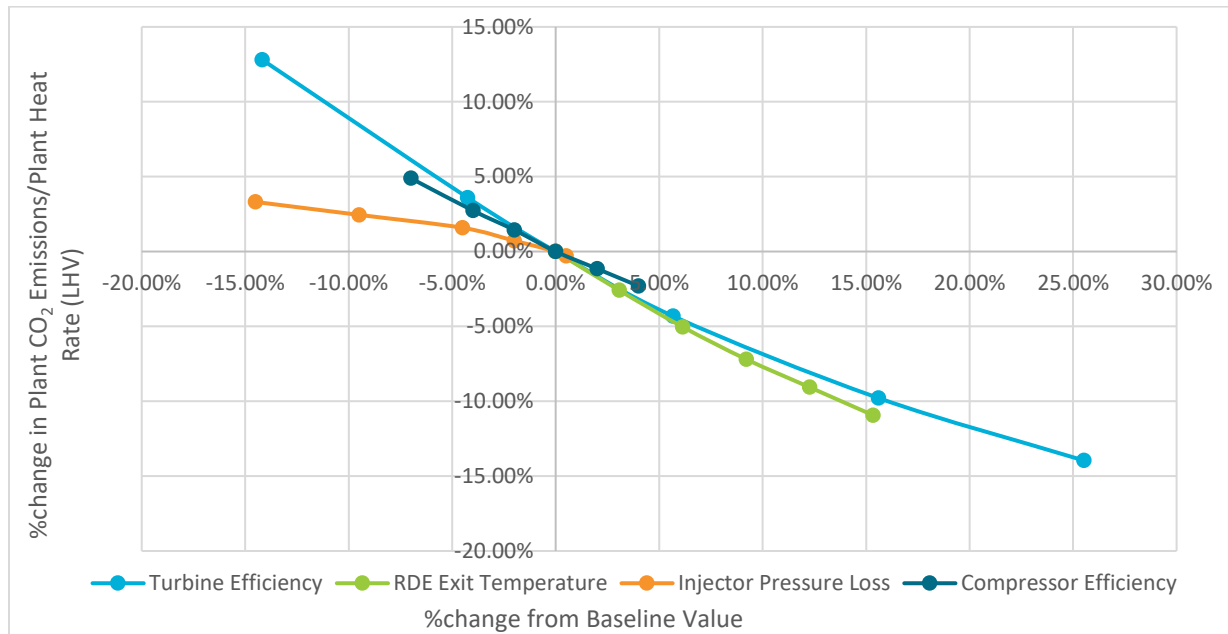


For the analyzed system configuration, the by-pass cooling air is extracted from the compressor and when the RDE exit temperature is increased, more coolant is extracted from the compressor. Because of the increased compressor demand, the power output of the GT did not increase much and caused the change in the impact rankings from the efficiency plot.

The impact strengths of the studied sensitivity parameters on plant CO₂ emissions and heat rate (LHV) are compared in Exhibit 5-16.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 5-16. NGCC CO₂ emissions and heat rate (LHV) sensitivity to analysis parameters



The sensitivity trends for plant CO₂ emissions and heat rate are almost the same because both parameters are impacted by the changes in the fuel consumption. Increasing the RDE exit temperature provides the highest reduction; this is followed by increasing turbine efficiency, compressor efficiency, and reduction of injector pressure losses.

6 FEASIBLE RDE-GT SYSTEM CONFIGURATIONS AND TECHNO-ECONOMIC ANALYSIS

The results of the sensitivity analysis show that the impacts of studied RDE-GT system components to NGCC performance are different. The turbine efficiency and RDE exit temperature are determined to impact the NGCC performance highest among the studied parameters. However, the discussed levels of improvements regarding engine components might not be available in the near future or by the time RDE-GT systems become operational. Therefore, several technology improvement paths are determined and used in determining the suggested system configurations for the techno-economic analysis.

A cost estimation analysis is then made for each feasible RDE-GT configuration. The Quality Guidelines for Energy System Studies (QGESS) method [50] was used for cost estimation by using the “BBR4 Cost Spreadsheet Rev. E” template. The cost estimation made for H-Class GT using NGCC plants [15] is used as the baseline for the QGESS cost scaling methodology [51] applied to NGCC components other than the RDE-GT. The capital cost of the RDE-GT system is calculated by using a specific methodology described in Section 6.2.

6.1 DETERMINATION OF FEASIBLE RDE-GT SYSTEM CONFIGURATIONS

6.1.1 Relations Between RDE-GT System Components

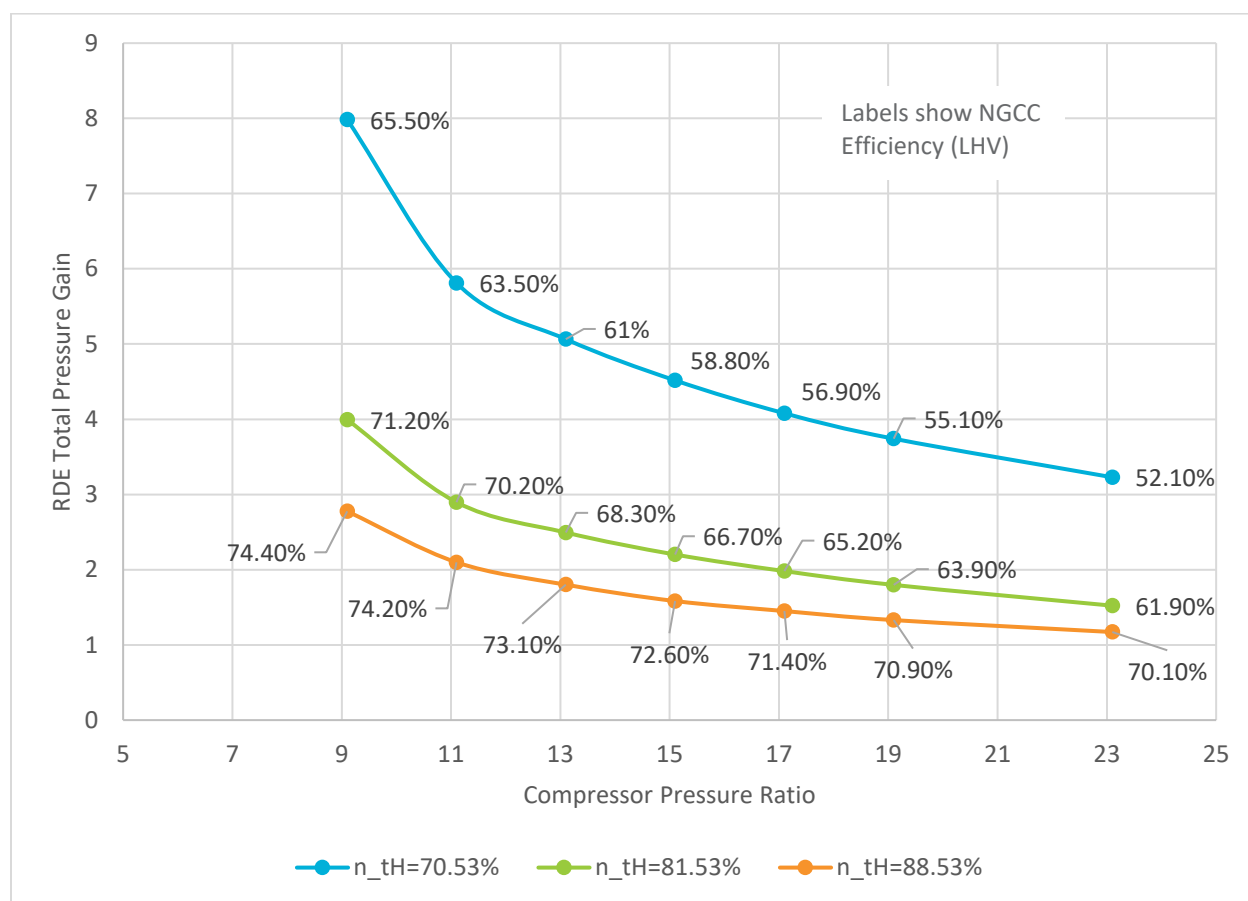
In this study, the GT exit temperature and mass flowrate is kept constant with the conventional H-Class GT conditions in order to minimize the system development efforts and costs for the RDE-GT system.

In the RDE-GT system, there are two pressure gain devices: the compressor and the RDE. To have certain exit conditions, the GT must have a certain amount of pressure at the turbine inlet; however, resourcing of this pressure gain is important for system performance. When the turbine inlet pressure is resourced mostly from the compressor, less pressure gain from the RDE is required, which reduces the fuel consumption and can overcome the RDE injector pressure losses. However, especially for the case when the turbine efficiency is lower, having most of the pressurization from the RDE is more beneficial, which provides higher power output and efficiency depending on other system parameters.

In Exhibit 5-15, different possibilities for compressor pressure ratio and RDE pressure gain combinations are investigated for the constant GT exit conditions of Exhibit 6-1. The analysis is repeated for three different turbine isentropic efficiency levels: 70.53 percent (current levels), 81.53 percent (attained in near future), and 88.53 percent (advanced level).

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-1. The relation between RDE pressure gain, compressor pressure ratio, and turbine isentropic efficiency



Resourcing pressurization mostly from the compressor has certain disadvantages—increased power demand from the turbine might eventually reduce the NGCC efficiency and power output. However, high levels of RDE pressure gain, such as more than twice the RDE inlet pressure, might require lower wave heights and might also have high flow instabilities and several operational challenges that might not be addressed with the current or foreseeable future technologies, which would necessitate the usage of a compressor as the secondary pressure generation device.

The advantages and disadvantages of the RDE-GT pressurization resourcing distribution is summarized in Exhibit 6-2.

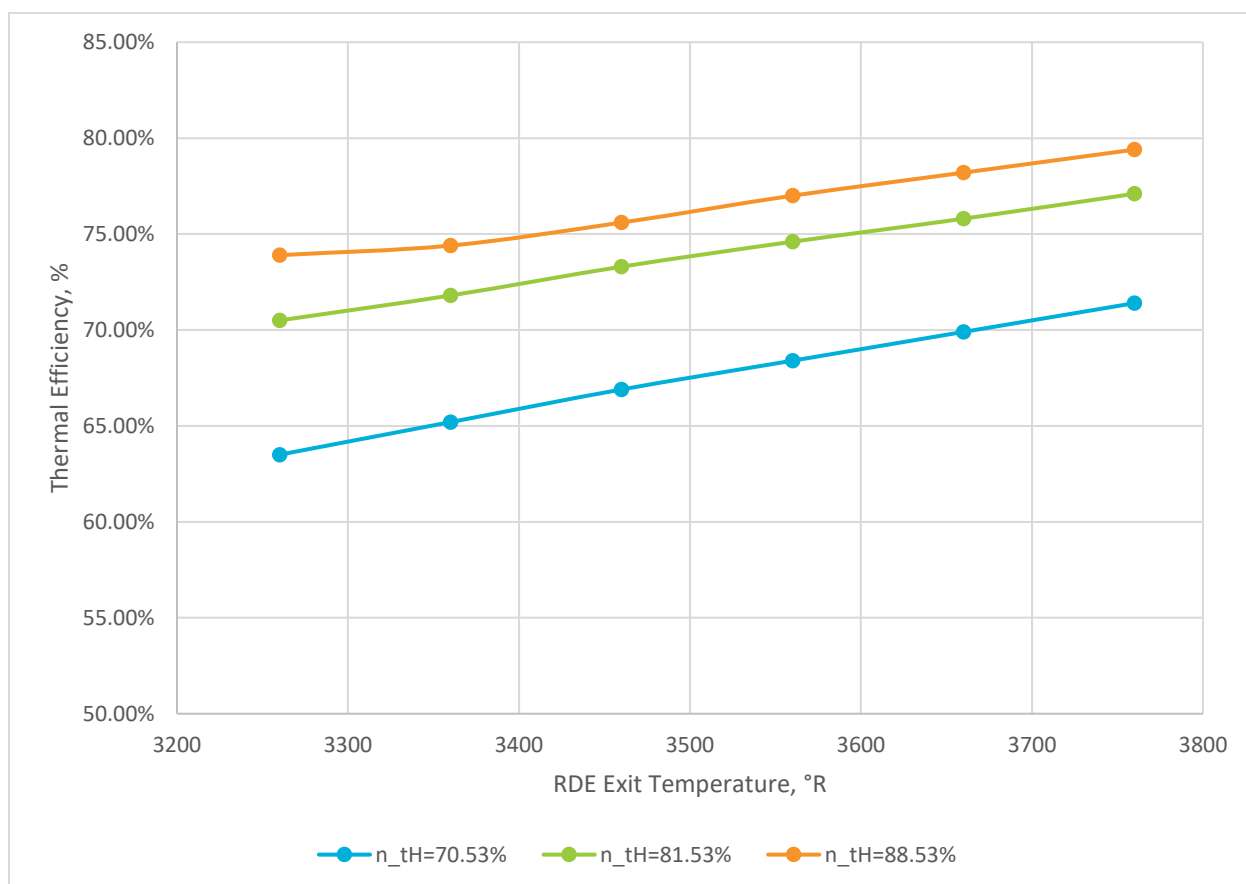
COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-2. RDE-GT pressurization distribution resource comparison for system design

More Compression Comes from Compressor		More Compression Comes from RDE	
Advantages	Disadvantages	Advantages	Disadvantages
Less Pressure Gain from RDE Required	Takes Power from the Turbine	More Power Output	More Pressure Gain from RDE Required
Can Overcome Injector Pressure Losses	Less NGCC Power Output	Higher Efficiency	Lower Wave Heights Required
Less Fuel Consumption	Lower NGCC Efficiency	Less Compressor Power	

If a choice must be made between improving turbine integration or having higher RDE exit temperatures, each path would have certain advantages and disadvantages. Exhibit 6-3 shows that for a fixed RDE exit temperature, increasing the turbine efficiency always provides significant improvement in NGCC efficiency. If the RDE exit temperature or RDE pressure gain is limited, then improving the turbine integration would be the best alternative development path.

Exhibit 6-3. The impact of RDE exit temperature on NGCC LHV efficiency for different turbine isentropic efficiency levels



COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Higher RDE exit temperatures provide the steepest increase in NGCC efficiency; however, the studied exit temperature values might not be attained with single waves and would require lower detonation wave heights and cause more coolant requirements at the by-pass section. For the turbine development path, the main challenges are the requirement of an advanced turbine design and the dependence on the RDE exhaust nozzle performance.

The advantages and disadvantages of selecting to improve turbine efficiency versus increasing the RDE exit temperature are summarized in Exhibit 6-4.

Exhibit 6-4. RDE-GT improvement path comparison for system design

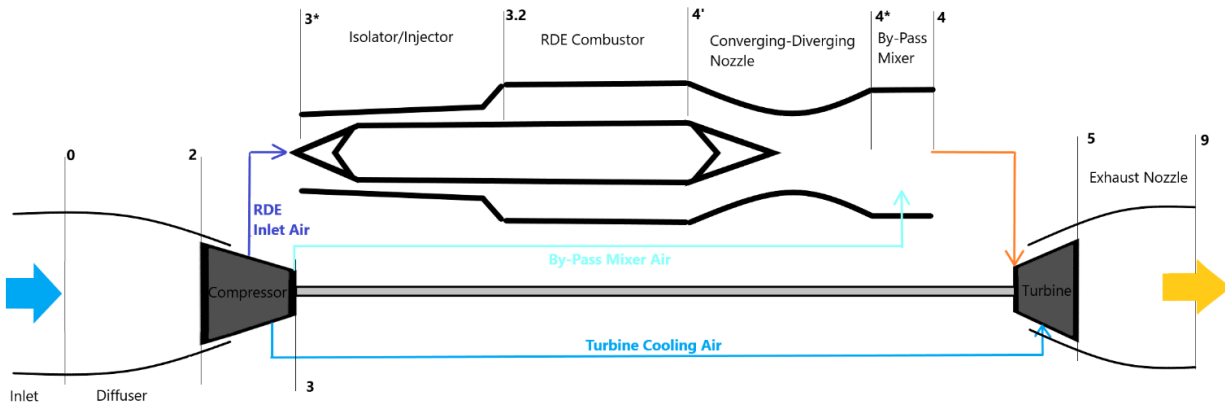
Increasing Turbine Efficiency		Increasing RDE Exit Temperature	
Advantages	Disadvantages	Advantages	Disadvantages
High NGCC Efficiency with Lower Pressure Gain	Requires New Advanced Turbine Design	Higher NGCC Efficiency than Improving Turbine Performance Alone	Might Be Hard to Attain with Single Wave
Less Cooling Requirement	Relies on RDE Nozzle Performance	Small Changes in Pressure Gain Could Give High Gains in NGCC Efficiency	Low Wave Heights Required
Can be Increased with Advanced Nozzles			More Cooling Requirement for Turbine

6.1.2 Feasible RDE-GT System Configurations

The trends observed in the sensitivity analysis show that the GT pressure ratio distribution between the compressor and RDE is very important. Each side has its own advantages and disadvantages and an optimum distribution should be used by considering the turbine integration performance, maximum possible RDE pressure gain, amount of RDE exit temperature increase, and amount of injector pressure loss. Based on the discussed advantages and disadvantages for several development paths in the previous chapter, six different RDE-GT system configurations are identified for techno-economic analysis part of the study. The general configuration of the RDE-GT hybrid engine is shown in Exhibit 6-5.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-5. Engine configuration, components, and engine station numbering for RDE-GT systems



The feasible system configurations are determined with following parameters:

- Compressor Pressure Ratio
- Compressor Isentropic Efficiency
- Injector/Plenum Pressure Loss
- Total Pressure Gain at RDE
- By-Pass Cooling
- Turbine Isentropic Efficiency

Each configuration might represent either a particular stage in the historical development of the RDE-GT system or a preferred technological development path due to having challenges in developing some of the RDE-GT system components.

Case 1: “An RDE-GT System matching Current Level NGCC Efficiency”

This case configuration is determined to provide an NGCC efficiency slightly higher than current systems. The engine has a low-pressure ratio compressor with moderate efficiency and low injector pressure losses. It has very high total pressure gain from the RDE in order to compensate for the low turbine efficiency due to problems in RDE-turbine section integration. The system has no by-pass cooling, so the RDE exit temperature is equal to the turbine inlet temperature. The system configuration parameters are listed in Exhibit 6-6.

Exhibit 6-6. Case 1 RDE-GT system configuration parameters

Parameter	Value
Compressor Pressure Ratio	11.1
Compressor Isentropic Efficiency	92%
Injector/Plenum Loss	-0.5%
RDE Total Pressure Ratio	5.81
RDE Exhaust Temperature	3260 °R

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Parameter	Value
By-Pass Cooling	None
Turbine Isentropic Efficiency	70%
Turbine Inlet Temperature	3260 °R
Turbine Exit Temperature	1610 °R
Turbine Exit Pressure	15.5 psia

Case 2: “Low Loss Turbine Integration and Moderate Pressure Gain”

This case configuration differs from Case 1 with higher turbine efficiency that is closer to the efficiency levels of conventional GTs. In this configuration, RDE exhaust flow is successfully stabilized such that the turbine does not have significant performance reduction and, therefore, has an isentropic efficiency close to conventional GT values. The RDE pressure gain is at a moderate level and injector pressure losses are low. A lower pressure ratio compressor is able to provide the necessary inlet conditions for the RDE to have indicated pressure gain. The system configuration parameters are listed in Exhibit 6-7.

Exhibit 6-7. Case 2 RDE-GT system configuration parameters

Parameter	Value
Compressor Pressure Ratio	8.0
Compressor Isentropic Efficiency	92%
Injector/Plenum Loss	-0.5%
RDE Total Pressure Ratio	3.73
RDE Exhaust Temperature	3260 °R
By-Pass Cooling	None
Turbine Isentropic Efficiency	89%
Turbine Inlet Temperature	3260 °R
Turbine Exit Temperature	1610 °R
Turbine Exit Pressure	15.5 psia

Case 3: “Low Loss Turbine Integration but High Injector/Plenum Losses”

Similar to the previous case in this configuration, the turbine integration to RDE exit flow does not induce significant efficiency reductions in the turbine. However, due to the challenges in injector design the inlet/plenum pressure losses are high. In order to compensate for this loss, a moderate pressure ratio compressor is used. The RDE pressure gain is lower, and the system has no by-pass cooling. The system configuration parameters are listed in Exhibit 6-8.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-8. Case 3 RDE-GT system configuration parameters

Parameter	Value
Compressor Pressure Ratio	11.1
Compressor Isentropic Efficiency	92%
Injector/Plenum Loss	-15%
RDE Total Pressure Ratio	2.12
RDE Exhaust Temperature	3260 °R
By-Pass Cooling	None
Turbine Isentropic Efficiency	89%
Turbine Inlet Temperature	3260 °R
Turbine Exit Temperature	1610 °R
Turbine Exit Pressure	15.5 psia

Case 4: “Limited RDE Pressure Gain and High Exit Temperature RDE”

In this configuration, the maximum RDE pressure gain is limited to be less than two times the inlet pressure due to several challenges in operability and technology development. However, the turbine integration is successful, and injectors do not provide significant pressure loss. To have higher performance, this engine uses high RDE exit temperature with by-pass cooling. A higher-pressure ratio compressor is needed to be used in this configuration to provide necessary pressurization to the turbine. The system configuration parameters are listed in Exhibit 6-9.

Exhibit 6-9. Case 4 RDE-GT system configuration parameters

Parameter	Value
Compressor Pressure Ratio	13.0
Compressor Isentropic Efficiency	92%
Injector/Plenum Loss	-0.5%
RDE Total Pressure Ratio	1.86
RDE Exhaust Temperature	3560 °R
By-Pass Cooling	Yes
Turbine Isentropic Efficiency	89%
Turbine Inlet Temperature	3260 °R
Turbine Exit Temperature	1610 °R
Turbine Exit Pressure	15.5 psia

Case 5: “Limited Maximum RDE Pressure Gain and Advanced Compressor Design”

In this configuration, the maximum pressure gain from the RDE is limited (as in the previous case). The turbine integration success is moderate, which provides the currently expected turbine efficiency values for RDE coupled systems. This engine does not have by-pass cooling to avoid further increase in the compressor power demand. The injector pressure losses are low, and an advanced technology compressor is used to improve the system efficiency. The system configuration parameters are listed in Exhibit 6-10.

Exhibit 6-10. Case 5 RDE-GT system configuration parameters

Parameter	Value
Compressor Pressure Ratio	17.1
Compressor Isentropic Efficiency	94%
Injector/Plenum Loss	-0.5%
RDE Total Pressure Ratio	1.98
RDE Exhaust Temperature	3260 °R
By-Pass Cooling	None
Turbine Isentropic Efficiency	81%
Turbine Inlet Temperature	3260 °R
Turbine Exit Temperature	1610 °R
Turbine Exit Pressure	15.5 psia

Case 6: “High RDE Exit Temperature for High Pressure Gain”

In this configuration, RDE exhaust flow swirl is not fully stabilized by the convergent-divergent nozzle and has a negative impact on the turbine performance. However, the disadvantage of having poor turbine integration is balanced by using high RDE exit temperature for the highest-pressure gain. The injector pressure losses are low and by-pass cooling is provided with a lower range pressure ratio compressor. The system configuration parameters are listed in Exhibit 6-11.

Exhibit 6-11. Case 6 RDE-GT system configuration parameters

Parameter	Value
Compressor Pressure Ratio	11.1
Compressor Isentropic Efficiency	92%
Injector/Plenum Loss	-0.5%
RDE Total Pressure Ratio	5.95
RDE Exhaust Temperature	3560 °R
By-Pass Cooling	Yes
Turbine Isentropic Efficiency	71%

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Parameter	Value
Turbine Inlet Temperature	3260 °R
Turbine Exit Temperature	1610 °R
Turbine Exit Pressure	15.5 psia

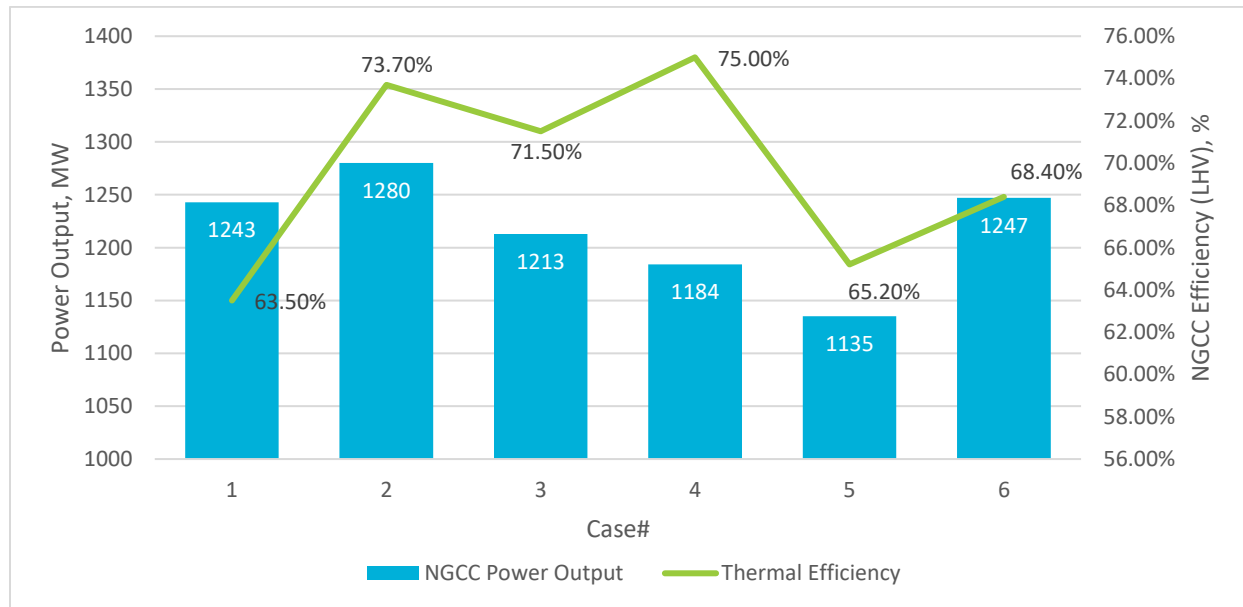
6.2 NGCC PERFORMANCE WITH THE RDE-GT SYSTEM CONFIGURATIONS

The modified NGCC-Sim for PGC-GTs (see Section 5) is used in this part of the study with the RDE-GT system configurations from Section 6.1. The following NGCC performance parameters are selected for the case performance comparisons made in this section:

- Power Plant Net Power Output
- Power Plant LHV Thermal Efficiency
- CO₂ Emissions
- Power Plant LHV Heat Rate
- Balance of Plant (Auxiliary Power)

The performance comparison of each engine scenario is shown in Exhibit 6-12 for the net power output and NGCC efficiency.

Exhibit 6-12. RDE-GT system case configurations plant power output and LHV thermal efficiency comparison



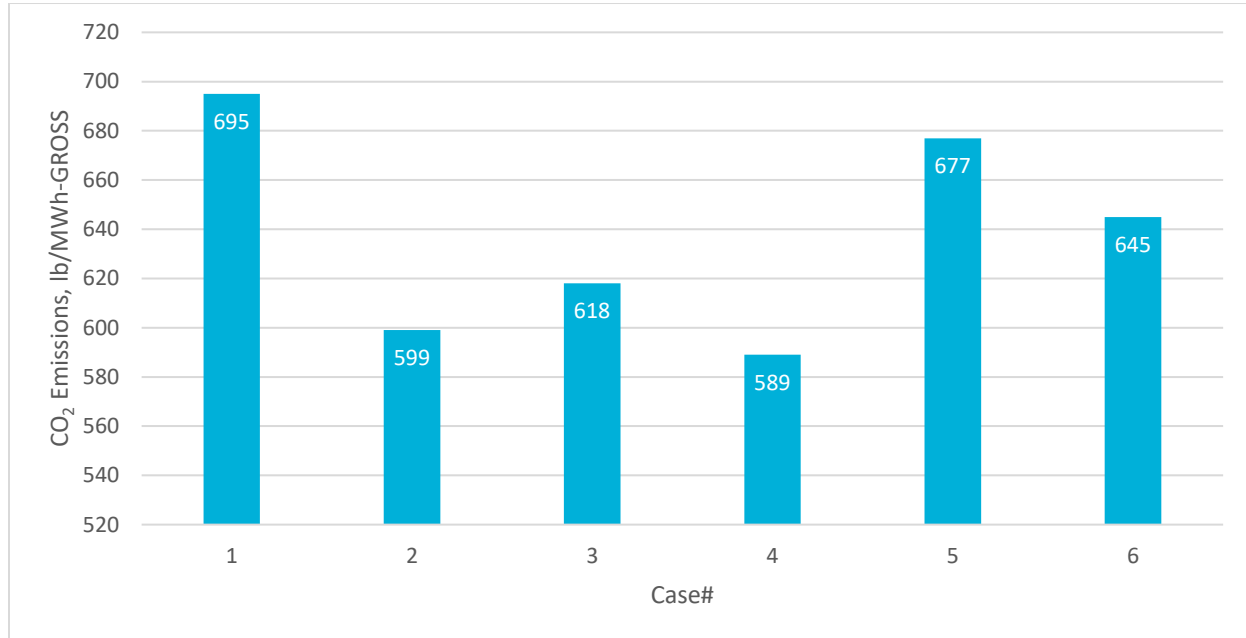
Based on the power output, cases 2 and 6 provided the highest values. Whereas the efficiency is highest for Case 4, followed by Case 2, and Case 3. Although Case 3 had the highest injector pressure losses, increased RDE pressure gain and compressor pressure ratio is enough to compensate for the losses. Following results can be deduced from the analysis:

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

- The highest power output cases are the ones with moderate to high RDE pressure gains
- The highest efficiency cases have the highest turbine efficiency values in common
- If the RDE pressure gain is low, having higher exit temperature provided significant advantage

The power plant CO₂ emissions are compared in Exhibit 6-13. The calculation method of the emissions is detailed in the NETL NGCC Performance Baseline Report. [14]

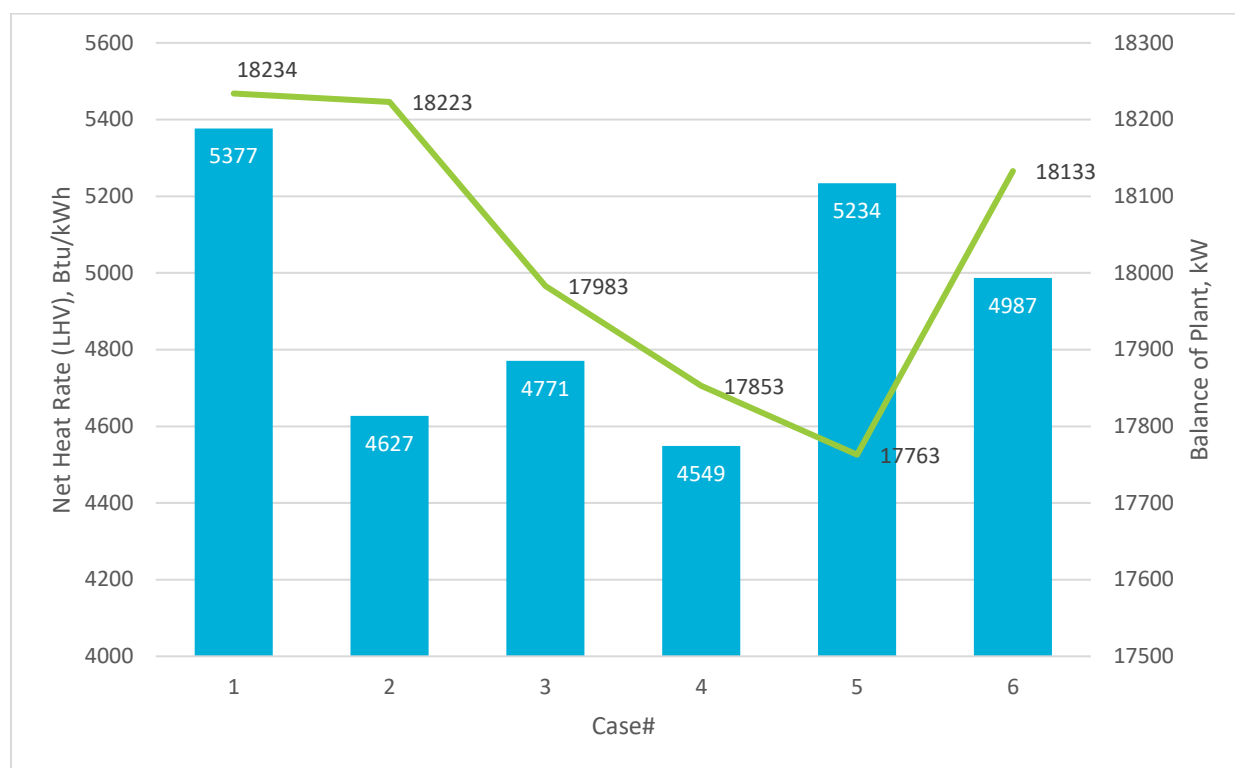
Exhibit 6-13. RDE-GT system case configurations CO₂ emissions comparison



The emission rates are directly proportional to the fuel consumption at the RDE, which is the highest for Case 1 and Case 5. The power plant net heat rate rankings are also proportional with the fuel consumption and are shown in Exhibit 6-14.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-14. RDE-GT system case configurations LHV heat rate and balance of plant load comparison



Balance of plant loads are higher for the cases with higher power output. The calculation methods for the balance of plant loads are assumed to be the same with a conventional NGCC plant [14] due to not changing the GT exhaust conditions (therefore causing minimum to no change in the steam cycle components) from the conventional GT exhaust conditions.

A summary of the NGCC performance from each RDE-GT case configuration is shown in Exhibit 6-15.

Exhibit 6-15. NGCC performance parameters comparison for each RDE-GT configuration case

Parameter	Unit	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
$\Pi_{\text{Compressor}}$	-	11.1	8.0	11.1	13.0	17.1	11.1
$\eta_{\text{Compressor}}$	-	92%	92%	92%	92%	94%	92%
$P_{t,\text{loss (inj./plenum)}}$	-	-0.5%	-0.5%	-15%	-0.5%	-0.5%	-0.5%
Π_{RDE}	-	5.81	3.73	2.12	1.8	1.9	5.96
T_{t4^*}	°R	3260	3260	3260	3560	3260	3560
η_{Turbine}	-	70%	89%	89%	89%	81%	70%
T_{t9}	°R	1610					
P_{t9}	psia	15.5					

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Parameter	Unit	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
NGCC Power (net)	MW	1243	1280	1213	1184	1135	1247
NGCC Heat Rate (LHV)	Btu/kWh	5377	4627	4771	4549	5234	4987
NGCC Thermal Eff. (LHV)	%	63.5%	73.7%	71.5%	75.0%	65.2%	68.4%
CO ₂ Emissions	lbm/MWh-gross	695	599	618	589	677	645
Balance of Plant Aux.	kW	18234	18223	17983	17853	17763	18133

6.3 TECHNO-ECONOMIC ANALYSIS FOR THE NGCC PLANTS WITH RDE-GT SYSTEM CONFIGURATIONS

The biggest challenge in performing techno-economic analysis for an NGCC power plant with RDE-GT system is determining the capital costs of the RDE section and subsequently calculating the capital cost of the RDE-GT system. Once the RDE-GT system capital cost is determined, conventional NGCC cost estimation methods, such as QGESS methodology [50], can easily be used to obtain owner's costs, operating costs, and COE.

6.3.1 Determination of RDE-GT System Capital Cost

6.3.1.1 RDE Capital Cost

6.3.1.1.1 Methodology

As of the time of performing techno-economic analysis for RDE-GT systems, the literature on RDE cost estimates is scarce due to low TRL. However, RDEs are very similar to ramjets in terms of the type of the components used. Therefore, cost estimation methods developed for ramjets could be used with several modifications and safety factors to determine RDE capital costs.

Ramjets are used extensively in long range cruise missiles and hypersonic aircrafts today; in the 1970s, ramjets were at a similar TRL as RDEs of today. In 1977, the Air Force Aero Propulsion Laboratory conducted a cost estimation study for this technology to assess possible impacts on missile development costs. [16, 17] The cost calculation methodology is primarily based on the price quotes taken from different vendors for predetermined ramjet parts and generating formulas from these data.

The ramjet study considered eight different possible ramjet-rocket configuration alternatives, each determined by changing the fuel type and the integration of the ramjet section to the missile body. The cost calculations of the "podded" configuration, where the ramjet section is separate from the missile body and attached with a pylon, has separate cost estimation for the ramjet booster and the missile parts. In this particular configuration, the costs of the ramjet booster are calculated separately from the missile and the missile specific components in the ramjet part are very low. Standard manufacturing techniques such as rolling, welding, casting, etc., are assumed for related costs, but different manufacturing methods (i.e., additive manufacturing) can also be used if its learning curves and standard hours are known.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

The method assumes the cost of a part comprises the shown items in Exhibit 6-16, where the direct costs are related to the manufacturing of the part and the indirect costs are related to the labor spent to manufacture it.

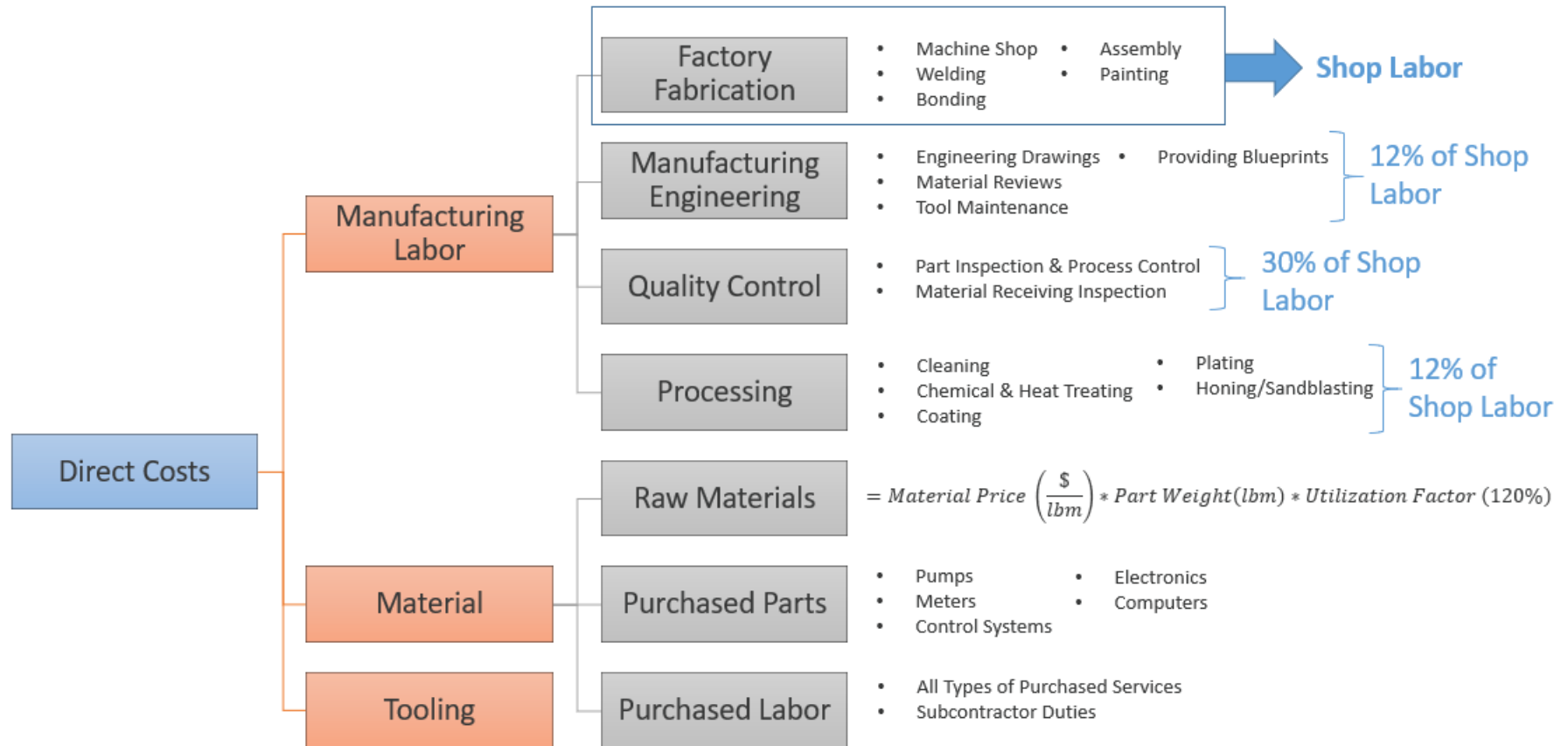
Exhibit 6-16. Part cost component assumptions of the capital cost estimation methodology

	Direct	Indirect
Non-Recurring	Design	Labor Overhead
	Development	Material Overhead
	Test	General & Administrative
	Production Tooling	
Recurring	Manufacturing Labor	Labor Overhead
	Materials	Material Overhead
	Support Services	General & Administrative

According to the method, the biggest cost components (production tooling, manufacturing labor, and materials) already include other direct costs in them. In the method, quoted costs are used to generate the cost estimation formulas for these items. The indirect costs (for both non-recurring and recurring), however, are applied as fixed percentages to calculated direct cost components.

The direct cost components used in the cost estimation are divided into the subcategories shown in Exhibit 6-17. Manufacturing labor costs are the costs related to manhours spent manufacturing the part; material cost is the cost related to raw materials used for the part or the purchase price of the part if the part is not manufactured. Tooling costs are the costs related to developing tools to manufacture the part.

Exhibit 6-17. Capital cost estimation methodology direct cost item breakdown



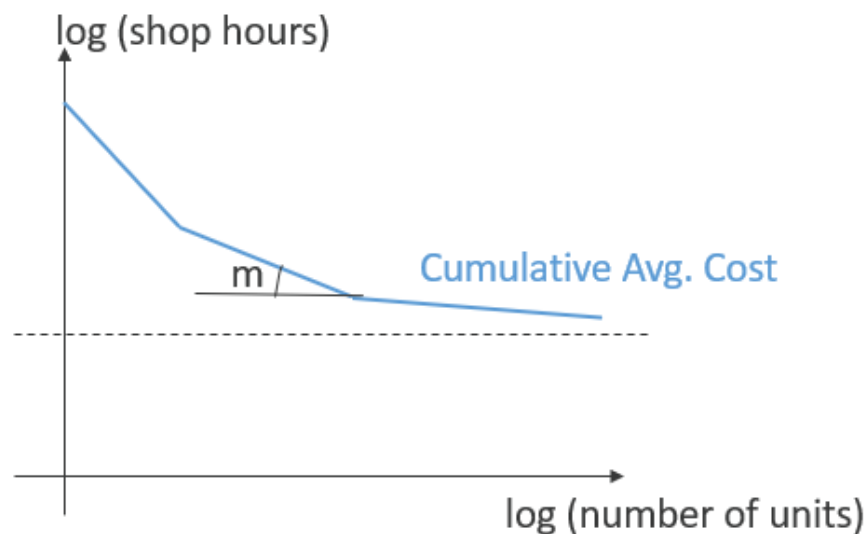
COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

The calculated single part cost is then used to determine the serial production part cost, which is done by using manufacturing improvement curves for the particular type of traditional manufacturing method used to manufacture the part. Improvement curves are historically developed by using the following data:

- Shop Production Cost Data
- Allowances for Operator Familiarity with the Job
- Engineering Changes
- Lot Size Changes
- Tool Adjustments
- Give and Receive Instructions
- Work Stoppage

The manufacturing improvement curves provide the required shop hours for the part for a variety of production rates and are typically represented as log-log charts. An illustration of a typical improvement curve is shown in Exhibit 6-18.

Exhibit 6-18. Typical manufacturing improvement curve and definitions



The slope of the manufacturing improvement curves is different for a different number of production units. Typical values for traditional manufacturing methods are provided in Exhibit 6-19.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM
PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-19. Manufacturing improvement curve slopes for traditional manufacturing techniques

# of Units Produced	m (Improvement Slope)
1–5	85%
6–100	80%
101–600	88%
601–2000	95%
2001–∞	98%

The method assumes the baseline part cost can be divided into three total direct cost components:

1. Tooling Cost
2. Material Cost
3. Manufacturing Cost

The method uses the general formula in

Equation 6-1 to compute the baseline cost of the part, which is the cost that is later adjusted by the production scale, inflation, design changes, and several other factors.

$$\text{Baseline Part Cost} = \sum_n^{\text{tooling, mat., mfg.}} (\text{Total Direct Cost})_n * \left(1 + \frac{\text{General \& Administrative}\%}{100}\right) * \left(1 + \frac{\text{Fee}\%}{100}\right)$$

Equation 6-1

Baseline cost is calculated for each cost component where the general and administrative charges and fees are applied as 24 percent and 10 percent, respectively. The general and administrative and fee percentages are used from standards for aerospace manufacturing. The overall part baseline cost is the sum of all the cost components.

1. **Tooling Cost:** This total direct cost item includes costs for the tool fabrication for part production and all non-recurring costs by subcontractors. For the ramjet method, these cost formulas are obtained from curve-fits to various quotes taken from candidate manufacturers for each part. If this is a purchased part, this cost does not exist because it is assumed that it is already included in the part purchase price. This total direct cost item is calculated by using Equation 6-2.

$$(\text{Total Direct Cost})_{\text{tooling}} = \left(\begin{array}{c} \text{Non-recurring} \\ \text{costs} \\ \text{by subcontractors} \\ \text{+ Material Costs} \\ \text{for} \\ \text{Tool Fabrication} \end{array} \right) * \left(1 + \frac{\text{Material Overhead}\%}{100}\right) + \left(\begin{array}{c} \text{Manf.} \\ \text{Eng.} \\ \text{Labor} \end{array} \right) * \left(\begin{array}{c} \text{Manf.} \\ \text{Eng. Hourly} \\ \text{Rate} \end{array} \right) * \left(1 + \frac{\text{Manufacturing Overhead}\%}{100}\right)$$

Equation 6-2

The following items in Equation 6-2 should be multiplied with inflation factor for cost estimation years other than 1976:

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- Non-recurring costs by subcontractors
- Material Costs for Tool Fabrication

The following items in Equation 6-2 should be replaced by current year rates for cost estimation years other than 1976:

- Manufacturing Engineering Hourly Rate

Material and Manufacturing Overhead factors are applied as fixed percentages, which are 8 percent and 140 percent, respectively.

- 2. Material Cost:** This total direct cost item includes the raw material cost plus any additional material for cut-off allowances, scrap, defect, or spoiled material. The additional material allowance for each part is assumed to be 20 percent, that is covered with a utilization factor. If the part is purchased and not manufactured, which is the case for electronics, coating, and wiring, then this cost item is directly replaced by the purchase price of the part. This total direct cost item is calculated by using Equation 6-3.

$$(Total\ Direct\ Cost)_{material} = \left(\frac{\text{Material Price} \left(\frac{\$}{lbm} \right) * \text{Part Weight} (lbm) * \text{Utilization Factor}}{\text{Material Price} \left(\frac{\$}{lbm} \right) * \text{Part Weight} (lbm) * \text{Utilization Factor}} \right) * \left(1 + \frac{\text{Mat. Overhd}\%}{100} \right) * \left(1 + \frac{\text{Shipping}\%}{100} \right) + \left(\frac{\text{Mat. Handling Labor}}{\text{Hdlg. Hourly Rate}} \right) * \left(\frac{\text{Mat. Hdlg. Hourly Rate}}{\text{Hdlg. Hourly Rate}} \right) * \left(1 + \frac{\text{Manf. Overhd.}\%}{100} \right)$$

Equation 6-3

The following items in Equation 6-3 should be replaced by current year rates for cost estimation years other than 1976:

- Material Price
- Material Handling Hourly Rate

The following items in Equation 6-3 should be scaled if the part size is different than the sizes used in the baseline methodology:

- Part Weight

In the cost calculation, the utilization factor is used as 120 percent, shipping fee percentage is used as 1 percent, material overhead factor is used as 8 percent and manufacturing overhead factor is used as 140 percent.

- 3. Manufacturing Cost:** This total direct cost item comprises labor hours spent for producing the part and is calculated using Equation 6-4. The shop labor hours are specific to the particular manufacturing method used to produce the part; manufacturing engineering and quality labor hours are then calculated as 12 percent and 30 percent of the shop labor hours, respectively.

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$$(Total\ Direct\ Cost)_{mfg} = \left\{ \left(\frac{Shop}{Labor} \times \frac{Shop}{Rate} \right) + \left(\frac{Mfg.\ Eng.}{Labor} \times \frac{Mfg.\ Eng.}{Rate} \right) + \left(\frac{Quality}{Labor} \times \frac{Quality}{Rate} \right) \right\} * \left(1 + \frac{Manf.\ Overhead\%}{100} \right)$$

Equation 6-4

The following items in Equation 6-4 should be replaced by current year rates for cost estimation years other than 1976:

- Shop Labor Rate
- Manufacturing Engineering Labor Rate
- Quality Labor Rate

In the cost calculation, manufacturing overhead cost factor is used as 140 percent.

The cost methodology provides scaling allowance from reference part values for the following features:

- Part Size (diameter and length)
- Part Design Complexity (with respect to reference parts)
- Production Quantity (1–5000 units/project period)
- Production Rate (1–80 units/month)
- Year of Production (1976 to any year)
- Materials (steels and nickel alloys)
- Labor Rates

Scaling uses scaling factors that are multiplied with the direct cost values calculated with Equation 6-2 through Equation 6-4.

6.3.1.1.2 Application of the Method to RDE Capital Cost Calculation

A spreadsheet for calculating the ramjet reference part costs was developed in this study to automate the process and allow for future modifications to the method. The spreadsheet shown in Exhibit 6-20 is for the inlet section of the ramjet, where the yellow cells indicate the required user inputs.

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Exhibit 6-20. Developed spreadsheets for RDE part cost calculation

COMPONENT ID NO:	A-1-7					NO OF ENGINES REQ'D	20	TOTAL COMPONENTS REQ'D	20	
COMPONENT DESCRIPTION:	AXISYMMETRIC PODDED INLET ASSY.-CAST/SHEET METAL CONSTRUCTION					ASSUMED PRODUCTION	5 YEARS;	MID-YEAR	2035	
BASLINE COST COMPONENT SIZE:	D=	72	IN ²	L=	IN	ASSUMED INFLATION FACTOR	4.917557154			
SELECTED COMPONENT OPTION						COMPONENT PRODUCTION RATE	0.333			
SELECTED COMPONENT SIZE	D=	13.4	IN ²	L=	IN	TOOLING RATE FACTOR	1			
NO OF COMP'S REQ'D PER ENGINE	1					SPECIAL FACTORS				
BASELINE COST PER INLET	OPTIONS					SELECTED MATERIAL OPTION	17-4 STAINLESS STEEL			
	17-4 STAINLESS STEEL		4130 STEEL	INCONEL-718		QUANTITY FACTOR CURVES	QUANTITY FACTOR	COMPUTED SIZE FACTOR	OTHER FACTORS	
TOOLING	\$58,543		\$66,860	\$58,543		T-1	1.013	0.409	1	
MATERIALS	\$1,728		\$2,215	\$3,391		MT-1	17.005	0.178	1	
MANUFACTURING	\$4,428		\$4,497	\$13,785		MF-1	11.897	0.695	1	
SIZE FACTOR COST ELEMENT	SIZE FACTOR COEFFICIENTS									
	17-4 STAINLESS STEEL			4130 STEEL			INCONEL-718			DESIGN COMPLEXITY
	A01	A02	A03	A01	A02	A03	A01	A02	A03	1.5
TOOLING	0.23445	0.013603	-0.00004047	0.22096	0.014027	-0.00004445	0.32894	0.011333	-0.00002801	
MATERIALS	0.10534	0.0038026	0.00012189	0.10534	0.0038026	0.00012189	0.10534	0.0038026	0.00012189	
MANUFACTURING	0.65744	0.0023628	0.00003398	0.63611	0.0024046	0.00003679	0.65107	0.0023878	0.00003414	
SIZE FACTOR EQUATION: SF=A01+ {A02}D +{A03}D ² WHERE D= CAPTURE AREA OF INLET										
TOOLING COST										
TOOLING										
BASELINE COST*		SIZE FACTOR*	QUANTITY FACTOR*	RATE FACTOR*	# PER ENGINE*	OTHER FACTORS	=TOTAL TOOL COST			
\$58,543.00		0.409	1.013	1	1	1.5	\$36,439			
MATERIALS COST										
BASELINE COST*		SIZE FACTOR*	QUANTITY FACTOR*		# PER ENGINE*	OTHER FACTORS	=TOTAL MAT COST			
\$1,728.00		0.178	17.005		1	1.5	\$7,854			
MANUFACTURING COST										
BASELINE COST*		SIZE FACTOR*	QUANTITY FACTOR*		# PER ENGINE*	OTHER FACTORS	=TOTAL MAT COST			
\$4,428.00		0.695	11.897		1	1.797	\$65,814			
TOTAL COST PER ENGINE						\$110,107				

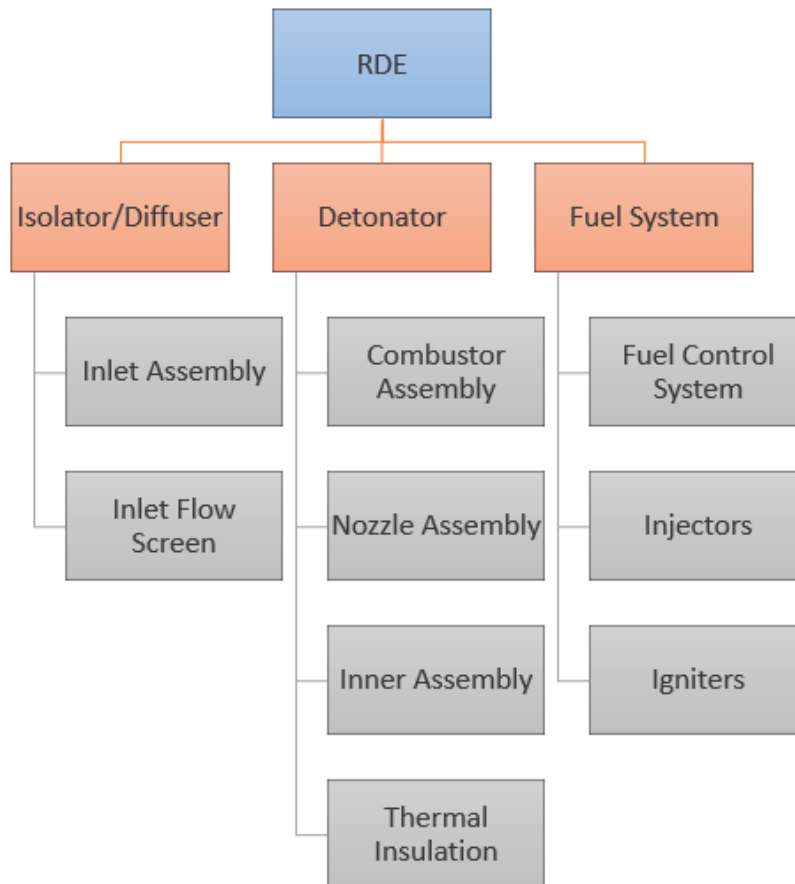
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The required user inputs are listed as follows:

- The critical dimensions of the component for size scaling
- Number of components required for each engine
- Number of engines that will be produced in total
- Duration of the production
- Production year
- Material type
- Design complexity with respect to reference ramjet part
- Other special factors for scaling

After validating the developed spreadsheet with example scenarios for the ramjet method, the RDE part costs were calculated. The first step in determining the RDE cost is to develop the work breakdown structure (WBS) of the RDE. The WBS diagram in Exhibit 6-21 is used in determining the RDE part cost, where each item has a corresponding ramjet part in the reference ramjet method presented in Section 6.3.1.1.1.

Exhibit 6-21. Work breakdown structure used for RDE capital cost calculation



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The modifications to the ramjet cost sheets made for calculating RDE part costs are listed in Exhibit 6-22.

Exhibit 6-22. Changes made to baseline Ramjet part cost sheets used for each RDE WBS element

Component	Resource for Baseline Cost	Modifications
Inlet Assembly	Ramjet Study by AFAPL [16, 17]	Dimensions and Materials
Inlet Flow Grid	Ramjet Study by AFAPL [16, 17]	Dimensions and Materials
Combustor Assembly	Ramjet Study by AFAPL [16, 17]	Dimensions and Materials
Thermal Insulation	TBC Coating Prices [52]	Insulation Material changed to TBC
Nozzle Assembly	Ramjet Study by AFAPL [16, 17]	Dimensions and Materials
Igniters	Ramjet Study by AFAPL [16, 17]	Quantity, Ignition Frequency
Fuel Control System	GE Mark VI-e Fuel Control System [53]	Design Complexity Factor
Injectors	Ramjet Study by AFAPL [16, 17]	Modified to include the entire inner assembly and all injectors and Dimensions and Materials

The igniters are assumed to be typical ramjet igniters with the ignition frequency that matches the RDE; fuel control system cost is obtained for GE Mark VI system cost, which is one of the systems used in current H-Class GTs and later scaled with design complexity from a typical combustor to RDE. The injector cost in the ramjet method also includes the inner assembly, but the part cost is modified here to include the aerospike nozzle.

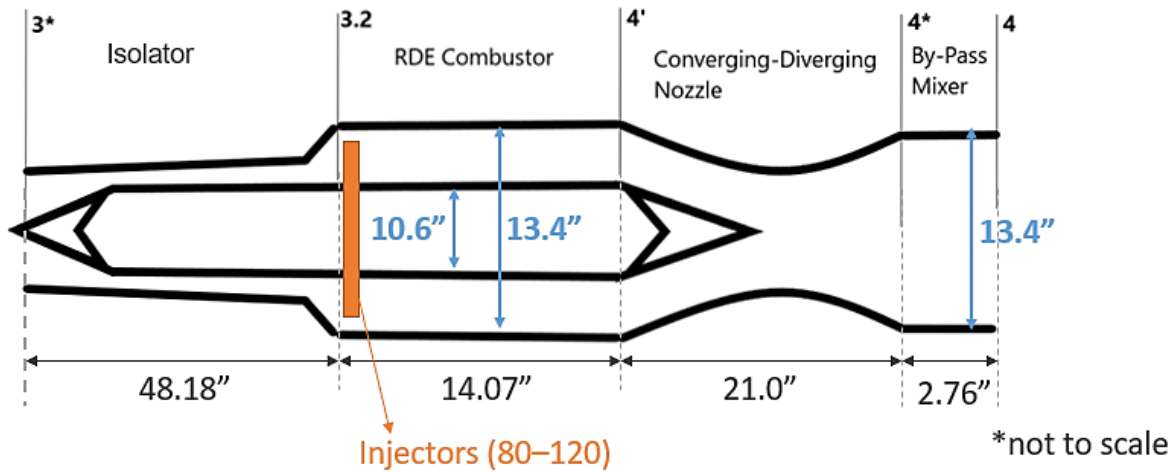
The specifics of the modifications are given in the following subsections.

6.3.1.1.2.1 RDE Dimensions

The sizes of the RDE sub-components used in the cost calculation are obtained from the test rig configurations used by Aerojet-Rocketdyne [49], Purdue University [54], University of Michigan [55], and NETL. [24] The lengths are scaled for the RDE diameter used by Aerojet-Rocketdyne for H-Class GT integration. Wall thickness of casings are scaled from NETL test rig [24] set-ups. The overall dimensions of the RDE configuration used in cost analysis are shown in Exhibit 6-23.

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Exhibit 6-23. RDE dimensions and specifications used in capital cost calculation



6.3.1.1.2.2 Materials

The materials used in the reference ramjet method are different than the typical combustor materials used in GTs, due to the differences in the cooling needs and the way of cooling the components. Steels are typically used in ramjets due to their low cost and their ability to be cooled by convection during the flight. For RDE production, typical GT combustor materials are selected from GT materials databases [56, 57, 58] by using their creep rupture strengths and service temperatures.

Selected materials for RDE production are nickel alloys that satisfies the following criteria:

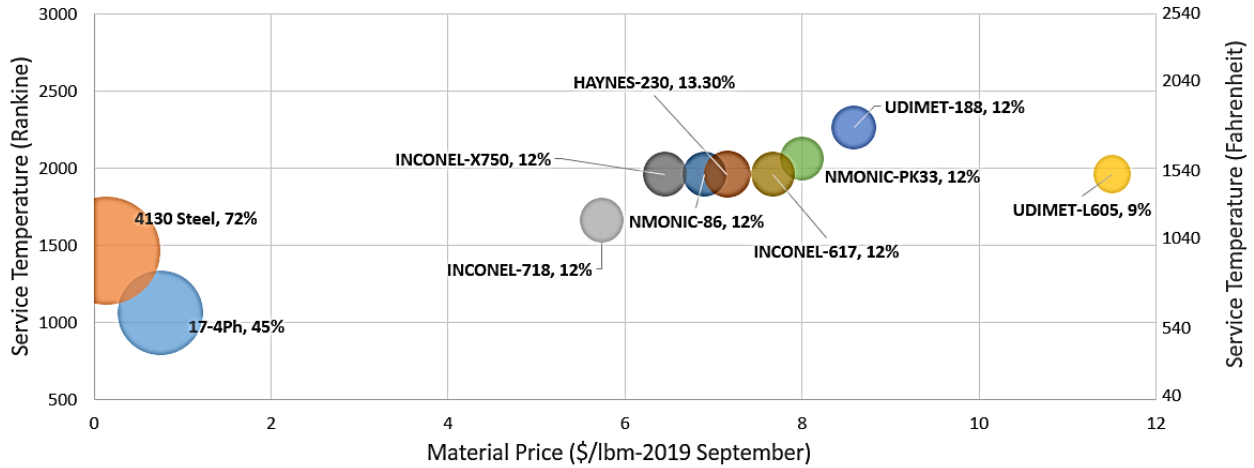
- 1000h creep rupture strength values greater than 15000 psi for the sheet form of the material
- Service temperatures are greater than 1500 °F

RDE temperatures for the GT scale are expected to change between 2430–3560 °R (2000–3100 °F). For the RDE temperature ranges of this study, all selected materials will require wall cooling and thermal barrier coating (TBC).

Possible RDE manufacturing materials are shown in Exhibit 6-24, which shows the material cost per lbm with respect to its service temperatures. The bubble sizes in the chart indicate the machinability index of each material, which is used to scale the tooling and manufacturing costs when these new materials are selected over the baseline materials of the ramjet method (4130 Steel, 17-4Ph and INCONEL-718). The material options are used to find the minimum and maximum of the RDE costs. Material costs are obtained for September 2019 from open literature.

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Exhibit 6-24. RDE part building material costs, service temperatures, and machinability indexes



6.3.1.1.2.3 Thermal Barrier Coating

The working temperatures of the RDE cases in this study would require the detonator and nozzle section inner walls to be coated. Typical TBC type applied to GT combustor liners are varieties of yttria stabilized zirconia (YSZ). The varieties of YSZ are usually determined by the molar fraction of Y_2O_3 and grade. The ZrO_2 doped with 7–8 mole percent Y_2O_3 is the typical YSZ type used in the TBCs of GT combustor liners. [59]

The reference method uses DC-93-104 thermal insulation material and includes a cost sheet for the thermal insulation that includes the costs related to the application of the layer. The adaptation of the cost calculation method requires modifying the thermal insulation material related costs of the ramjet method to the TBC application. Therefore, the TBC material cost needs to be known to update the thermal insulation cost sheet accordingly. The cost of the TBC materials changes with the type of YSZ, its grade, and the application thickness.

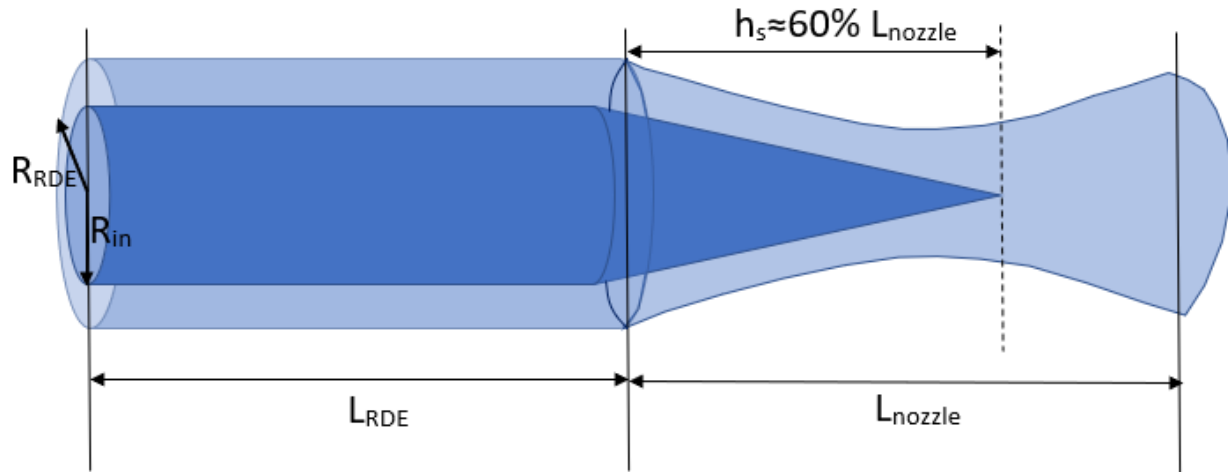
To calculate the relative cost difference of TBC from DC-93-104 insulation material, the amount of coating material needed for the RDE should be calculated. The amount of coating material needed for RDE can be found by using Equation 6-5.

$$m_{coating} = V_{coating} \rho_{coating} = (A_{coating} t_{coating}) \rho_{coating} \quad \text{Equation 6-5}$$

In Equation 6-5, the coating thickness, $t_{coating}$, is typically 0.01–0.015 inch for GT combustor liners. [60, 61] The coating material density, $\rho_{coating}$, is around 0.2204 lbm/in³ for ZrO_2 doped with 8 mole percent Y_2O_3 type YSZ material. [63] $A_{coating}$ is the surface area inside the RDE that must be coated. Based on the temperature data calculated with PGC-Sim (from Section 3) and with the dimensions from Exhibit 6-20, the TBC application area is determined. The total coating surface area is parametrized with Equation 6-6 with the dimension parameters shown in Exhibit 6-25.

$$A_{coating} \approx 2\pi R_{RDE}(L_{RDE} + L_{nozzle}) + \pi R_{in}(2L_{RDE} + \sqrt{h_s^2 + R_{in}^2}) \quad \text{Equation 6-6}$$

Exhibit 6-25. RDE TBC application area



The average height of the aerospike nozzle (the conical structure extends from RDE inner body to the converging-diverging nozzle) is obtained from NETL [24], Aerojet-Rocketdyne [49], and Purdue University [54] test setups and scaled to the RDE dimensions of Exhibit 6-20.

Then the costs for ZrO_2 doped with 8 mole percent Y_2O_3 type YSZ material in nano powder form (30-60 μm application thickness) (\$114/lbm [52]) and DC-93-104 thermal insulation material (\$130/lbm [62]) are used to calculate the total coating cost for the area shown in Exhibit 6-23. The relative difference between two costs is then used to scale the thermal insulation material cost sheet.

6.3.1.1.2.4 Changes Made in Labor Rates, Inflation, Production Quantity, and Labor Hours

The labor rates of the reference method [16] are updated with the U.S. Department of Labor (DOL) [63], Department of Defense (DoD) [57], and Chemical Engineering Index (CEI) data [64] for the RDE part cost calculation. The labor rates of the original method are compared with the rates used in the calculations compared in Exhibit 6-26.

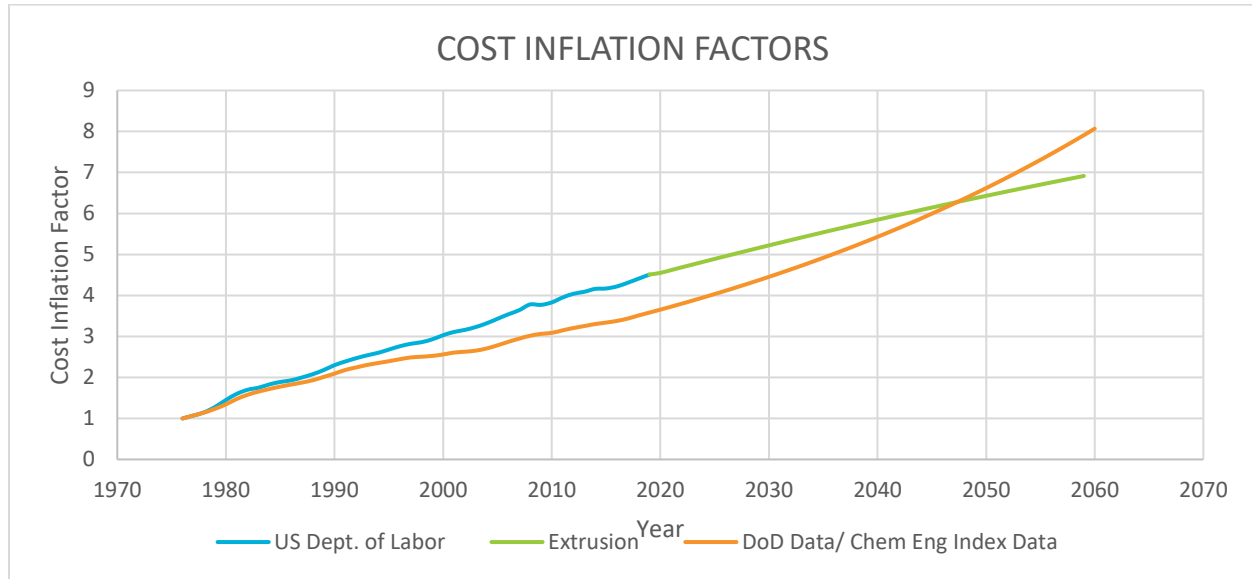
Exhibit 6-26. Labor rates used for scaling from 1976 rates of the base method

Labor Rate	1976 [16]	2019 [63]
Shop	\$7.04/hr	\$26.38/hr
Manufacturing Engineering	\$9.89/hr	\$39.48/hr
Quality and Inspection	\$7.73/hr	\$28.46/hr
Materials Handling	\$6.69/hr	\$24.79/hr

The cost inflation factors used to update the cost calculations for each cost spreadsheet of RDE parts are calculated using U.S. DOL [63], DoD [57], and CEI data. [64] Curve fits to the inflation factor from 1976 to 2060 are used in the spreadsheets, by using the data plotted in Exhibit 6-27.

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Exhibit 6-27. Cost inflation factor data from 1976 to 2060 used in the cost spreadsheets



The quantity factor formulations are scaled to match typical GT production rates, which are much less than the production rates for the missiles that is as much as 400 units per year for the ramjet methodology. [65] The current H-Class GT production rate is obtained from open literature [66], which is ~15 engines per year for a single manufacturer.

All manufacturing labor hours are scaled with the machinability index of the listed RDE materials in Exhibit 6-28, with respect to INCONEL-718 index.

Exhibit 6-28. Machinability index used for labor hour scaling

Material	Machinability Index [65, 58]
17-4Ph Steel	45%
4130 Stainless Steel	72%
INCONEL-718	12%
UDIMET-L605	9%
UDIMET-188	12%
NMONIC-PK33	12%
NMONIC-86	12%
HAYNES-230	13.3%
INCONEL-X750	12%
INCONEL-617	12%

6.3.1.1.3 Results

With the indicated modifications to part cost calculation methods, the total RDE cost is calculated by summing up the sub-component costs for the inlet, RDE combustor and nozzle

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section, fuel control system and inner assembly, and final assembly cost that includes the listed cost items in Exhibit 6-29. The RDE cost shown in Exhibit 6-29 is for a case that uses 17-4Ph Steel for the inlet and UDIMET-188 for the RDE and nozzle sections. Estimated production start year is 2035 and production rate is assumed to be four engines per year. The total cost is then calculated to be around 18 million dollars for RDE.

Exhibit 6-29. RDE cost results with 17-4Ph steel used at inlet and UDIMET-188 used for other RDE components

AIR INDUCTION SYSTEM		
COMPONENT NAME	SUB-ASSEMBLY	COMPONENT PRICE
INLET ASSEMBLY	AXISYMMETRIC PODDED INLET ASSY- CAST/SHEET METAL CONSTRUCTION	\$394,422
INLET OPTIONS	CIRCULAR AERODYNAMIC GRID	\$46,670
TOTAL FOR AIR INDUCTION SYSTEM		\$441,092
COMBUSTOR		
COMPONENT NAME	SUB-ASSEMBLY	COMPONENT PRICE
COMBUSTION CHAMBER	RDE OUTER WALLS-ROLL & WELD CONSTRUCTION	\$816,148
NOZZLE	RDE NOZZLE SECTION METALLIC CONSTRUCTION	\$2,324,735
IGNITERS	RAMJET IGNITERS ASSUMED	\$2,730,065
COMBUSTOR OPTIONS	TBC OF RDE AND NOZZLE	\$1,585,007
TOTAL FOR COMBUSTOR		\$7,455,956
FUEL SYSTEM		
COMPONENT NAME	SUB-ASSEMBLY	COMPONENT PRICE
FUEL CONTROL SYSTEM	MARK VI-E ELECTRONIC FUEL CONTROL	\$6,721,283
MANIFOLDS/INJECTORS	INCLUDES RDE INJECTORS, INNER BODY AND AEROSPIKE NOZZLE	\$2,103,500
TOTAL FOR FUEL SYSTEM		\$8,824,783
E-3 FINAL ASSEMBLY		\$1,061,736
TOTAL RDE SYSTEM COST (in 2019-\$)		\$17,783,567

The cost range of RDE is calculated by varying the material options for the inlet and RDE-nozzle sections. The minimum and maximum RDE costs are obtained with the material combinations shown in Exhibit 6-30.

Exhibit 6-30. Material combinations for minimum and maximum calculated costs for RDE

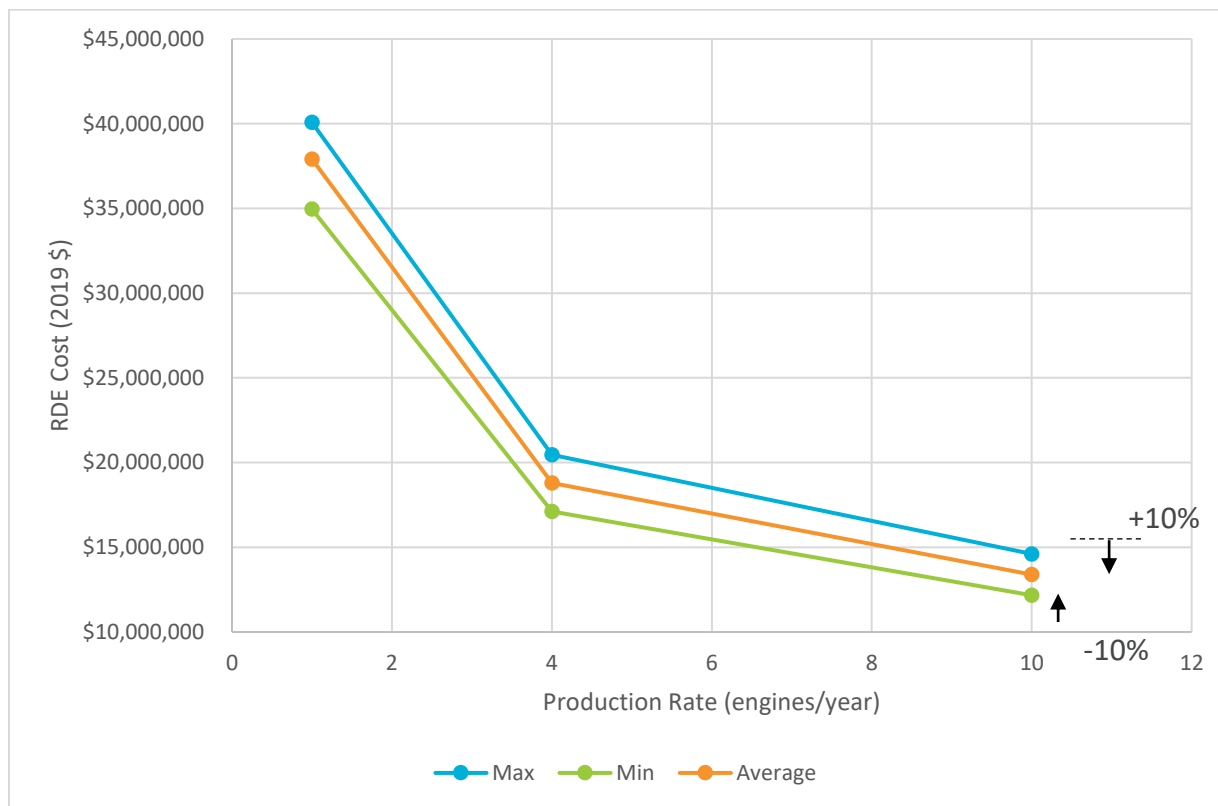
	RDE and Nozzle Material	Inlet Assembly
Min Price	HAYNES-230	17-4Ph Steel
Max Price	UDIMET L-605	INCONEL-718

The total RDE cost is different for different production rates. If the RDE-GT production rate is higher than four units per year then the RDE capital cost decreases and it increases if the production rate is lower than four units per year. All possible material combinations for the

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inlet, RDE, and nozzle assembly are used to obtain the average RDE capital cost shown in Exhibit 6-31.

Exhibit 6-31. RDE cost limits for different production rates



The average cost is calculated to be within 10 percent for all production rate cases. Average RDE capital cost for 4 engines per year production rate (\$18,786,678) is used in determining the RDE-GT system capital cost.

6.3.1.2 RDE-GT System Capital Cost

RDE cost is the biggest and the most important unknown for the capital cost estimation of the integrated RDE-GT system. The turbine section of the studied system is assumed to be exactly the same with a conventional H-Class GT, in order to minimize the overall design efforts and reduce the system development costs. In all RDE-GT configurations, the compressor has a lower pressure ratio than for an H-Class engine due to having the RDE as the secondary pressurization source; therefore, it would have fewer stages and less cost than the H-Class counterpart. The compressor cost is scaled from typical H-Class compressor component cost; the turbine cost is the same as the H-Class turbine component cost. Combustor cost is replaced with the RDE cost.

The RDE-GT system cost calculation uses Equation 6-7.

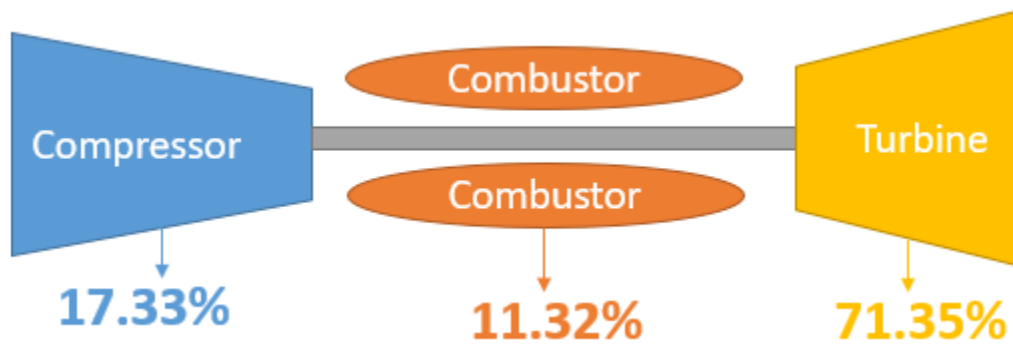
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$$GT \sim RDE \text{ Price} = \underbrace{(GT \text{ Price} - \text{Combustor Price} - \text{Compressor Price})_{H\text{-class}}}_{\text{Turbine Cost}} + \frac{RDE}{\text{Price}} + \text{Scaled Compressor Price}$$

Equation 6-7

In order to make the indicated capital cost calculation with Equation 6-7, the cost distributions of each GT component in the overall conventional GT cost should be known. A study made for small GTs for combined heat and power applications [67] provides the shown fractions in Exhibit 6-32 for major GT components.

Exhibit 6-32. GT component cost distribution in the overall GT cost for small GTs



The applicability of the fractions shown in Exhibit 6-27 to larger GT frames needed to be verified before using these distributions in the RDE-GT capital cost estimation. A DOE cost analysis report [68] for F-Class GT combustor options to reduce NO_x emissions provides the installed cost of a dry low NO_x (DLN) type combustor, which is the combustor type that H-Class GT engines are currently using. A price quote for an H-Class engine using the similar DLN combustor type in 2018 has been used to verify the combustor cost fraction on overall GT cost. The calculation shows that the combustor cost of a large frame GT is about 10.79 percent of the overall GT cost.

An average H-Class GT cost is then obtained by using several price quotes for such engines used in the NETL Bituminous Baseline Rev.4 study. [14] The average component costs for an H-Class GT (in 2019 \$) is shown in Exhibit 6-33.

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Exhibit 6-33. Average component costs for an H-Class GT

Compressor	Combustor	Turbine	GT Cost
\$15,925,285	\$9,797,665	\$64,807,050	\$90,530,000

6.3.1.2.1 Compressor Cost

The compressor cost for each RDE-GT configuration is scaled by using the pressure ratio with the general cost scaling formula in Equation 6-8. The value of the cost component, m , is found by comparing the F- and H-Class compressor costs and pressure ratios and calculated as 1.94.

$$Q_{new} = Q_{base} \left(\frac{\vartheta_{new}}{\vartheta_{base}} \right)^m \quad \text{Equation 6-8}$$

In Equation 6-8, the scaling factor ϑ is the compressor pressure ratio and Q_{base} is the cost of an H-Class GT compressor, which is from Exhibit 6-33. The compressor cost of each RDE-GT configuration is calculated as shown in Exhibit 6-34.

Exhibit 6-34. Compressor component cost for each RDE-GT configuration case

Case #	Pressure Ratio	Cost
1	11.1	\$4,074,632
2	8.0	\$2,164,148
3	11.1	\$4,074,632
4	13.0	\$5,591,320
5	17.1	\$9,466,991
6	11.1	\$4,074,632
Baseline H-Class Engine	23.1	\$15,925,285

6.3.1.2.2 RDE Cost

The RDE specifications used in the RDE capital cost estimation in Section 6.3.1.1 are mainly used from Aerojet-Rocketdyne's configuration, which is predicted to provide similar NGCC performance as the Case 5 configuration. [33] Therefore, Case 5 is used as the baseline for RDE cost scaling of other case configurations of this study, which is performed by using the scaling equation given in Equation 6-9.

$$Q_{new} = Q_{base} \left(\frac{\vartheta_{1,new}}{\vartheta_{1,base}} \right)^m \left(\frac{\vartheta_{2,new}}{\vartheta_{2,base}} \right) \quad \text{Equation 6-9}$$

In Equation 6-9, the first scaling factor, ϑ_1 , is the RDE total pressure gain, and the second scaling factor, ϑ_2 , is the RDE exit temperature. The biggest impact to RDE cost is expected to come from the amount of total pressure gain obtained because it would affect the materials, design complexity, and effort for the system. Secondary impact comes from the exit temperature,

because it affects the type and amount of coating and the type of material used in the construction. The cost exponent, m , is used from typical GT cost exponent value of 0.9. [51]

With the cost scaling formula in Equation 6-9, the RDE component cost for configurations other than Case 5 is calculated as shown in Exhibit 6-35. Case 5 RDE cost is the calculated average RDE cost for four engines per year production rate from Section 6.3.1.1.

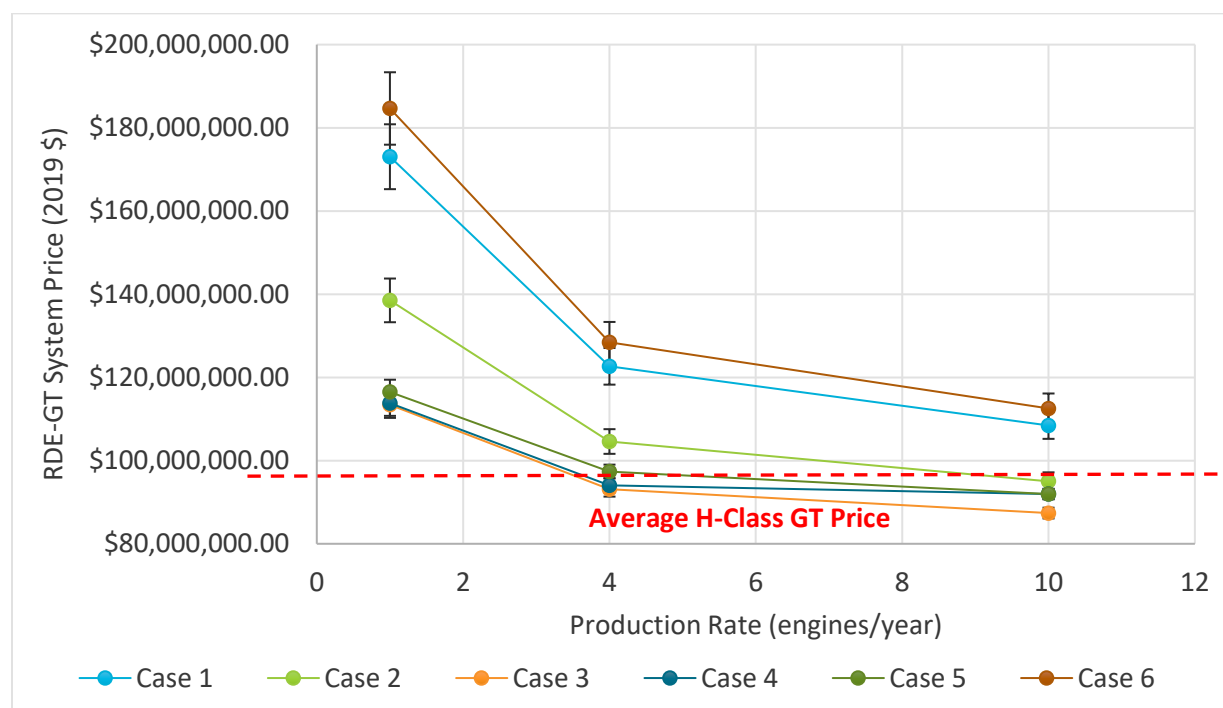
Exhibit 6-35. Calculated RDE cost for each RDE-GT configuration case

Case #	Total Pressure Gain	RDE Exit Temperature	Cost
1	5.81	3260 °R	\$49,485,857
2	3.75	3260 °R	\$33,321,327
3	2.12	3260 °R	\$19,935,758
4	1.86	3560 °R	\$19,379,689
6	5.95	3560 °R	\$55,234,145
Baseline (Case 5)	1.98	3260 °R	\$18,786,678

6.3.1.2.3 RDE-GT System Cost

With the indicated cost calculation methodology in the previous sections, the capital cost of each configuration is calculated for different production rates. The change in the RDE-GT system capital cost with respect to the different engine production rates is shown in Exhibit 6-36.

Exhibit 6-36. Capital cost values of RDE-GT system configuration cases for different production rates

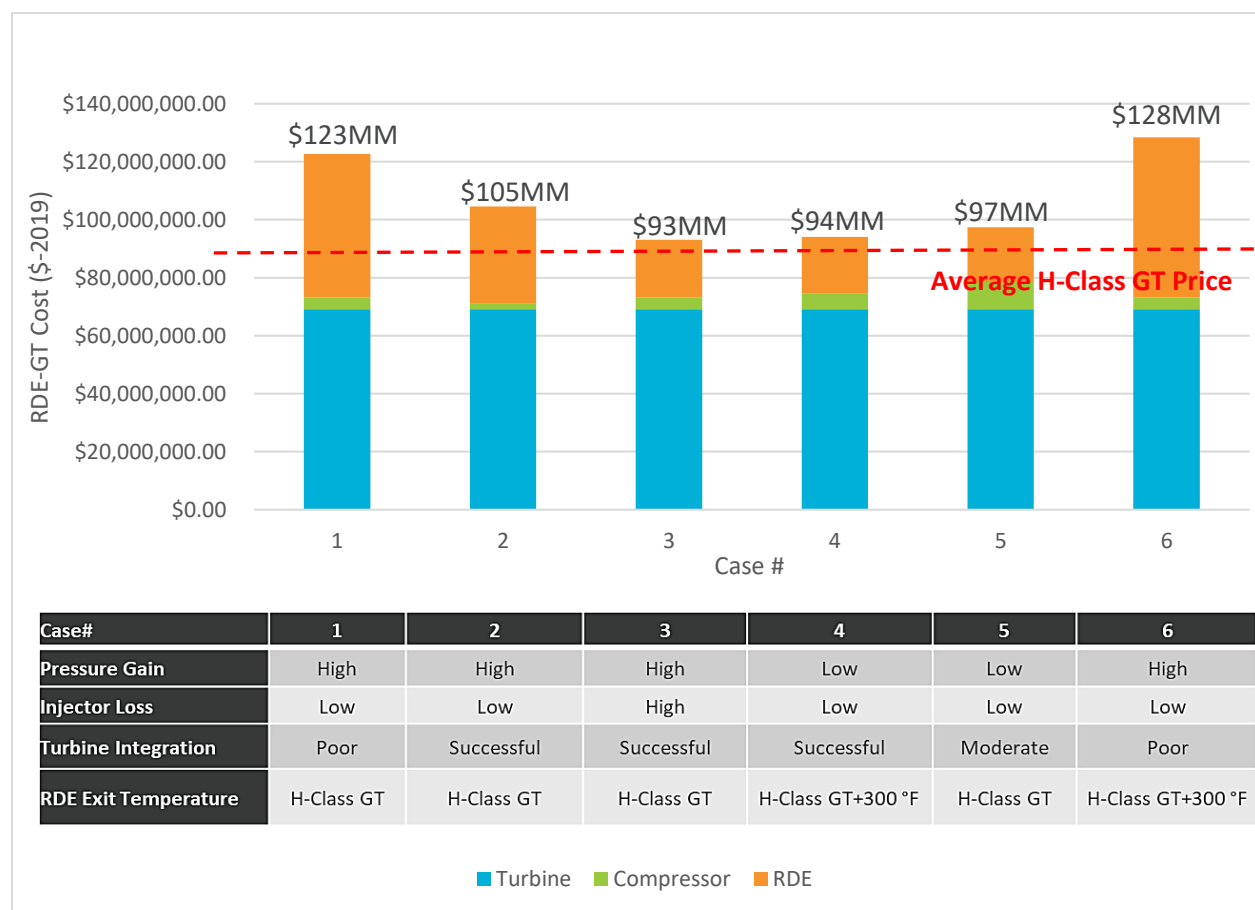


COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

From the values calculated in Exhibit 6-31, some of the case configurations can achieve lower cost than an average H-Class GT, if the production rates of these systems become as high as the conventional GT production rates.

The average values for the RDE-GT capital costs for each configuration are presented in Exhibit 6-32 together with the component cost distributions. The presented values in Exhibit 6-37 are used as the “Gas Turbine Capital Cost” component in the techno-economic analysis calculations.

Exhibit 6-37. Calculated capital cost values for each RDE-GT system configuration



Reduction in the compressor cost is overcome by the increase in the RDE cost for Case 1 and Case 6, which leads to the highest capital costs. Because the turbine cost is the same for all configurations, in general, RDE cost is more deterministic on the capital cost ranks. The compressor cost affected the ranks of Case 4 and Case 5 only. The details of the calculated capital costs for each RDE-GT case configuration are shown in Exhibit 6-38.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-38. RDE-GT systems capital costs

Case #	Compressor	RDE/Combustor	Turbine	Total
1	\$4,074,632	\$49,485,857	\$64,807,050	\$122,664,139
2	\$2,164,148	\$33,321,327		\$104,589,125
3	\$4,074,632	\$19,935,758		\$93,114,040
4	\$5,591,320	\$19,379,689		\$94,074,658
5	\$9,466,991	\$18,786,678		\$97,357,319
6	\$4,074,632	\$55,234,145		\$128,412,427
Baseline H-Class Engine	\$15,925,285	\$9,797,665	\$64,807,050	\$90,530,000

6.3.2 Cost Analysis of NGCC Plant with RDE-GT Systems

6.3.2.1 Methodology

The methodology used to estimate the capital costs, operation and maintenance costs, and first-year COE is from the NETL QGESS: Cost Estimation Methodology for NETL Assessments of Power Plant Performance. [50] The NGCC plant with RDE-GT capital costs is calculated at four levels:

1. Bare Erected Cost (BEC)
2. Total Plant Cost (TPC)
3. Total Overnight Cost (TOC)
4. Total as Spent Cost (TASC)

BEC, TPC, and TOC are “overnight” costs and expressed in “base-year” dollars. The base year is the first year of the capital expenditure, which is 2019 for this study. TASC is expressed in mixed year, current year dollars over the entire capital expenditure period, which is assumed to last three years for natural gas plants (2019–2022). The TPC and operation and maintenance costs for each of the cases in this study were calculated by using the Bituminous Baseline Rev.4 NETL Cost Spreadsheet Template Revision E (“NETL Cost Spreadsheet”). [14]

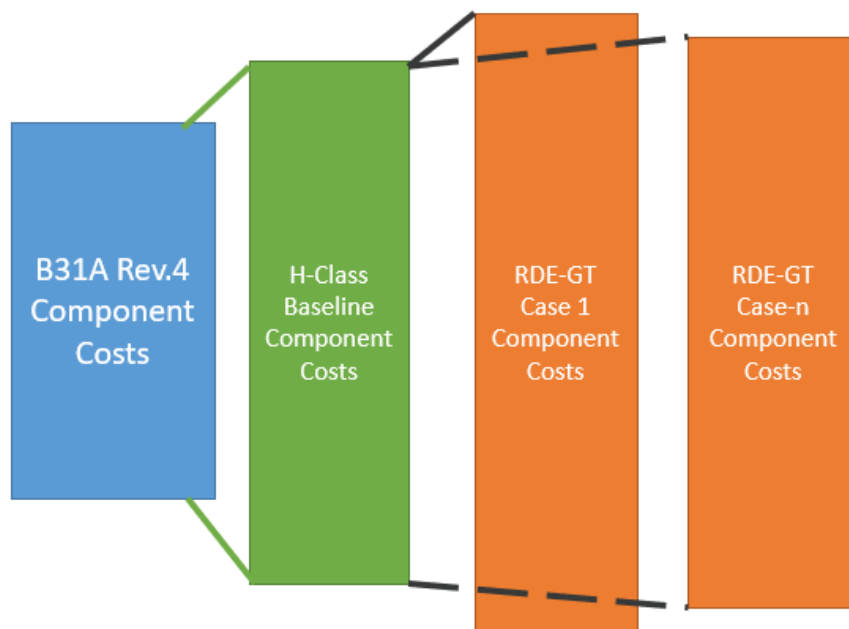
The calculated RDE-GT system capital costs in Section 6.3.1 are used as “Combustion Turbine Equipment Cost” item in the NETL Cost Spreadsheet. BEC of the RDE-GT system is calculated as 106.85 percent of the capital cost of each RDE-GT system. The fixed fraction for calculating the BEC of RDE-GT systems is used from the ratio of BEC to capital cost used for the combustion turbine in the Bituminous Baseline Rev.4. [14]

The raw capital cost data in the NETL Cost Spreadsheet [14] are updated periodically by NETL from cost databases and conceptual estimating models for each of the NGCC power plant subcomponents. The current raw capital cost data of the NETL Cost Spreadsheet is for NGCC systems using F-Class GTs, and a cost scaling was previously performed by using the QGESS: Capital Cost Scaling Methodology [51] to obtain the BEC for H-Class GT integrated NGCC power plants. [15]

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

For all NGCC power plant components except for the RDE-GT system, such as the HRSG components, steam turbines and related accessories, generators, pumps etc., the related raw capital costs are scaled from the raw capital costs of an H-Class GT integrated NGCC plant costs. [10] The general idea applied to cost scaling of NGCC sub-components other than the combustion turbine, illustrated in Exhibit 6-39.

Exhibit 6-39. Cost scaling ideology for NGCC sub-components other than combustion turbine



The NETL QGESS: Cost Estimation Methodology [50] uses process and project contingencies in the calculations to include all uncertainties on the component or process cost. The amounts of contingencies depend on the TRL of each cost component. [69] According to the criteria presented in the DOE Technology Readiness Assessment Guide [70], RDE-GT system can be considered at TRL 3–4, which is the component technology level where data from individual technology system components are available for actual system working conditions. The basis for the selected TRL comes from the availability of RDE test data for power plant-like conditions from various UTSR program partners [49, 55, 54] as of the time of performing this study.

The Electric Power Research Institute (EPRI) Guidelines for Process and Project Contingencies was used to determine the project and process contingency levels for the RDE-GT system, which are listed in Exhibit 6-40 and Exhibit 6-41.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-40. EPRI guidelines for process contingencies

Technology Status	Process Contingency
New Concept with Limited Data	40+%
Concept with Bench Scale Data	30–70%
Small Pilot Plant Data	5–20%
Process is Used Commercially	0–10%

Exhibit 6-41. EPRI guidelines for project contingencies

Cost Classification	Design Effort	Project Contingency
Class I (AACE 4-5)	Simplified	30–50%
Class II (AACE 3)	Preliminary	15–30%
Class III (AACE 2–3)	Detailed	10–20%
Class IV (AACE 1)	Finalized	5–10%

The assumed TRL level of the RDE-GT system corresponds to “Concept with Benchscale Test Data” for the Process Contingency and “Class II (AACE 3)-Preliminary Design Effort” for the project contingency criteria. For the RDE-GT system costs, assumed process contingency is 30 percent and project contingency is 24 percent.

For all other NGCC power plant sub-components other than the combustion turbine, the respective contingency values for each NGCC sub-component listed in the NETL QGESS: Cost Estimation Methodology [50] are used.

6.3.2.2 Cost Analysis Results

For each RDE-GT system configuration, owner’s costs, operating costs, COE, and the sensitivity of COE on the natural gas price, engine production rate and plant capacity factor were analyzed for each RDE-GT configuration and compared with baseline cases for state-of-art H-Class GTs.

6.3.2.2.1 Owner’s Costs

Owner’s costs consist of the pre-production costs, inventory capital, initial cost for catalyst and chemicals, land, financing costs, TPC, and other costs.

Pre-production (Start-Up) Costs: These costs are the costs that will incur within 1–6 months after the plant starts to operate. This item consists of the costs for 6-month operating labor, 1-month maintenance materials at full labor, 1-month non-fuel consumables at full capacity, 1-month waste disposal, 25 percent of 1-month fuel cost at full capacity, and 2 percent of the TPC. [50]

Inventory Capital: These costs include the costs for spare parts (0.5 percent of TPC) and 60-day supply of chemicals and catalysts (at full capacity) except the selective catalytic reduction (SCR) catalysts.

Initial Costs for Catalysts and Chemicals: These costs are related to all initial fills that are not included in the BEC.

Land: Costs for purchasing the land. Calculated from \$3000/acre and 100 acres is assumed for the NGCC plant [50]

Financing Costs: This cost item covers the cost of securing financing, including fees and closing costs. It is 2.7 percent of the TPC. [50]

Other Costs: This is the lumped sum of costs related to preliminary feasibility studies of the plant, economic development, construction and/or improving the infrastructure outside the plant, legal fees, permitting costs, owner's engineering costs, and owner's contingency costs. It is 15 percent of the TPC. [50]

TPC is the sum of the BEC and the cost of services provided by EPC contractor and project and process contingencies. EPC services include detailed design, contractor permitting, and project/construction management costs. TPC is an overnight cost and expressed in base-year dollars and is calculated for each RDE-GT configuration.

TOC is the cost to manufacture the plant as if it could be built in one day. TASC is the actual cost to build the plant. TOC is calculated by adding the pre-production costs, inventory capital costs, initial costs for catalysts and chemicals, land costs, financing costs, and other costs. TASC is obtained by multiplying the TOC with the TASC factor.

Owner's costs breakdowns are compared for each configuration in Exhibit 6-42 and compared with H-Class GT integrated NGCC costs. The rank mostly follows the capital cost rank (Exhibit 6-37) but efficiency also affects the TOC and TASC ranks.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-42. Total overnight cost and total as spent cost comparison for each RDE-GT configuration case



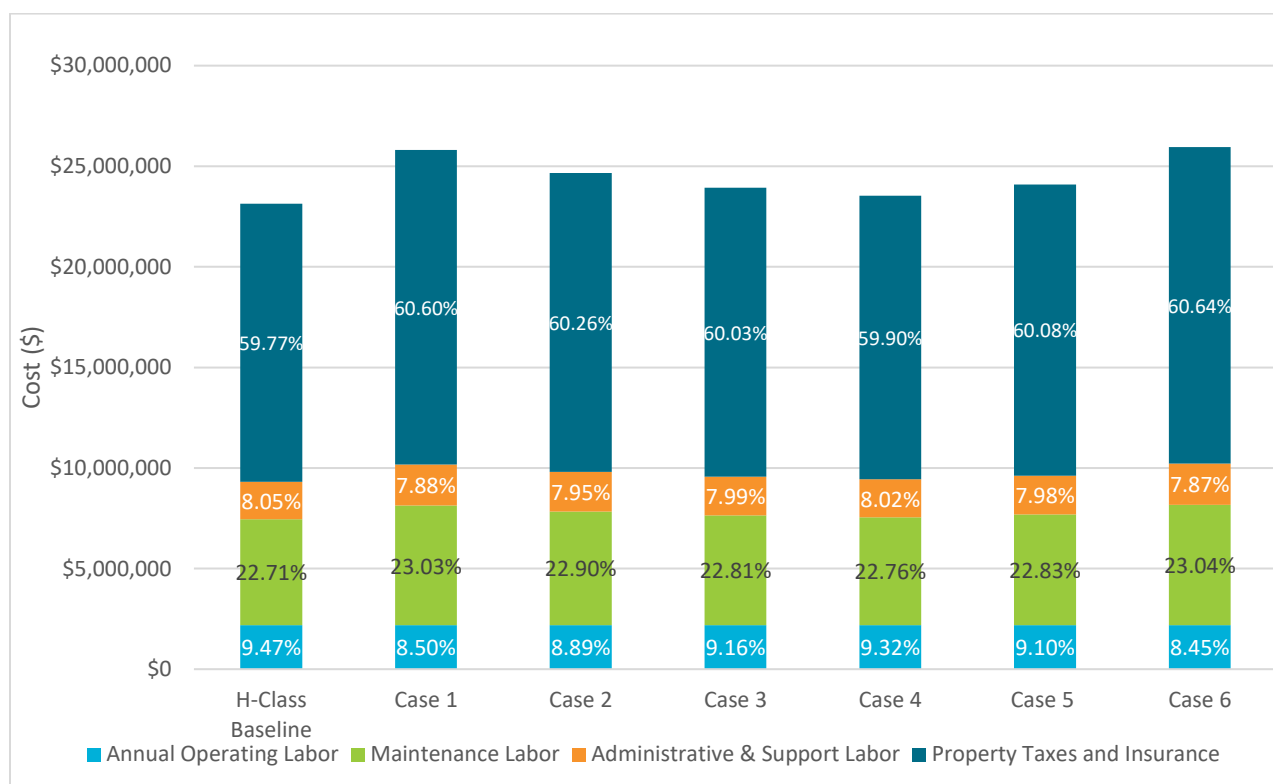
6.3.2.2.2 Operating Costs

Operating costs and related maintenance expenses refer to the incurred costs during the expected life of the power plant. These cost items include operating labor, maintenance material and labor, administrative and support labor, consumables, fuel, and waste disposal.

Itemized fixed operating costs are calculated per net kWh from the power plant for each RDE-GT configuration case and compared with H-Class baseline values [15] in Exhibit 6-43.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

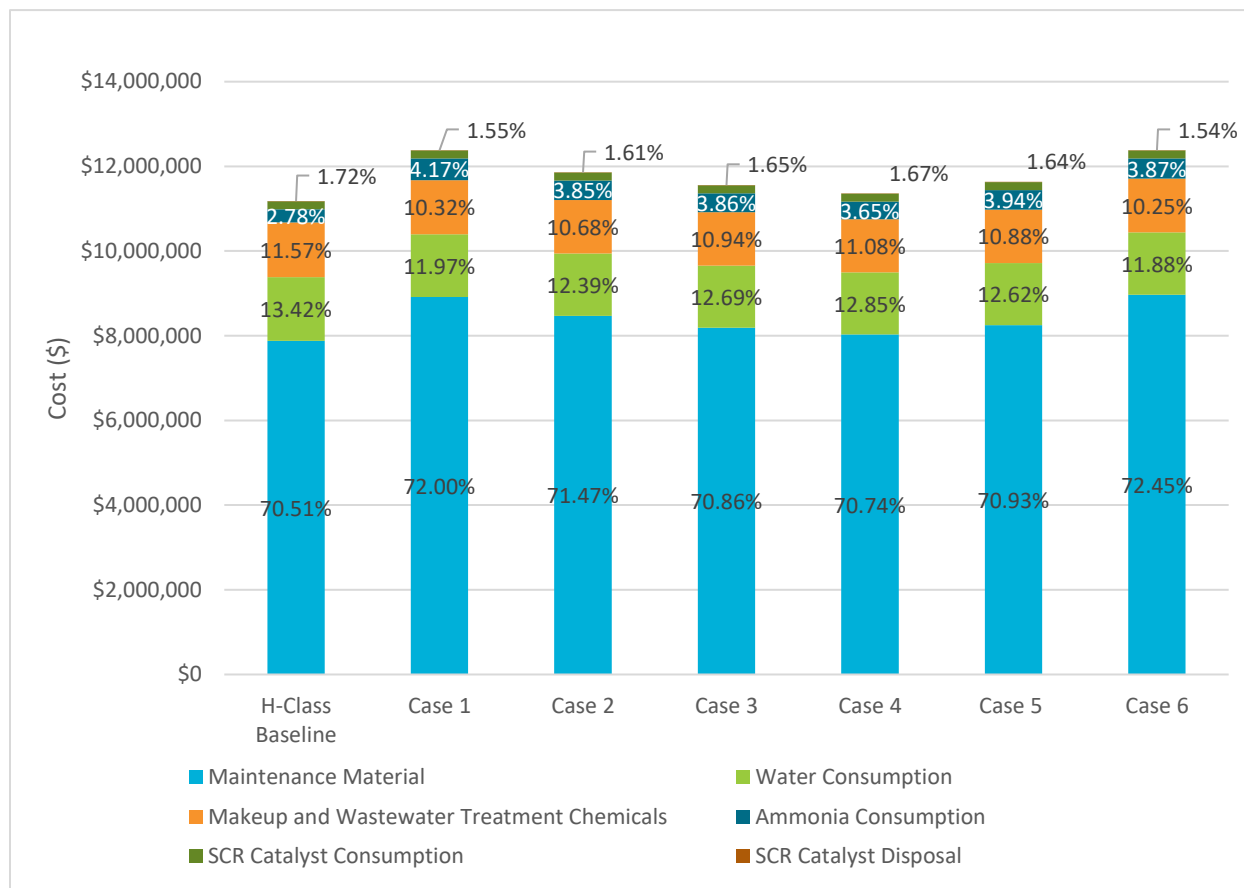
Exhibit 6-43. Fixed operating costs and cost breakdown is compared for each RDE-GT configuration case



The variable operating costs are related to the power plant power output and the consumption rates of water, wastewater treatment chemicals, ammonia, SCR catalyst, and natural gas fuel. Variable operating costs are calculated for all cost items per net MWh produced from the power plant for each RDE-GT configuration case and compared with H-Class baseline values [15] in Exhibit 6-44 for non-fuel items.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-44. Non-fuel variable operating costs and cost breakdown is compared for each RDE-GT configuration case



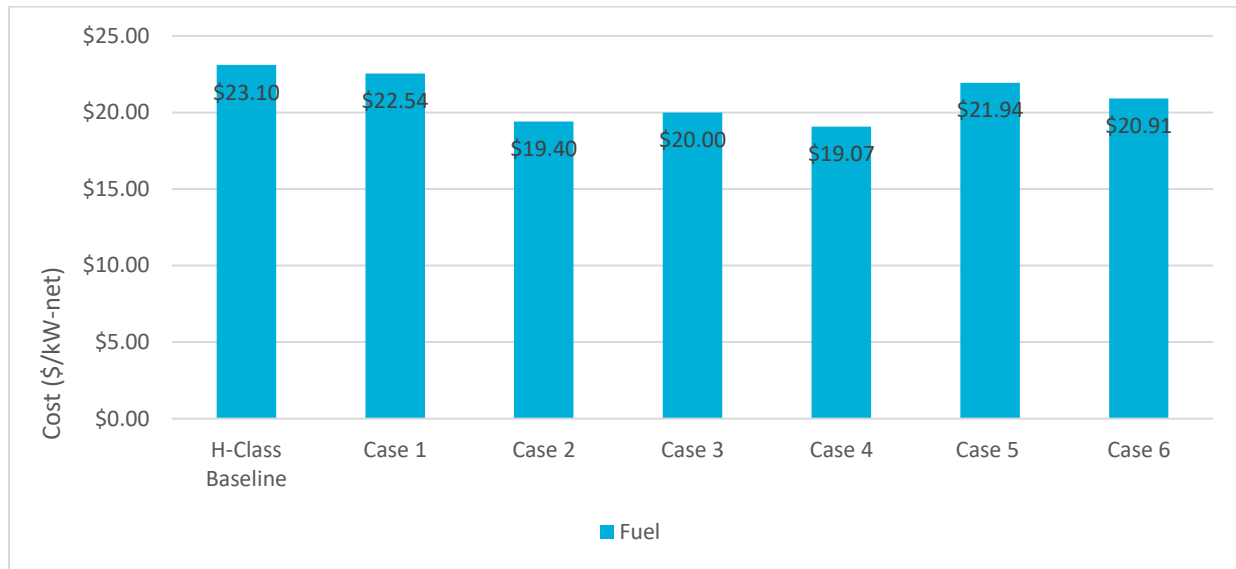
The rank for the operating costs (both variable and fixed) for the RDE-GT configurations is as follows:

1. Case 4 (lowest)
2. Case 3
3. Case 5
4. Case 2
5. Case 1
6. Case 6 (highest)

Fuel costs expressed as \$/MWh are calculated for each RDE-GT configuration case and compared with H-Class baseline values [15] in Exhibit 6-45.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-45. Fuel cost per net MWh is compared for each RDE-GT configuration case



The rank for the fuel costs per net MWh for the RDE-GT configurations is as follows:

1. Case 4 (lowest)
2. Case 2
3. Case 3
4. Case 6
5. Case 5
6. Case 1 (highest)

From the comparison of the operating costs, Case 4 provided the best results, followed by Case 2 and Case 3.

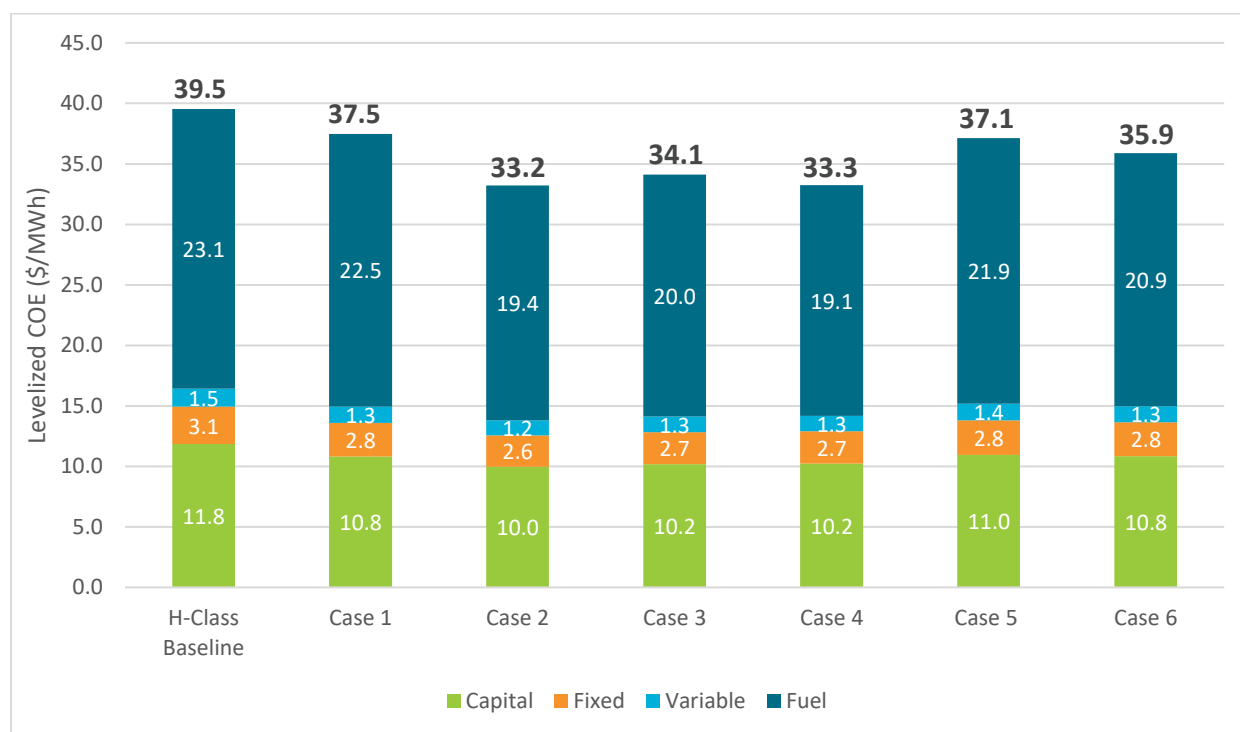
6.3.2.2.3 Levelized Cost of Electricity

6.3.2.2.3.1 Cost Comparison and RDE-GT System Capital Cost Margin

The levelized COE calculated for each RDE-GT configuration is compared in Exhibit 6-46. The RDE-GT systems provide 5 to 16 percent reduction in the COE from a conventional GT. From the comparison of COE values, the lowest rates are obtained for Case 2 and Case 4 (where the NGCC efficiency is the highest among all cases). The rank for the COE does not follow the rank for the capital costs due to the differences in the pressure gain levels and efficiencies of each configuration.

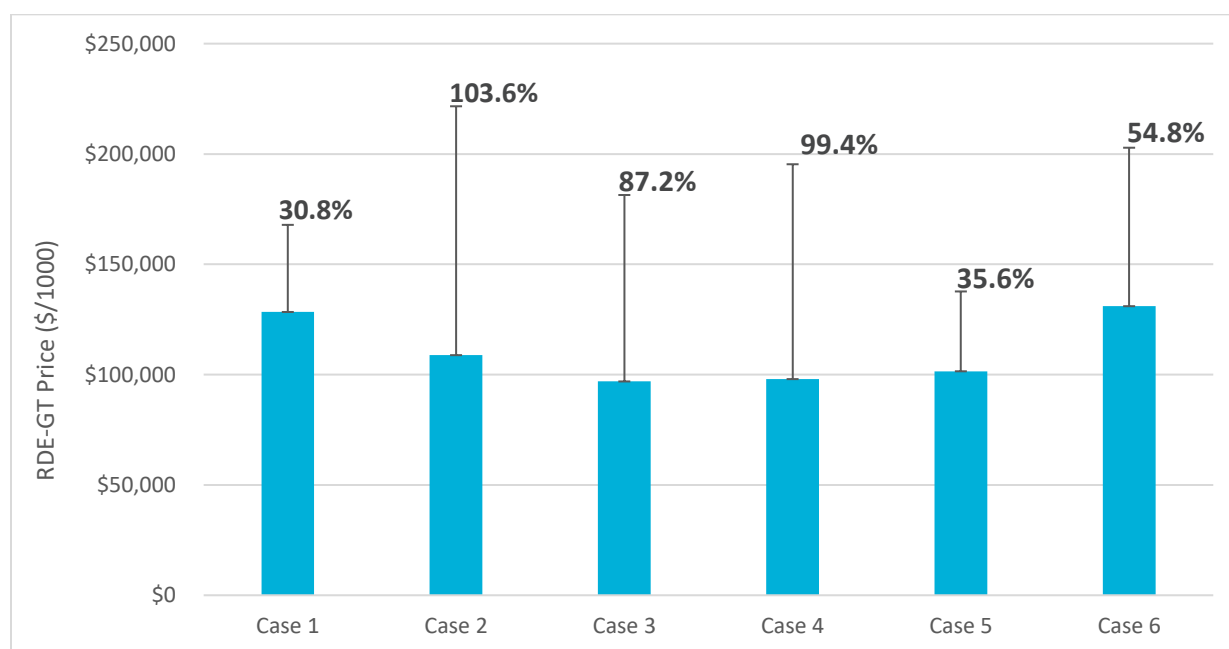
COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-46. Levelized COE comparison for each RDE-GT configuration case



The RDE-GT cost margins are determined for each configuration to understand how much the RDE-GT system cost could increase to have COE less than or equal to the current H-Class machines (\$39.5/MWh). The calculated cost margins for each configuration are compared in Exhibit 6-47.

Exhibit 6-47. RDE-GT capital cost margins for H-Class GT COE values



COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

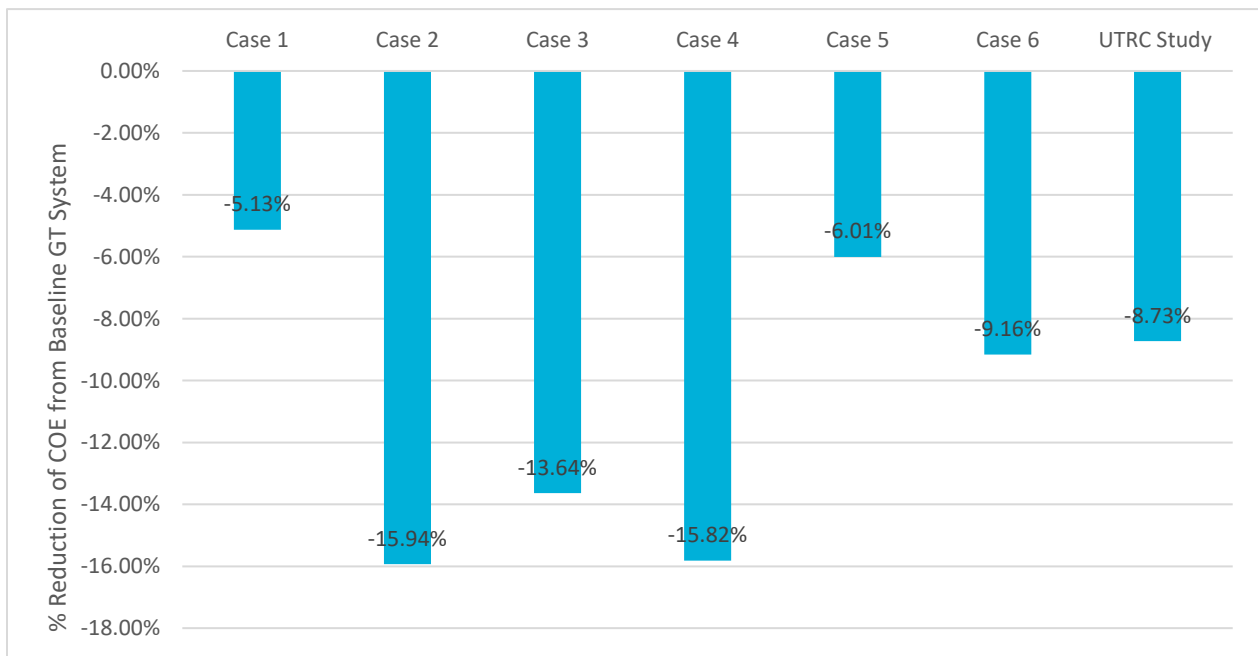
From the calculated margins, Case 2 and Case 4 provide the largest margins; even if the actual RDE-GT system cost doubles the costs calculated for these configurations, these cases would still be able to provide better rates than the conventional GTs (i.e., would have COE less than 39.5 \$/MWh). The ranks mostly follow the ranks obtained for NGCC thermal efficiency except for Case 2 and Case 4, where the power output determined their respective positions.

The COE rank of each RDE-GT system configuration obtained from the analysis is as follows:

1. Case 2 (lowest)
2. Case 4
3. Case 3
4. Case 6
5. Case 5
6. Case 1 (highest)

From the COE analysis of Exhibit 6-46, the RDE-GT systems have the potential to reduce H-Class GT COE about 5–16 percent, which is in line with a previous NETL study made by United Technologies Research Center (UTRC). [11] The reduction from the baseline H-Class COE values with the RDE-GT configurations is compared with the UTRC study results for the PGC systems potential to reduce F-Class GT COE results, see Exhibit 6-48.

Exhibit 6-48. RDE-GT case configurations reduction of COE from baseline GT system is compared with a previous study for general PGC systems [11]



COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

The studied PGC case in the UTRC study has 65 percent LHV efficiency, which is closer to the efficiency values for Case 1 and Case 6. Cases 2, 3, and 4 have more than 70 percent efficiency and, therefore, higher reduction in COE.

6.3.2.2.3.2 COE Sensitivity

In this part of the study, the sensitivity of COE to the following parameters was analyzed and compared for each RDE-GT configuration case.

- Natural Gas Price
- Plant Capacity Factor
- RDE-GT System Process Contingency
- RDE-GT Manufacturing Rate

The limits of the sensitivity parameters are shown in Exhibit 6-49.

Exhibit 6-49. COE sensitivity analysis limits

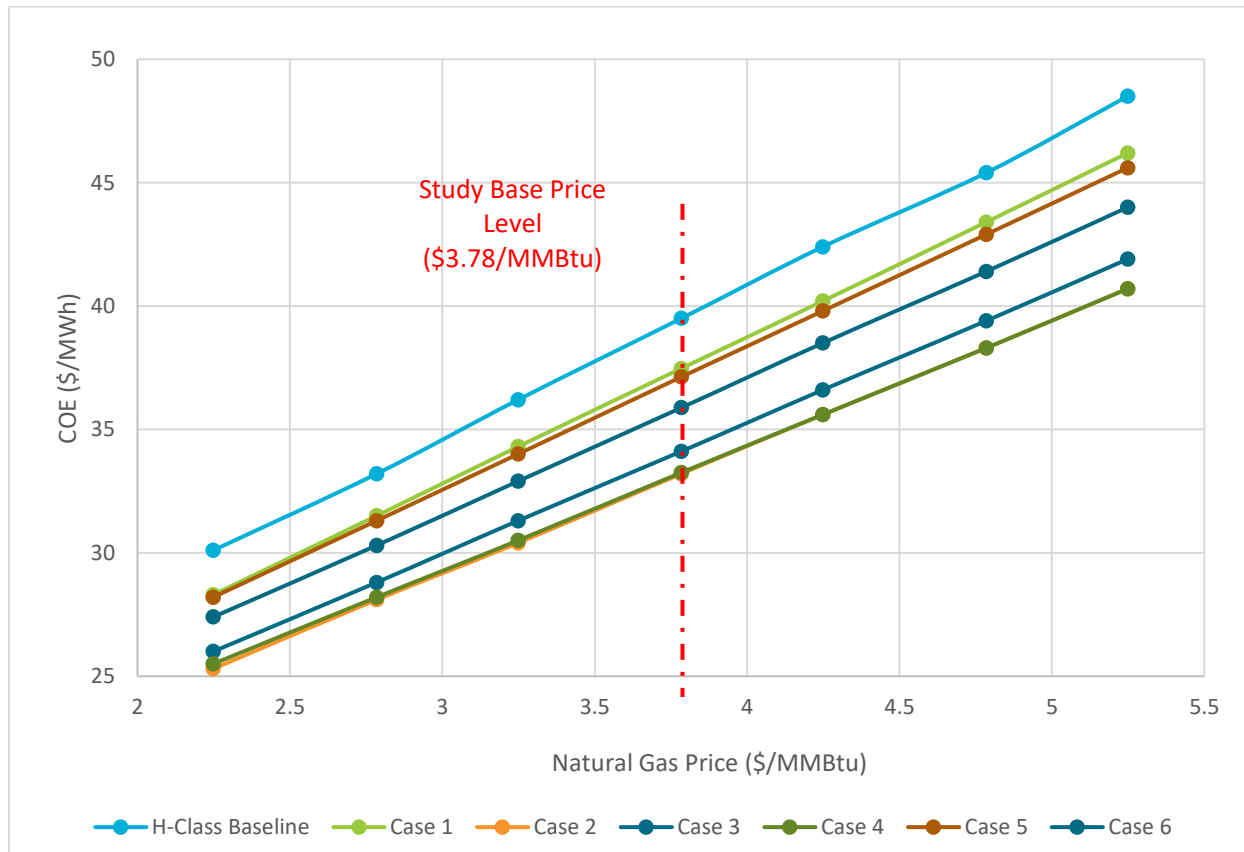
Parameter	Min Limit	Max Limit
Natural Gas Price	2.248 \$/MMBtu	5.248 \$/MMBtu
Plant Capacity Factor	70%	100%
Process Contingency	0%	30%
RDE-GT Manufacturing Rate	1 engine/year	10 engines/year

Similar to the methodology applied in Section 4 and Section 5, the sensitivity input parameters are increased and decreased by certain amounts to obtain the sensitivity charts; the slopes of the charts are used to quantify the sensitivity of COE to the analysis input parameter.

The baseline natural gas price used in this study is changed from \$3.78/MMBtu by ± 40 percent to analyze the fuel price sensitivity of the COE calculated for each RDE-GT Configuration. The purpose in this sensitivity analysis is to find which case configurations offer the best protection against natural gas price volatility. The sensitivity chart is presented in Exhibit 6-50.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-50. Sensitivity of COE to natural gas price

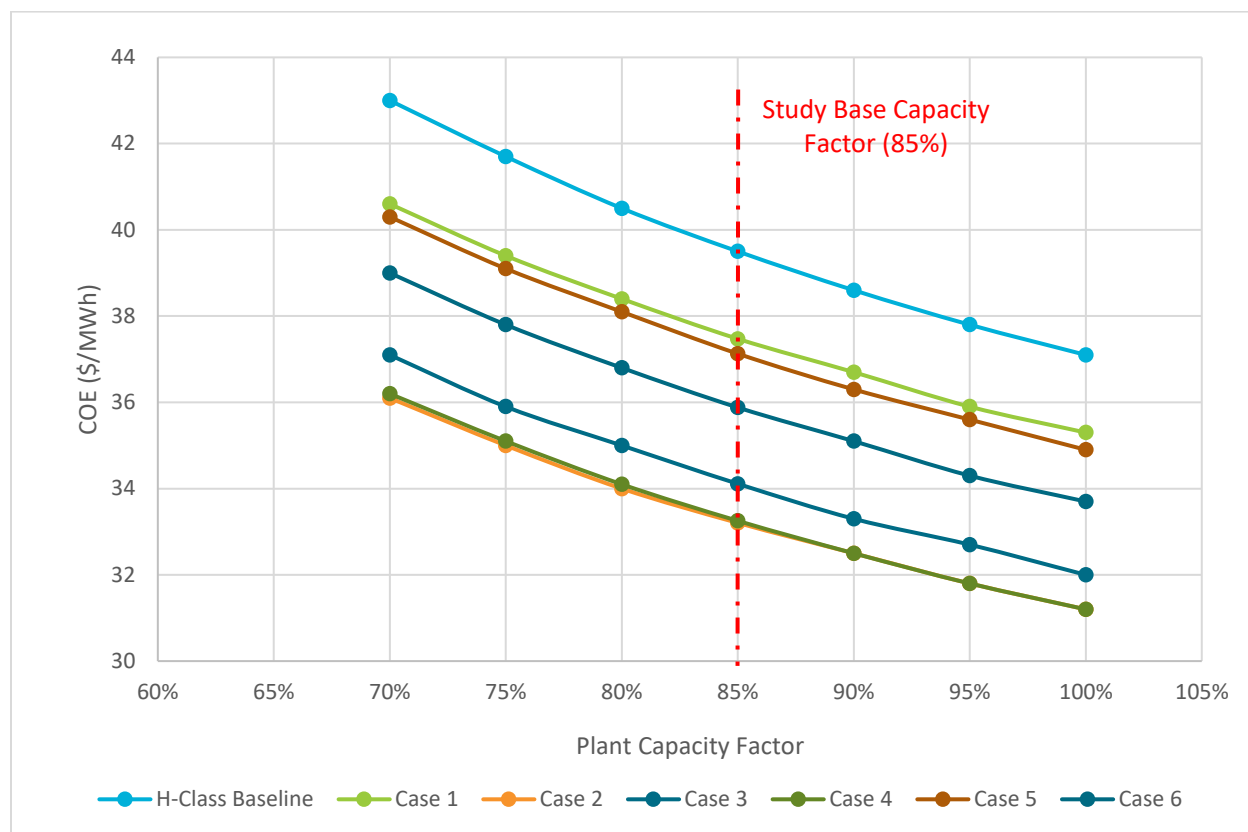


Price sensitivity is directly related to the thermal efficiency of the power plant; therefore, the sensitivity follows the same order as the NGCC thermal efficiency from each RDE-GT configuration. From the results in Exhibit 6-50, the power plant with the Case 4 type RDE-GT configuration is the least sensitive to the changes in natural gas price, whereas the sensitivity is the highest for the plant using the RDE-GT configuration Case 1. The ranking is obtained by comparing the slopes of the sensitivity graph.

The plant capacity factor is the amount of electricity produced in a given period divided by the total electricity that would be generated if the plant operates at full load without interruption over that same period. This study assumes that the power plant would be dispatched anytime it is available and would be capable of generating maximum capacity when online; therefore, availability is equal to capacity factor. The plant capacity factor is changed from 85 percent by ± 15 percent (absolute) to analyze the capacity factor sensitivity of the COE calculated for each RDE-GT configuration. The sensitivity chart is presented in Exhibit 6-51.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-51. Sensitivity of COE to plant capacity factor

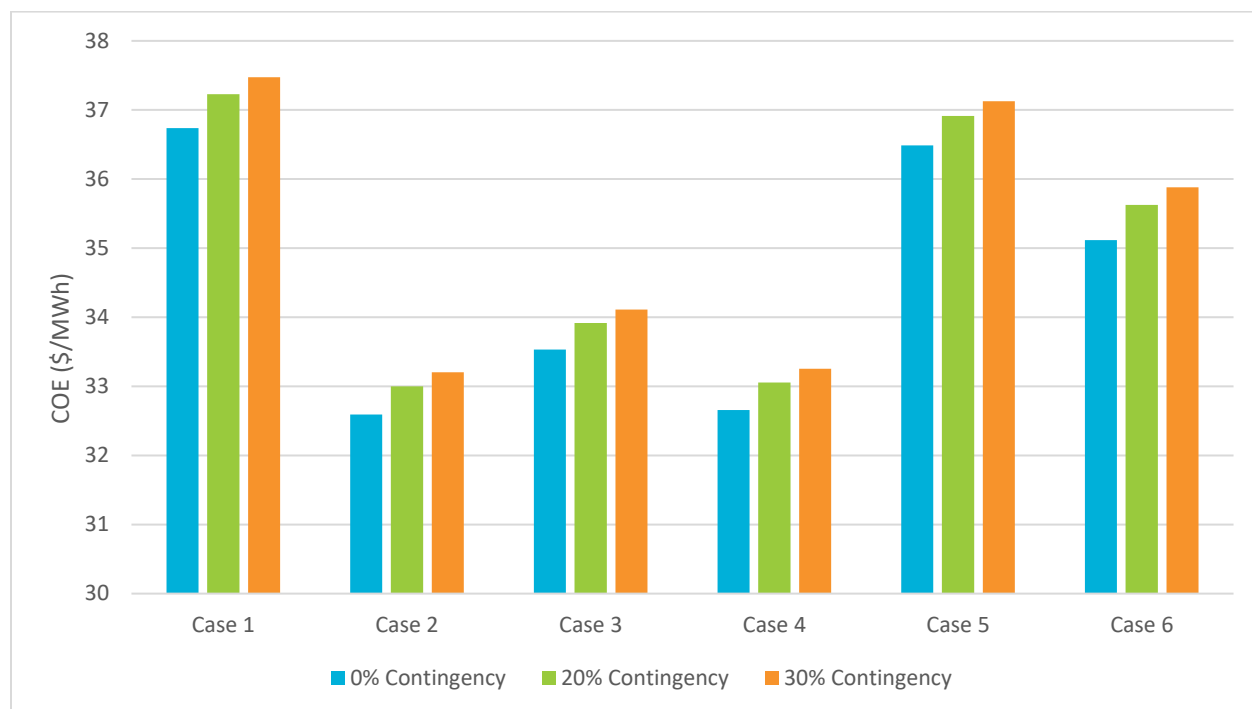


Case 2 and Case 3 have the lowest sensitivity to capacity factor, whereas Case 1 and Case 5 have the highest sensitivity to the plant capacity factor.

The sensitivity of the COE to the process contingency is also studied to understand how much reduction in the COE occurs as the technology attains higher TRLs. As the RDE-GT technology achieves higher maturity, the process contingencies will approach 0 percent from the study value of 30 percent, which corresponds to TRL 3–4. The sensitivity of COE is compared for each RDE-GT configuration case in Exhibit 6-52.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 6-52. Sensitivity of COE to process contingency of the RDE-GT system

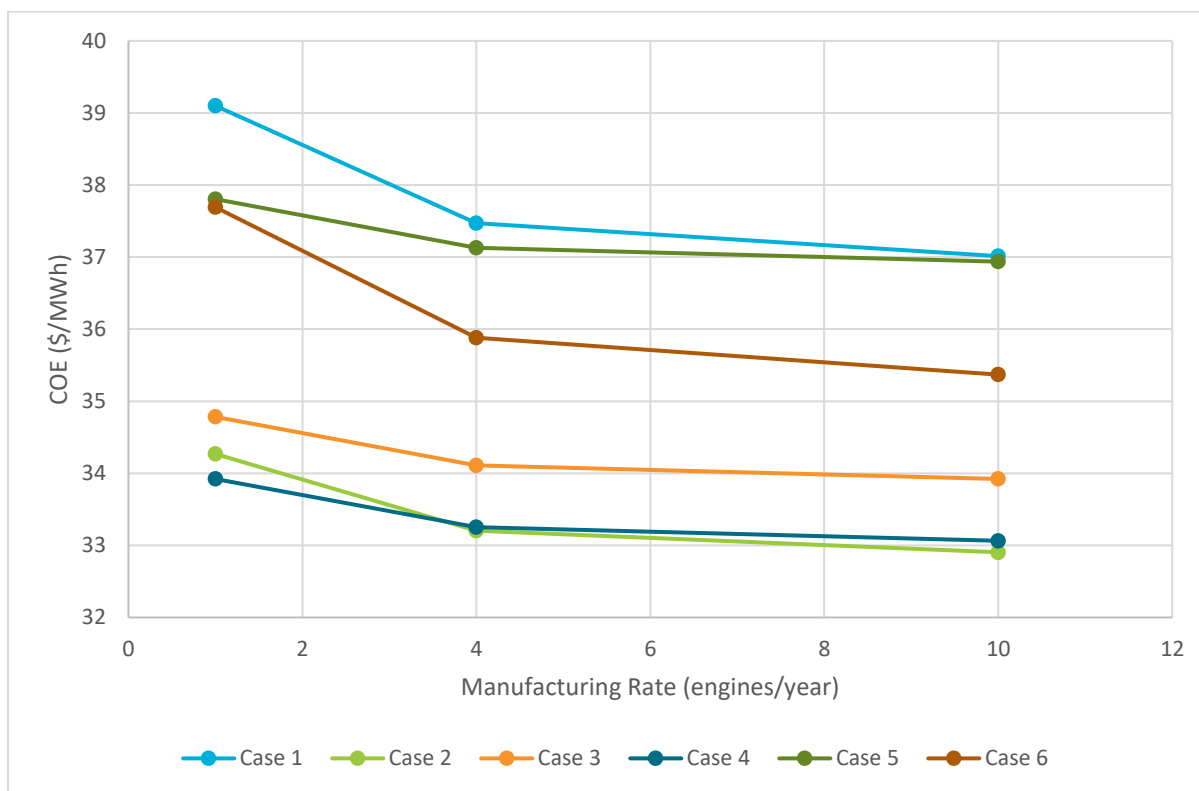


For the RDE-GT configurations of the study, COE reduces by 0.70 \$/MWh in average for all cases when the process contingency is reduced from 30 percent to 0 percent (i.e., high technological maturity level).

The manufacturing rate of the engine affects the capital cost and capital cost affects the COE. The sensitivity of COE to engine manufacturing rate is compared for each RDE-GT configuration case in Exhibit 6-53. The study baseline manufacturing rate is four engines per year.

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Exhibit 6-53. Sensitivity of COE to the manufacturing rate of the RDE-GT system



The engine manufacturing rate affects COE from Case 1 and Case 6 the highest, and Case 2 and Case 4 the lowest.

7 CONCLUSION

In this study, a scoping analysis on the application of PGC concepts to NGCC power plants was performed by using simplified analytical models for the RPC, PDE, WRC, and RDE types of pressure gain devices. The analytical models were then used in a GT simulation to compare the impact of using PGC technologies on key GT performance parameters. A sensitivity analysis was also performed to understand the ease of improving the baseline GT performance for each PGC type. Based on the results for the GT performance, the RDE system provided the highest GT efficiency and potential for 70 percent and higher NGCC efficiency.

The NGCC power plant performance using an RDE integrated H-Class GT was studied by using a steady-state power plant simulation model developed in Aspen. A sensitivity analysis was performed for the RDE-GT systems to determine the impact strength of several RDE parameters on the overall GT performance. The results of the sensitivity analysis show that successful turbine integration to RDE systems provides the potential for more than 70 percent NGCC efficiency while providing high power output. Increasing the RDE exit temperature provides the steepest gain in NGCC efficiency but it might be a challenging path when the cooling requirements and operational stability issues are considered. Injector pressure loss should be kept as low as possible but if it is unavoidable, using higher compressor pressure ratio would be an alternative. High efficiency compressors should be used for 70 percent and greater NGCC efficiency. The trends observed in the sensitivity analysis show that the GT pressure ratio distribution between the compressor and RDE is very important. Each side has its own advantages and disadvantages and an optimum distribution should consider the turbine integration performance, maximum possible RDE pressure gain, amount of RDE exit temperature increase, and amount of injector pressure loss.

The results of the sensitivity analysis show that the impacts of studied RDE-GT system components to NGCC performance are different. The turbine efficiency and RDE exit temperature are determined to impact the NGCC performance most among the studied parameters. However, the discussed levels of improvements regarding engine components might not be available in the near future or by the time RDE-GT systems become operational. Therefore, several technology improvement paths were determined and used in determining the six different system configurations for the techno-economic analysis.

The capital cost of the RDE was calculated by using a previous study on ramjets, which was modified with current labor rates, inflation rates, materials, and other factors. A scaling was made to determine the capital cost of the compressor and the RDE sections of each RDE-GT system configuration, where the turbine section of the engine was used as the same from a conventional H-Class GT. The RDE-GT capital cost results showed that the highest-pressure gain configuration cases have the highest capital costs.

Calculated RDE-GT capital costs were then used in the QGESS Cost Estimation Tool to calculate the owner's costs, operating costs, COE and the sensitivity of COE to natural gas price, plant capacity factor, process contingencies, and engine manufacturing rates. The performance and cost analysis of each RDE-GT configuration is summarized in Exhibit 7-1.

COMPARATIVE STUDY FOR PRESSURE GAIN COMBUSTION-GAS TURBINE SYSTEM PERFORMANCE IN NGCC CONFIGURATIONS

Exhibit 7-1. RDE-GT system configuration cases performance and cost analysis comparison

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Power (Net) MWe	1,243	1,280	1,213	1,184	1,135	1,247
CC Efficiency (LHV) (%)	63.50%	73.70%	71.50%	75.00%	65.20%	68.40%
COE (\$/MWh)	36.10	31.99	32.91	32.17	35.81	34.41
TOC (\$/kW)	704	652	668	677	717	701
Fixed Operating Costs (\$/kWh)	\$19.235	\$17.922	\$18.407	\$18.688	\$19.764	\$19.152
Variable Operating Costs (\$/MWh)	\$1.258	\$1.174	\$1.211	\$1.227	\$1.300	\$1.247
Natural Gas Price Sensitivity	6.00	5.13	5.30	5.06	5.80	5.53
Capacity Factor Sensitivity	-16.14	-15.21	-15.21	-15.57	-16.29	-16.07

The results show that cases with successful turbine integration give the best performance and COE. If the maximum amount of the pressure gain from RDE is limited, then increasing the RDE exit temperature is the best possible alternative. If the injector and plenum losses are inevitable, then focusing on increasing the turbine efficiency would reduce the negative impact.

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APPENDIX A: BRENT METHOD ALGORITHM

The MATLAB m-script for the Brent Method for iterative root solving schemes used in the simplified pressure gain combustion model (PGC-Sim) is presented as follows:

```
root=BrentMethod(funcnt_no,x1,x2,tolr,Pa_over_P3,mdot3,mo,cp3,cv3,gamma3,eta_3
a,T3,T4,M_cj)

itmax=100;
eps=3E-8;

a=x1;
b=x2;

if(funcnt_no==3)
fa=Qpr(a,Pa_over_P3,mdot3,mo,cp3,cv3,gamma3,eta_3a,T3,T4);
fb=Qpr(b,Pa_over_P3,mdot3,mo,cp3,cv3,gamma3,eta_3a,T3,T4);
elseif(funcnt_no==1)
fa=funcnt1(a,gamma3,T3,T4);
fb=funcnt1(b,gamma3,T3,T4);
else
    fa=funcnt2(a,M_cj);
    fb=funcnt2(b,M_cj);

end
if(fa*fb>0.0)
    disp("Root is not bracketed");
end

fc=fb;

for iter=1:itmax
    if(fb*fc>0)
        c=a;
        fc=fa;
        e=b-a;
        d=b-a;
    end

    if(abs(fc)<abs(fb))
        a=b;
        b=c;
        c=a;
        fa=fb;
        fb=fc;
        fc=fa;
    end

    tol1=2*eps*abs(b)+0.5*tolr;

    xm=0.5*(c-b);

    if(abs(xm)<=tol1 || fb==0)
        root=b;
```

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```
break;
end
if(abs(e)>=tol1 && abs(fa)>abs(fb))
    %attempt inverse quadratic interpolation
    s=fb/fa;
    if(a==c)
        p=2.0*xm*s;
        q=1.0-s;
    else
        q=fa/fc;
        r=fb/fc;
        p=s*(2.0*xm*q*(q-r)-(b-a)*(r-1.0));
        q=(q-1.0)*(r-1.0)*(s-1.0);
    end

    %check whether in bounds
    if(p>0.0)
        q=-1.0*q;
    end

    p=abs(p);
    min1=3.0*xm*q-abs(tol1*q);
    min2=abs(e*q);

    if(min1<min2)
        compr=min1;
    else
        compr=min2;
    end

    if(2.0*p < compr)
        %accept interpolation
        e=d;
        d=p/q;
    else
        %interpolation failed, use bisection
        d=xm;
        e=d;
    end

else
    %bounds decreasing too slowly, use bisection
    d=xm;
    e=d;
end
%move last best guess to a
a=b;
fa=fb;
%evaluate new trial root
if(abs(d)>tol1)
    b=b+d;
else
    if(xm>0.0)
        xx=abs(tol1);
    else
        xx=-abs(tol1);
```

```
end

b=b+xx;

end

if (funct_no==3)
fb=Qpr(b, Pa_over_P3, mdot3, mo, cp3, cv3, gamma3, eta_3a, T3, T4);
elseif (funct_no==1)
fb=funct1(b, gamma3, T3, T4);
else
fb=funct2(b, M_cj);

end

end

if (iter==itmax && abs(fb)>tolr)

disp("Maximum number of iterations exceeded, root could not be found");
end

end
```

The definitions of input variables used in the function are as follows:

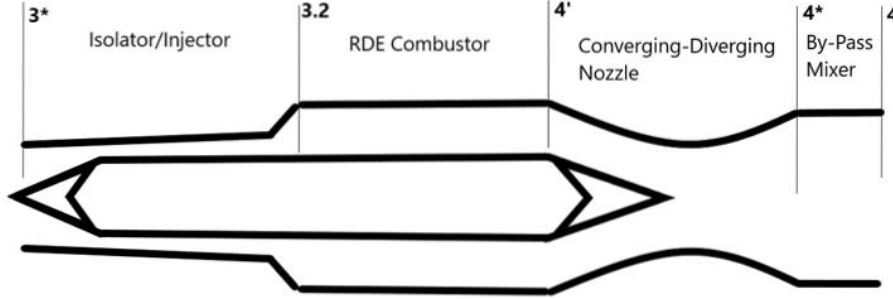
- funct_no: The iteratively solved functions in PGC-Sim are defined as separate functions and numbered from 1 to 5, where function 1 is the fuel-to-air ratio calculation used in resonant pulse combustor, function 2 is the Chapman-Jouget (CJ)-Mach number solution equation, function 3 is the heat balance equations of the wave rotor combustor, function 4 is the iterative equation for oblique shock angle β and function 5 is the equation used to check whether the rotating detonation engine plenum flow is choked
- X1: The minimum point for the interval that the root is believed to exist
- X2: The maximum point of the interval that the root is believed to exist
- tol_r: The tolerance level for the root solving method. Default value used in PGC-Sim is 1E-6

The rest of the input list is specific to the call function, which is identified with funct_no.

APPENDIX B: PLENUM MODEL EQUATIONS

The equations used for the plenum model of the rotating detonation engine (RDE) are provided in this section. The station numbering used in the equations refers to Exhibit B-1.

Exhibit B-1. RDE station numbering used in equations



If there is a difference between the isolator/injector inlet area at Station 3* and RDE inlet area at Station 3.2 and a pressure loss exists between these two stations, then the RDE inlet flow Mach number, $M_{3.2}$, will be different than the flow Mach number at the compressor exit, M_3 . In this case, the total pressure at the RDE inlet would be different than the total pressure at the compressor exit (i.e., $P_{t3.2} \neq P_{t3}$) but the total temperature can be assumed to be preserved between these two stations if the flow process from the compressor exit to RDE inlet is assumed to be isentropic. Then from the mass conservation and compressibility relations [8], Equation B-1 can be used to find the RDE inlet Mach number.

$$\frac{A_{3.2}}{A_{compr}} = (1 + f) \frac{M_3}{M_{3.2} \Pi_{inj}} \left\{ \frac{1 + \frac{\gamma_3 - 1}{2} M_{3.2}^2}{1 + \frac{\gamma_3 - 1}{2} M_3^2} \right\}^{\frac{(\gamma_3 + 1)}{2(\gamma_3 - 1)}} \quad \text{Equation B-1}$$

Equation B-1 requires an iterative solution scheme to solve for $M_{3.2}$. Π_{inj} , is the total pressure loss at the isolator/inlet region due to the injectors, which is defined as shown in Equation B-2.

$$\Pi_{inj} = \frac{P_{t3.2}}{P_{t3}} \quad \text{Equation B-2}$$

Then the static temperature at the RDE inlet, $T_{3.2}$, and the static pressure at the RDE inlet, $P_{3.2}$, can be found by using Equation B-3 and Equation B-4, respectively.

$$P_{3.2} = P_{t3.2} \left\{ 1 + \frac{\gamma_3 - 1}{2} M_{3.2}^2 \right\}^{\gamma_3 / \gamma_3 - 1} \quad \text{Equation B-3}$$

$$T_{3.2} = T_{t3.2} \left\{ 1 + \frac{\gamma_3 - 1}{2} M_{3.2}^2 \right\}^{-1} \quad \text{Equation B-4}$$

APPENDIX C: RDE FLOW PATH EQUATIONS

The equations used in each (Path a, Path b, Path c, and Path d) are provided in this section. In the entirety of the analysis, it is assumed that only two sets of thermodynamic properties exist; the first one is denoted with “r” that stands for the reactant mixture properties, the second one is denoted with “p” that stands for the post-detonation mixture properties. A thermodynamic property function is embedded into the simplified pressure gain combustion model (PGC-Sim) to calculate associated thermodynamic properties.

Path a Flow - “Detonation Only” Path a calculation includes detonation calculations to find post-detonation properties by using Heiser and Pratt’s method. [1] The Chapman-Jouget (CJ)-Mach number is calculated by using Equation 3-4. Then the static temperature at Station 3.4a is found by using Equation C-1 from Shah’s algorithm. [4]

$$T_{3.4a} = \frac{T_{3.2}}{M_{CJ}^2 \left(\frac{\gamma_r + 1}{1 + \gamma_r M_{CJ}^2} \right)^{\gamma_r + 1 / \gamma_r}} \quad \text{Equation C-1}$$

The static pressure at Station 3.4a is found by using Equation C-2.

$$P_{3.4a} = \frac{P_{3.2}(1 + \gamma_r M_{CJ}^2)}{\gamma_r + 1} \quad \text{Equation C-2}$$

The CJ-Velocity, V_{CJ} , can be found by using the definition of speed of the sound for the CJ-Mach Number as shown in Equation C-3.

$$V_{CJ} = M_{CJ} \sqrt{\gamma_r R_r T_{3.2}} \quad \text{Equation C-3}$$

The vertical velocity component at Station 3.2, $V_{3.2y}$, and the axial velocity component at Station 3.4, $V_{3.4xw}$, are used together with the CJ-Wave speed, V_{CJ} , to obtain the total temperature at Station 3.4a from a flow kinetic energy analysis in the static frame. [4, 6, 7] Flow speeds are calculated by using methods similar to Braun et al. [6, 7], where the speeds are calculated for the wave frame and then translated to static frame of reference to obtain total properties.

In Equation C-4,

$$T_{t3.4a} = T_{3.4a} + \frac{V_{3.4xw}^2 - V_{CJ}^2 + V_{3.2y}^2}{2c_{p,p}} \quad \text{Equation C-4}$$

the axial velocity component $V_{3.4xw}$ is calculated by using Equation C-5.

$$V_{3.4xw} = \sqrt{\gamma_p R_p T_{3.4a}} \quad \text{Equation C-5}$$

The vertical velocity component at Station 3.2 can be found by using Equation C-6.

$$V_{3.2y} = M_{3.2} \sqrt{\gamma_r R_r T_{3.2}} \quad \text{Equation C-6}$$

Total and static entropy change through Path a are then calculated by applying the second law analysis. The static and total entropy change are calculated for Path a with Equation C-7 and Equation C-8, respectively.

$$\Delta S_{3.4a} = c_{p,p} \ln \left(T_{3.4a} / T_0 \right) - c_{p,r} \ln \left(T_{3.2a} / T_0 \right) - \left\{ R_p \ln \left(P_{3.4a} / P_0 \right) - R_r \ln \left(P_{3.2} / P_0 \right) \right\} \quad \text{Equation C-7}$$

$$\Delta S_{t3.4a} = c_{p,p} \ln \left(T_{t3.4a} / T_0 \right) - c_{p,r} \ln \left(T_{t3.2} / T_0 \right) - \left\{ R_p \ln \left(P_{t3.4a} / P_0 \right) - R_r \ln \left(P_{t3.2} / P_0 \right) \right\} \quad \text{Equation C-8}$$

Path a exit station properties are then equated to the static and total properties calculated for Station 3.4a, because no other thermodynamic process exists between Station 3.4a and Station 4a.

$$\begin{aligned} T_{t4a} &= T_{t3.4a} \\ P_{t4a} &= P_{t3.4a} \\ T_{4a} &= T_{3.4a} \\ P_{4a} &= P_{3.4a} \\ C_{p4a} &= C_{p3.4a} \\ \gamma_{4a} &= \gamma_p \\ R_{4a} &= R_{3.4a} \\ \Delta S_{3.4a} &= \Delta S_{4a} \end{aligned}$$

Path b Flow - “Detonation + Oblique Shock” Post-detonation properties are the same with Path a, therefore, some of the results from Path a are directly used here for pre-shock states.

$$\begin{aligned} T_{t3.4b} &= T_{t4a} \\ P_{t3.4b} &= P_{t4a} \\ T_{3.4b} &= T_{4a} \\ P_{3.4b} &= P_{4a} \\ C_{p3.4b} &= C_{p4a} \\ \gamma_{3.4b} &= \gamma_{4a} \\ M_{3.4b} &= M_{CJ} \end{aligned}$$

The oblique shock solver (Appendix D: 2-Dimensional Oblique Shock Solver Equations) is called in this part to calculate post-shock properties, as well as the shock angles. The exit state Mach number, $M_{3.6b}$, exit state static temperature $T_{3.6b}$, exit state static pressure, $P_{3.6b}$, and exit state total pressure, $P_{t3.6b}$, are calculated by the oblique shock solver. The axial flow speed at Station 3.6b on the wave frame, $V_{3.6bxw}$, is then used to calculate the total temperature at Station 3.6b with Equation C-9 by using a similar kinetic energy analysis used in Path a.

$$T_{t3.6b} = T_{3.6b} + \frac{V_{3.6bxw}^2 - V_{CJ}^2 + V_{3.2y}^2}{2c_{p,p}} \quad \text{Equation C-9}$$

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The axial flow speed at Station 3.6b on the wave frame can be found by using Equation C-10, which is from the definition of the speed of sound.

$$V_{3.6bwx} = M_{3.6b} \sqrt{\gamma_{3.4b} R_p T_{3.6b}} \quad \text{Equation C-10}$$

Total and static entropy change through Path a are then calculated by applying the second law analysis. The static and total entropy change are calculated for Path b with Equation C-11 and Equation C-12, respectively.

$$\Delta S_{3.6b} = \Delta S_{3.4a} + c_{p,3.4b} \ln \left(T_{3.6b} / T_{3.4b} \right) - R_p \ln \left(P_{3.6b} / P_{3.4b} \right) \quad \text{Equation C-11}$$

$$\begin{aligned} \Delta S_{t3.6b} = & c_{p,p} \ln \left(T_{t3.6b} / T_0 \right) - c_{p,r} \ln \left(T_{t3.2} / T_0 \right) \\ & - \left\{ c_p \ln \left(P_{t3.6b} / P_0 \right) - R_r \ln \left(P_{t3.2} / P_0 \right) \right\} \end{aligned} \quad \text{Equation C-12}$$

Then the Path-b exit station properties are equated to the static and total properties calculated for Station 3.6b, because no other thermodynamic process exists between Station 3.6b and Station 4b.

$$\begin{aligned} T_{t4b} &= T_{t3.6b} \\ P_{t4b} &= P_{t3.6b} \\ T_{4b} &= T_{3.6b} \\ P_{4b} &= P_{3.6b} \\ c_{p4b} &= c_{p3.6b} \\ \gamma_{4b} &= \gamma_p \\ R_{4b} &= R_{3.6b} \\ \Delta S_{4b} &= \Delta S_{3.6b} \end{aligned}$$

Path c Flow – “Deflagration” For the deflagration calculations, thermodynamic states before the shock are found differently from Path a and Path b, depending on the relative amounts of the deflagration to detonation fuel consumption.

If the fuel-to-air ratio for detonation is more than the fuel-to-air ratio spent for deflagration, then the thermodynamic properties for Station 3.4c can be found by using Equation C-13.

$$\begin{aligned} \gamma_{3.4c} &= \gamma_3 + (\gamma_p - \gamma_3) \frac{f_{defl}}{f_{det}} \\ R_{3.4c} &= R_r + (R_p - R_r) \frac{f_{defl}}{f_{det}} \\ c_{p3.4c} &= c_{pr} + (c_{p,p} - c_{p,r}) \frac{f_{defl}}{f_{det}} \end{aligned} \quad \text{Equation C-13}$$

If the fuel-to-air ratio for detonation is less than for the fuel-to-air ratio for deflagration, then the State 3.4c properties are equal to post-detonation properties (i.e., properties denoted with “p”).

The static pressure at Station 3.4c is equal to the static pressure at RDE inlet, $P_{3.4c}=P_{3.2}$. Then the vertical velocity component of the Mach number at Station 3.4c can be found by using Equation C-14.

$$M_{3.4cy} = \sqrt{\frac{V_{3.2y}^2}{\gamma_{3.4c} R_{3.4c} T_{3.4c} - 0.5(\gamma_{3.4c} - 1) V_{3.2y}^2}} \quad \text{Equation C-14}$$

The total temperature at Station 3.4c can be found by using Equation C-15, which is derived from the first law analysis for combustion processes.

$$T_{t3.4c} = \frac{c_{p,r} T_{t3.2} + f_{defl} h_{PR} \eta_b}{c_{p,3.4c} (1 + f_{defl})} \quad \text{Equation C-15}$$

In Equation C-15, η_b is the deflagration efficiency and h_{PR} is the fuel heating value for combustion process. The static temperature at Station 3.4c can be found by using Equation C-16.

$$T_{3.4c} = \frac{T_{t3.4c}}{1 + 0.5(\gamma_{3.4c} - 1) M_{3.4cy}^2} \quad \text{Equation C-16}$$

The flow velocity component in the axial direction is then found by using Equation C-17.

$$V_{3.4cx} = \sqrt{\gamma_p R_p T_{3.4c}} \quad \text{Equation C-17}$$

The corresponding Mach number in the axial direction can then be calculated by using Equation C-18.

$$M_{3.4cx} = \frac{V_{3.4cx}}{\sqrt{\gamma_{3.4c} R_{3.4c} T_{3.4c}}} \quad \text{Equation C-18}$$

The total Mach number at Station 3.4c, $M_{3.4c}$, is found by using Equation C-19.

$$M_{3.4c} = \sqrt{M_{3.4cx}^2 + M_{3.4cy}^2} \quad \text{Equation C-19}$$

The total pressure at Station 3.4c is found by using Equation C-20, derived from the isentropic flow relations.

$$P_{t3.4c} = P_{3.4c} \left(\frac{T_{t3.4c}}{T_{3.4c}} \right)^{\gamma_{3.4c}/\gamma_{3.4c}-1} \quad \text{Equation C-20}$$

Total and static entropy change at Station 3.4c are then calculated by applying the second law analysis. The static and total entropy change are calculated with Equation C-21 and Equation C-22, respectively.

$$\Delta S_{3.4c} = c_{p,p} \ln \left(\frac{T_{3.4c}}{T_0} \right) - c_{p,r} \ln \left(\frac{T_{3.2}}{T_0} \right) - \left\{ R_p \ln \left(\frac{P_{3.4c}}{P_0} \right) - R_r \ln \left(\frac{P_{3.2}}{P_0} \right) \right\} \quad \text{Equation C-21}$$

$$\Delta S_{t3.4c} = c_{p,p} \ln \left(\frac{T_{t3.4c}}{T_0} \right) - c_{p,r} \ln \left(\frac{T_{t3.2}}{T_0} \right) - \left\{ R_p \ln \left(\frac{P_{t3.4c}}{P_0} \right) - R_r \ln \left(\frac{P_{t3.2}}{P_0} \right) \right\} \quad \text{Equation C-22}$$

Similar to Path b, the oblique shock solver is used here with the calculated shock angle from Path b to find properties before the mixing, i.e., for Station 3.6c. The oblique shock solver is denoted $M_{3.4c}$ and used to find the exit state Mach number, $M_{3.6c}$; exit state static temperature, $T_{3.6c}$; exit state static pressure, $P_{3.6c}$; and exit state total pressure, $P_{t3.6c}$.

The axial flow speed at Station 3.6c on the wave frame, $V_{3.6cwx}$, is then used to calculate the total temperature at Station 3.6c with Equation C-23 by using a similar kinetic energy analysis used in Path a.

$$T_{t3.6c} = T_{3.6c} + \frac{V_{3.6cwx}^2 - V_{CJ}^2 + V_{3.2y}^2}{2c_{p,p}} \quad \text{Equation C-23}$$

The axial flow speed at Station 3.6c on the wave frame can be found by using Equation C-24, which is from the definition of the speed of sound.

$$V_{3.6cwx} = M_{3.6c} \sqrt{\gamma_{3.4c} R_p T_{3.6c}} \quad \text{Equation C-24}$$

Total entropy change and static entropy change through Path a are then calculated by applying the second law analysis. Total entropy change and static entropy change are calculated for Path b with Equation C-25 and Equation C-26, respectively.

$$\Delta S_{3.6c} = \Delta S_{3.4c} + c_{p3.4c} \ln \left(\frac{T_{3.6c}}{T_{3.4c}} \right) - R_p \ln \left(\frac{P_{3.6c}}{P_{3.4c}} \right) \quad \text{Equation C-25}$$

$$\Delta S_{t3.6c} = \Delta S_{t3.4c} + c_{p3.4c} \ln \left(\frac{T_{t3.6c}}{T_{t3.4c}} \right) - R_p \ln \left(\frac{P_{t3.6c}}{P_{t3.4c}} \right) \quad \text{Equation C-26}$$

Path d Flow - "Mixing" Properties from paths a, b, and c are used to find the mixed flow's thermodynamic properties, which is denoted as Path d. A mass averaging is made to find average quantities. Second law thermodynamic analysis for mixing flows is used to find the pressure of the exiting flow. The mixing fractions used in the equations are from Section 3.1.4.

The mixture constant specific heat, gas constant, and the ratio of specific heats can be found by using Equation C-27.

$$\begin{aligned} c_{p3.6d} &= (1 - \varepsilon)(1 - \psi)\phi c_{p3.4a} + \psi \varepsilon \xi (1 - \phi) c_{p3.6b} + (1 - \psi) c_{p3.6c} \\ R_{3.6d} &= (1 - \varepsilon)(1 - \psi)\phi R_{3.4a} + \psi \varepsilon \xi (1 - \phi) R_{3.6b} + (1 - \psi) R_{3.6c} \end{aligned} \quad \text{Equation C-27}$$

$$\gamma_{3.6d} = (1 - \varepsilon)(1 - \psi)\phi\gamma_{3.4a} + \psi\varepsilon\xi(1 - \phi)\gamma_{3.6b} + (1 - \psi)\gamma_{3.6c}$$

Similar mixing analysis with the above can be performed to obtain equations to calculate mixture total and static temperatures with Equation C-28 and Equation C-29, respectively.

$$T_{t3.6d} = (1 - \varepsilon)(1 - \psi)\phi T_{t3.4a} + \psi\varepsilon\xi(1 - \phi)T_{t3.6b} + (1 - \psi)T_{t3.6c} \quad \text{Equation C-28}$$

$$T_{3.6d} = (1 - \varepsilon)(1 - \psi)\phi T_{3.4a} + \psi\varepsilon\xi(1 - \phi)T_{3.6b} + (1 - \psi)T_{3.6c} \quad \text{Equation C-29}$$

The mixture static and total entropy changes can be found by using Equation C-30 and Equation C-31, respectively.

$$\Delta s_{3.6d} = (1 - \varepsilon)(1 - \psi)\phi\Delta s_{3.4a} + \psi\varepsilon\xi(1 - \phi)\Delta s_{3.6b} + (1 - \psi)\Delta s_{3.6c} \quad \text{Equation C-30}$$

$$\Delta s_{t3.6d} = (1 - \varepsilon)(1 - \psi)\phi\Delta s_{t3.4a} + \psi\varepsilon\xi(1 - \phi)\Delta s_{t3.6b} + (1 - \psi)\Delta s_{t3.6c} \quad \text{Equation C-31}$$

The second law analysis is used here to find the mixture station exit total and static pressures, which are calculated by using Equation C-32 and Equation C-33, respectively.

$$P_{t3.6d} = P_0 e^{\left(c_{p3.6d} \ln(T_{t3.6d}/T_0) - c_{p,r} \ln(T_{t3.2}/T_0) + R_r \ln(P_{t3.2}/P_0) - \Delta s_{t3.6d} \right) / R_{3.6d}} \quad \text{Equation C-32}$$

$$P_{3.6d} = P_0 e^{\left(c_{p3.6d} \ln(T_{3.6d}/T_0) - c_{p,r} \ln(T_{3.2}/T_0) + R_r \ln(P_{3.2}/P_0) - \Delta s_{3.6d} \right) / R_{3.6d}} \quad \text{Equation C-33}$$

Path d exit station properties are then equated to the static and total properties calculated for Station 3.6d, because no other thermodynamic process exists between Station 3.6d and Station 4d.

$$\begin{aligned} T_{t4d} &= T_{t3.6d} \\ P_{t4d} &= P_{t3.6d} \\ T_{4d} &= T_{3.6d} \\ P_{4d} &= P_{3.6d} \\ c_{p4d} &= c_{p3.6d} \\ \gamma_{4d} &= \gamma_p \\ R_{4d} &= R_{3.6d} \\ \Delta s_{4d} &= \Delta s_{3.6d} \end{aligned}$$

Exit Flow Mixing Another mixing analysis is made to obtain the average thermodynamic properties at the exit of the RDE. Mass averaging is applied to obtain the total and static temperatures and specific heats; the gas constant and second law analysis are used to find the average exit pressures (both static and total)

The mixture constant specific heat, gas constant, and ratio of specific heats can be found by using Equation C-34.

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$$\begin{aligned}
 c_{p4} &= \psi\phi c_{p4a} + ((1-\varepsilon)(1-\psi)\phi + \phi\varepsilon\xi(1-\psi))c_{p4d} + (1-\xi)\varepsilon(1-\psi)c_{p4b} \\
 R_4 &= \psi\phi R_{4a} + ((1-\varepsilon)(1-\psi)\phi + \phi\varepsilon\xi(1-\psi))R_{4d} + (1-\xi)\varepsilon(1-\psi)R_{4b}
 \end{aligned}
 \tag{Equation C-34}$$

$$\gamma_4 = \psi\phi\gamma_{4a} + ((1-\varepsilon)(1-\psi)\phi + \phi\varepsilon\xi(1-\psi))\gamma_{4d} + (1-\xi)\varepsilon(1-\psi)\gamma_{4b}$$

Similar mixing analysis with above is used to obtain the RDE exit mixture total and static temperatures that are given by using Equation C-35 and Equation C-36, respectively.

$$\begin{aligned}
 T_{t4} &= \psi\phi T_{t4a} + ((1-\varepsilon)(1-\psi)\phi + \phi\varepsilon\xi(1-\psi))T_{t4d} \\
 &\quad + (1-\xi)\varepsilon(1-\psi)T_{t4b}
 \end{aligned}
 \tag{Equation C-35}$$

$$T_4 = \psi\phi T_{4a} + ((1-\varepsilon)(1-\psi)\phi + \phi\varepsilon\xi(1-\psi))T_{4d} + (1-\xi)\varepsilon(1-\psi)T_{4b} \tag{Equation C-36}$$

The mixture static and total entropy changes can be found by using Equation C-37 and Equation C-38, respectively.

$$\begin{aligned}
 \Delta s_4 &= \psi\phi\Delta s_{4a} + ((1-\varepsilon)(1-\psi)\phi + \phi\varepsilon\xi(1-\psi))\Delta s_{4d} \\
 &\quad + (1-\xi)\varepsilon(1-\psi)\Delta s_{4b}
 \end{aligned}
 \tag{Equation C-37}$$

$$\begin{aligned}
 \Delta s_{t4} &= \psi\phi\Delta s_{t4a} + ((1-\varepsilon)(1-\psi)\phi + \phi\varepsilon\xi(1-\psi))\Delta s_{t4d} \\
 &\quad + (1-\xi)\varepsilon(1-\psi)\Delta s_{t4b}
 \end{aligned}
 \tag{Equation C-38}$$

Finally, the second law analysis is used to find the RDE exit total and static pressures, which are calculated by using Equation C-39 and Equation C-40, respectively.

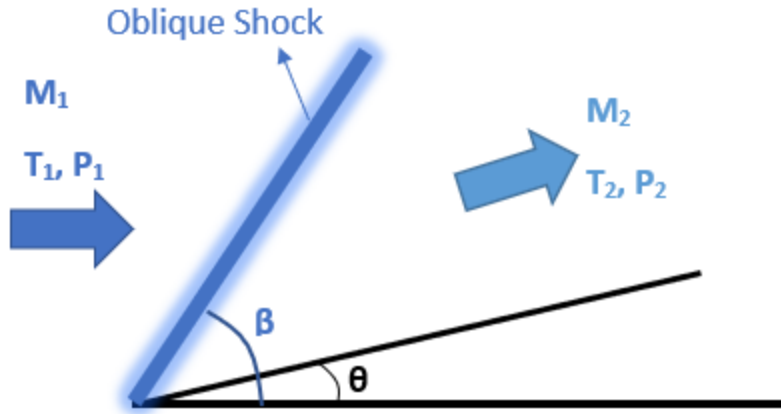
$$P_{t4} = P_0 e^{\frac{(c_{p4}\ln(T_{t4}/T_0) - c_{p,r}\ln(T_{t3.2}/T_0) + R_r\ln(P_{t3.2}/P_0) - \Delta s_{t4})}{R_4}} \tag{Equation C-39}$$

$$P_4 = P_0 e^{\frac{(c_{p4}\ln(T_4/T_0) - c_{p,r}\ln(T_{3.2}/T_0) + R_r\ln(P_{3.2}/P_0) - \Delta s_{t4})}{R_4}} \tag{Equation C-40}$$

APPENDIX D: 2-DIMENSIONAL OBLIQUE SHOCK SOLVER EQUATIONS

A 2-Dimensional Oblique Shock Solver, with the presented equations [8] in this section is used in the simplified pressure gain combustion model (PGC-Sim) to calculate the post-shock thermodynamic states and some of the shock angles. The oblique shock structure and the variables used in the equations are illustrated in Exhibit D-1.

Exhibit D-1. Oblique shock nomenclature used in the solver



In Exhibit D-1, properties with subscripts 1 refers to the pre-shock states; subscripts with 2 refers to the post-shock states. The angle β is known as the “shock angle” and is measured from the horizontal line assumed to be passing through the origination point of the shock wave. The angle θ is known as the “wedge angle” and can represent the angle formed by a geometrical structure causing the shock or can refer to the imaginary line aligned with the post-shock flow direction. For the rotating detonation engine (RDE) detonation wave, there is no geometrical structure causing the oblique shock wave; therefore, the angle θ is the post-shock flow direction.

For the case of the RDE detonation shock wave, the angle θ can be found by using the pre-shock flow properties by using Equation D-1.

$$\theta = \frac{1}{2} \sqrt{\frac{\gamma_1 + 1}{\gamma_1 - 1}} \arctan \left(\sqrt{\frac{\gamma_1 - 1}{\gamma_1 + 1}} (M_1^2 - 1) \right) - \frac{1}{2} \arctan \left(\sqrt{M_1^2 - 1} \right) \quad \text{Equation D-1}$$

The shock angle, β , is related to the flow angle θ with Equation D-2.

$$\tan \theta = 2 \cot \beta \left[\frac{M_1^2 \sin^2 \beta}{M_1^2 (\gamma_1 + \cos 2\beta) + 2} \right] \quad \text{Equation D-2}$$

Equation D-2 is a transcendental equation that must be solved iteratively. The Brent Root Solver method (Appendix A: Brent Method) is used in PGC-Sim to solve for the shock angle β with Equation D-2.

The post-shock thermodynamic properties are functions of shock angles θ and β and can be calculated once the values of these angles are calculated.

The Mach number of the post-shock flow can be calculated with Equation D-3.

$$M_2 = \frac{1}{\sin(\beta - \theta)} \sqrt{\frac{(M_1 \sin \beta)^2 + 2/(\gamma_1 - 1)}{\frac{2\gamma_1}{\gamma_1 - 1} (M_1 \sin \beta)^2 - 1}} \quad \text{Equation D-3}$$

The static temperature for the post-shock flow is calculated by using Equation D-4.

$$T_2 = T_1 \frac{\left[1 + \frac{\gamma_1 - 1}{2} (M_1 \sin \beta)^2\right] \left[\frac{2\gamma_1}{\gamma_1 - 1} (M_1 \sin \beta)^2 - 1\right]}{\frac{(\gamma_1 + 1)^2}{2(\gamma_1 - 1)} (M_1 \sin \beta)^2} \quad \text{Equation D-4}$$

The static pressure for the post-shock wave flow is calculated by using Equation D-5.

$$P_2 = P_1 \frac{2\gamma_1 (M_1 \sin \beta)^2 - (\gamma_1 - 1)}{\gamma_1 + 1} \quad \text{Equation D-5}$$

The total thermodynamic properties such as the total temperature and total pressure are calculated by using Hugoniot Relations. The total pressure for the post-shock flow is calculated by using Equation D-6.

$$P_{t2} = P_{t1} \left\{ \left[\frac{(\gamma_1 + 1)(M_1 \sin \beta)^2}{(\gamma_1 - 1)(M_1 \sin \beta)^2 + 2} \right]^{\gamma_1/(\gamma_1 - 1)} \left[\frac{\gamma_1 + 1}{2\gamma_1 (M_1 \sin \beta)^2 - (\gamma_1 - 1)} - 1 \right]^{1/(\gamma_1 - 1)} \right\} \quad \text{Equation D-6}$$

The total temperature of the post-shock flow can be calculated by using Equation D-7.

$$T_{t2} = T_{t1} \frac{\left(\frac{1 + \gamma_1 M_1^2}{1 + \gamma_1 M_2^2} \right) \left(\frac{M_1}{M_2} \right)^2 \left[1 + \frac{\gamma_1 - 1}{2} M_2^2 \right]}{\left[1 + \frac{\gamma_1 + 1}{2} M_2^2 \right]} \quad \text{Equation D-7}$$

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