GAS TURBINE REHEAT USING *IN-SITU* COMBUSTION

Topical Report:
Task 4 – Conceptual Design and Development Plan

Cooperative Agreement No. DE-FC26-00NT40913

May 6, 2004

by

R.A. Newby
D.M. Bachovchin
T.E. Lippert

Siemens Westinghouse Power Corporation
4400 Alafaya Trail
Orlando, FL 32826

Prepared for

U.S. Department of Energy
National Energy Technology Laboratory
3610 Collins Ferry Road
P. O. Box 880
Morgantown, WV 26507-0880

Charles Alsup — DOE/NETL Project Manager

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ABSTRACT

Siemens Westinghouse Power Corporation (SWPC) is developing *in-situ* reheat (fuel injection via airfoil injection) as a means for increasing cycle efficiency and power output, with possibly reduced emissions. This report discusses engineering cycle evaluations on various reheat approaches, using GateCycle and ChemCad software simulations of typical F-class and G-class engines, modified for alternative reheat cycles. The conclusion that vane 1 reheat offers the most advantageous design agrees with the conclusions of the detailed chemical kinetics (Task 2) as verified by high temperature testing (Task 3) and Blade path CFD (Task 1) tasks. The second choice design option (vane 2 reheat after vane 1 reheat) is also validated in all tasks. A conceptual design and next recommended development tasks are presented.

EXECUTIVE SUMMARY

In-situ reheat is an alternative to traditional gas turbine reheat design in which fuel is fed through airfoils rather than in a bulky discrete combustor separating HP and LP turbines. The goals are to achieved increased power output and/or efficiency without higher emissions. In this program the scientific basis for achieving burnout with low emissions has been explored. In Task 1, Blade Path Aerodynamics, design options were evaluated using CFD terms of burnout, increase of power output, and possible hot streaking. It was concluded that Vane 1 injection in a conventional 4-stage turbine was preferred. Vane 2 injection after vane 1 injection was possible, but of marginal benefit. In Task 2, Combustion and Emissions, detailed chemical kinetics modeling, validated by Task 3 experiments, resulted in the same conclusions, with the added conclusion that some increase in emissions was expected.

In the present Task 4, Conceptual Design and Development Plan, Siemens Westinghouse power cycle analysis software packages have been used to evaluate alternative ***in-situ*** reheat design options in terms of increase in power output and increase in (simple and combined) cycle efficiency. Only single stage reheat, via vane 1, was found to have merit. This is again consistent with conclusions from previous tasks.

Unifying the results of all the tasks, a conceptual design for single stage reheat utilizing 24 holes, 1.8 mm diameter, at the trailing edge of vane 1 is presented.

A development plan is presented. Tasks include verification at scaled up conditions, analytical evaluation of a more extensive matrix of design options (in search of lower emissions), and investigation into the use of hydrogen-including reheat fuels for accelerated burnout and incorporation into advanced cycles.

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1. INTRODUCTION AND BACKGROUND

Cooperative Agreement No. DE-FC26-00NT40913, “Gas Turbine Reheat Using *In-situ* Combustion,” between Siemens Westinghouse Power Corporation and the United States Department of Energy began on October, 1, 2000, and IS scheduled to end on May 31, 2004.

The overall objective of this project is to develop a novel gas reheat concept for gas turbine engines, in which fuel is injected directly into the turbine through one or more stages of vanes and/or blades. The key research goals involved in concept selection are to understand the combustion kinetics (burnout, emissions), blade performance and effects on turbine power output and efficiency. The concept is being evaluated for maximum energy efficiency (full reheat) and as a means to achieve power boost (minimum reheat)

Background. Increasing gas turbine firing temperature has historically increased gas turbine efficiency and power output. This approach is limited by the generation of thermal NOx and by the need for advanced materials at higher temperatures.

A well-known alternative approach is to add reheat combustion between turbine stages to achieve higher mean temperatures at which heat is extracted, without increasing maximum temperature. More fuel is burned, to give higher power output. If this is accompanied by increased pressure ratio, or used in combined cycle with higher steam cycle inlet temperature, then cycle efficiency is also increased.

Prior suggested reheat schemes have used discrete reheat combustors, either within a larger shell or externally, between two separate turbines. In the concept of this work [1], reheat fuel is injected directly into the turbine flow via injection holes in the turbine vanes or blades. The advantages are: 1) simplicity in turbine design with no increase in casing size and no external reheat combustor and transition. 2) Lower reheat peak combustion temperature; 3) near zero reheat NOx formation, with normalized NOx (to 15% oxygen) actually reduced; 4) reduced parasitic pressure loss; 5) substitution of fuel for some airfoil coolant flow.

Relevancy. The *in-situ* reheat concept represents a new approach that can allow gas turbine engines to move toward DOE goals of higher efficiency, higher power output, low emissions engines. This work will develop the scientific basis for the concept of *in-situ* reheat. In particular the work will identify the combustion kinetic basis for injection, will identify practical designs (simple or flame-held) for achieving injection, and will quantify effects on airfoil aerodynamics and turbine performance.

The project is divided into four technical tasks:

Task 1, Blade Path Aerodynamics (performed by Texas A&M University). A CFD model, CoRSI (Combustion and Rotor-Stator Interaction) was to incorporate simplified combustion kinetics with blade path flow. The model was used to investigate the effect of injection parameters (stage, fuel flow, fuel temperature, injection angle) on turbine performance (burnout location, forces on blades, power output, efficiency).

Task 2, Combustion and Emissions. Detailed (Chemkin and GRI data base) calculations are being performed to characterize reheat fuel burnout and emissions kinetics. Calculations are aimed at flameless (simple injection) and flame-held injection designs.

Task 3, Sub-Scale Testing. Direct injection is being studied experimentally in high-pressure, high-temperature test rigs. Blade path temperatures and velocities are used, with reduced pressure. The progress of direct injection combustion is being measured as a function of residence time. Results are used to calibrate Task 2 modeling and to check Task 1 model results.

Task 4, Conceptual Design and Development Plan. A preferred design approach will be identified and prepared for pre-commercial development based on the results of prior tasks.

The present document is the required Topical Report on Task 4.

2. CONCEPTUAL EVALUATION OF ALTERNATIVE REHEAT CONFIGURATIONS

2.1 Background And Objectives

Several software tools have been established as useful for advanced cycle evaluations, each having advantages for certain types of cycles or for certain aspects of cycle evaluations: GateCycle, and ChemCad. In this report, these are exercised to perform a preliminary, conceptual evaluation of alternative turbine reheat approaches.

The term "reheat" is used to mean utilizing oxygen remaining in a turbine expansion gas to combust additional fuel, thereby increasing the expansion gas temperature and permitting further, efficient power extraction from that gas. Various means for achieving reheat-type performance in gas turbine systems have been proposed. The “sequential combustion reheat” power system adds a high-pressure air compressor, primary-fuel combustor, a high-pressure expander stage, and a reheat-combustor to an existing low-pressure turbine expander. This sequential combustion reheat system requires the development of new equipment components, and extensive integration of new components with existing equipment.

A proposed, novel reheat method, called "*in-situ*" reheat [1], utilizes the injection of fuel through the turbine airfoils rather than through reheat combustor baskets, with reheat combustion proceeding in the wakes of the airfoils. The base concept is to add enough fuel at the vane 1 trailing edge to restore gas temperature to the turbine inlet temperature. A variation, that we will call “fractional reheat” has been proposed that applies moderate *in-situ* reheat to restore temperature only partially. Its main purpose is to compensate for the gas cooling effect when cooling air from the vane and blades mix.

One additional form of reheat is identified in this report, "partial oxidation" reheat that may be applied with reheat combustor baskets or with *in-situ* reheat. In this reheat concept the turbine fuel is first subjected to partial oxidation to generate a low heating-value fuel gas that is expanded in one or more turbine stages that include partial combustion reheat of the fuel gas. The *in-situ* reheat version of the partial oxidation concept utilized cooling air ejected from the airfoils to provide the oxidant needed for combustion of the fuel gas expanding through the turbine.

This report describes these alternative approaches at a conceptual level and makes estimates of their relative performance. Cycle performance estimates are reported using GateCycle and ChemCad software simulations of typical F and G class engines modified for the alternative reheat cycles. In general, all of the reheat approaches show potential advantages over the conventional reheat approach, but considerable development is required for all of the reheat concepts considered.

2.2 Reference Turbine Performance

Reference turbine cycles were first generated for the typical F and G class turbines to provide the framework for modification and comparison with the reheat turbine cycles. These simulations are only "representative" of the stage conditions and performance of turbines and do not function as detailed models of the turbines.

A conventional F-class simulation was set up using GateCycle (a power system simulator marketed by Enter Software, Inc.) and used to estimate the performance of the fractional and full *in-situ* reheat cycles at turbine off-design conditions. Standard F-class and G-class simulations were set up using ChemCad (a general process simulator marketed by Chemstations, Inc.) to be applied for full *in-situ* reheat and partial oxidation reheat cycles.

A process schematic of the Reference turbine model is shown in Figure 1. Ambient air is compressed, and vane and rotor coolant air streams are extracted from the compressor. The rotor coolant air is cooled and supplied to the four rotor stages of the turbine at near to the compressor outlet pressure. The vane coolant air is not cooled and is extracted at the appropriate pressure to supply coolant to each vane stage. Steam cooling of the combustor transition section is also shown. Representative compressor, combustor, and four-stage expander conditions (temperatures, pressures, flows, cooling flows, coolant temperatures, and component efficiencies) were used.

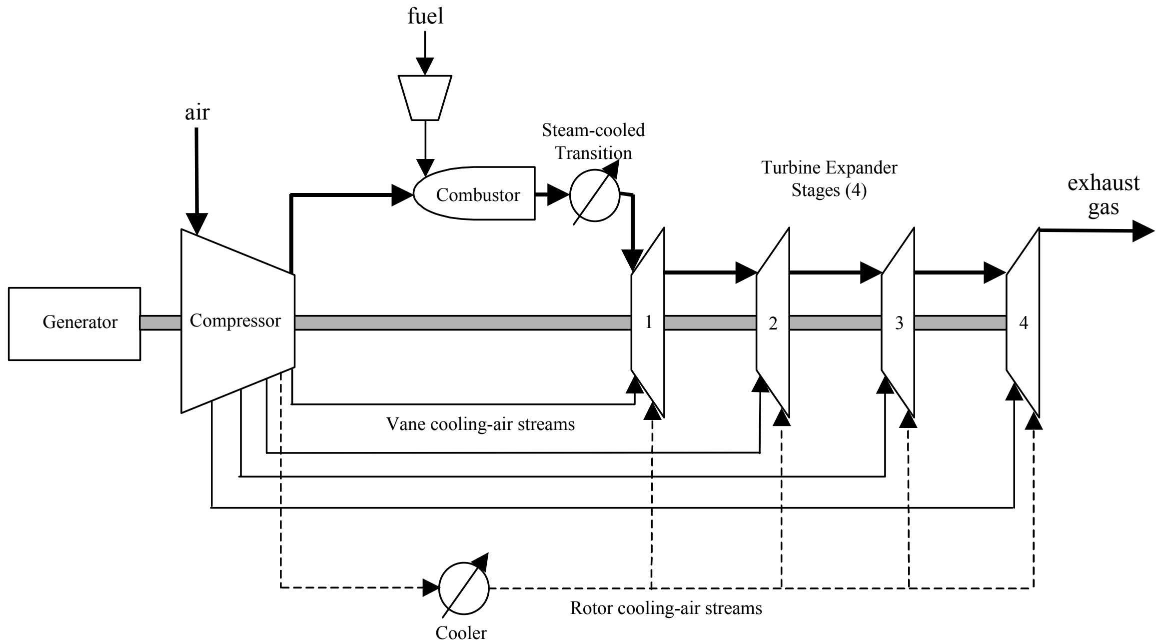

Figure 1 – Reference Turbine Model

ISO air inlet conditions were used in all of the simulations, and a natural gas fuel was applied. Natural gas was assumed available to the cycles at 300 psia. The air and natural gas compositions assumed were slightly different in the GateCycle and ChemCad simulations, and are listed in Table 1. The differences are relatively insignificant. All of the simulations assumed a compressor inlet air pressure loss of 0.14 psi, and representative exhaust system pressure losses were assumed for simple-cycle and combined-cycle cases.

Table 1 – GateCycle and ChemCad Air and Natural Gas Compositions

	GateCycle	**ChemCad**
	Air (vol%)	
O_2	20.74	20.72
N_2	77.29	77.23
Ar	0.92	1.01
CO_2	0.03	0.03
H_2O	1.02	1.01
	Natural gas (vol%)	
methane	H/C ratio = 3.8813	95.0
ethane		2.0
propane		0.5
I-butane		0.5
nitrogen		2.0
Lower heating value (Btu/lb mole)	$3.42X10^5$	$3.5x10^5$

The simulation performances for the reference turbines with simple-cycle and combined-cycle configurations are listed in Table 2. The steam bottoming cycle performance was estimated from Siemens Westinghouse correlations of steam bottoming cycle efficiency as a function of the turbine exhaust temperature.

The GateCycle model and ChemCad model provide comparable estimates of the simple-cycle power and efficiency, with some of the difference being due to fuel compression power not being included in the GateCycle estimate, and differences in generator efficiency assumptions. Overall, the performance results are close to performance numbers published in the open turbine literature.

Table 2 – GateCycle and ChemCad Reference Turbine Simulation Results

	GateCycle F-class S-C	**ChemCad** F-class S-C	**ChemCad** F-class C-C	**ChemCad** G-class C-C
Fuel input (10^9 Btu/hr)	1.6974	1.698	1.666	2.100
TIT (°F)	2584	2598	2598	2782
RIT (°F)	2450	2453	2453	2609
Exhaust temperature (°F)	1096	1103	1100	1111
Exhaust oxygen (vol%)	12.5	12.4	12.4	11.9
Compression ratio	15.9	15.9	17.1	19.2
GT shaft power (MW)	193.4	190.0	181.8	243.3
Fuel compressor (MW)	0	0.57	0.56	0.95
GT generator eff (%) / loss (MW)	98.0 / 3.9	98.5 / 2.8	98.5 / 2.7	99.0 / 2.4
Net GT power (MW)	189.5	186.6	178.5	239.9
ST power (MW)	0	0	96.7	127.1
Aux. and BOP losses (MW)	0	0	6.4	8.4
Net plant power (MW)	189.5	186.6	268.8	358.6
Net plant efficiency - LHV (%)	38.1	37.5	55.0	58.3

2.3 Sequential Combustion Reheat And *In-Situ* Reheat Turbine Performance

The sequential combustor reheat turbine concept consists of a high-pressure air compressor, a high-pressure combustor, a high-pressure expander stage, and a reheat-combustor added to an existing, low-pressure turbine expander. It is illustrated in Figure 2, and it is represented commercially by the ABB GT24/GT26 Sequential Combustion System. In the simulations made in this evaluation, vane and rotor coolant flows are provided to the high-pressure expander stage and to the four, low-pressure turbine stages. The possibility of transition steam cooling of both the high-pressure and the reheat combustor transitions is shown. Compression of high-pressure fuel and reheat fuel is required.

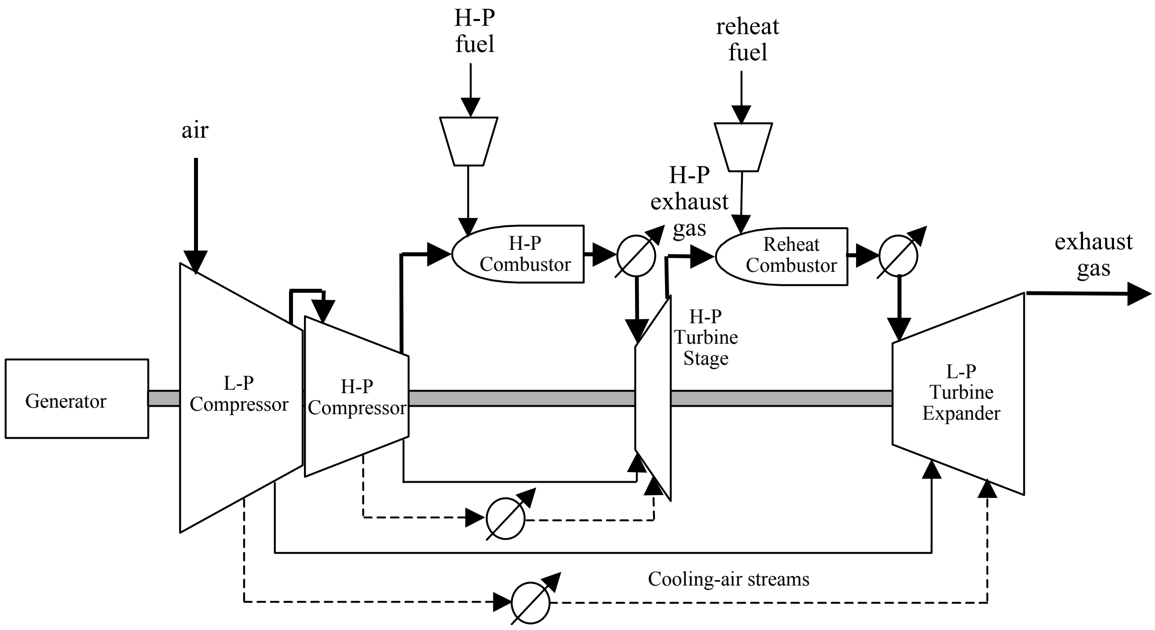

Figure 2 – Sequential Combustion Reheat Turbine Configuration

Simulations of the performance of sequential combustion reheat applied to the F-class and G-class turbines have been made using ChemCad. A simulation of two reheat-fired stages has also been made to judge the relative merits of multiple sequential combustion reheat. The results are summarized in Table 3. The high-pressure turbine stage was assumed to have an expansion ratio similar to the expansion ratio of the reference turbine stages. The firing temperatures applied in the high-pressure combustors and reheat combustors are approximately the same as those used in the reference turbine combustors. Estimates of both the simple-cycle and combined-cycle efficiencies are made.

Comparison on the net power generation and net plant efficiencies of Tables 2 and 3 indicates the relative benefits of the sequential combustion reheat cycle. The F-class reheat simple cycle gains 8.9 MW of power and 1.2 percentage points of efficiency, and the reheat combined cycle gains 18.4 MW and 1.9 percentage points. The G-class reheat simple-cycle gains 24.1 MW of power and 1.0 percentage points of efficiency, and the reheat combined-cycle gains 40.7 MW and 0.7 percentage points.

Table 3 – ChemCad Sequential Combustion Reheat Turbine Simulation Results

	501FD	501G	501FD two-reheats
Total fuel input (10^9 Btu/hr)	1.72	2.308	1.946
Primary fuel (lb/hr)	51,000	76,000	38,000
Reheat fuel (lb/hr)	32,200	35,500	56,000
HP-Turbine TIT(°F)	2583	2778	2583
HP-turbine RIT (°F)	2450	2604	2450
Reheat-turbine TIT (°F)	2583	2782	2583
Reheat-turbine RIT (°F)	2450	2611	2450
Exhaust gas rate (lb/hr)	3,714,684	4,401,494	3,725,503
Exhaust temperature (°F)	1107	1153	1105
Exhaust O_2 (vol%)	12.1	11.1	11.1
Compression ratio	33.9	37.1	58.7
H-P turbine shaft power (MW)	15.7	21.9	26.0
Total GT shaft power (MW)	199.5	268.3	213.7
Fuel compressor (MW)	1.0	1.6	2.1
GT generator eff (%)/ loss (MW)	98.5 / 3.0	99.0 / 2.7	98.5 / 3.2
Net GT power (MW)	195.5	264.0	208.3
ST power (MW)	98.2	144.9	98.7
Aux. and BOP losses (MW)	6.5	9.6	6.5
Net plant power (MW)	287.2	399.3	300.5
Net C-C efficiency - LHV (%)	56.9	59.0	52.7
Net S-C efficiency - LHV (%)	38.7	39.0	36.5

The benefits of two reheat stages diminishes greatly relative to one reheat stage, with the F-class reheat simple cycle gaining 12.8 MW of power and losing 2.2 percentage points of efficiency relative to the single reheat stage case, and the reheat combined-cycle gaining 13.3 MW and losing 4.2 percentage points relative to the single reheat stage case. The use of a single reheats stage results in substantial gains, but its cost and complexity must be weighed against those gains. A second reheat stage results in little additional gains and requires even greater complexity. The oxygen content of the turbine exhaust gas is lower in the reheat cases than in the reference cases, and is lower for two reheat stages than for a single reheat stage, showing a more effective utilization of compressed air in the reheat cases.

The *in-situ* reheat process model is basically identical to the sequential combustion reheat. The reheat combustor basket used with sequential combustion reheat is replaced by an "*in-situ* combustor" representing the flow path between vane and blade. This is illustrated in Figure 3. In *in-situ* reheat, sufficient fuel gas is injected through the high-pressure turbine stage airfoils rather than through reheat combustor baskets, with reheat-combustion proceeding in the wakes of the airfoils.

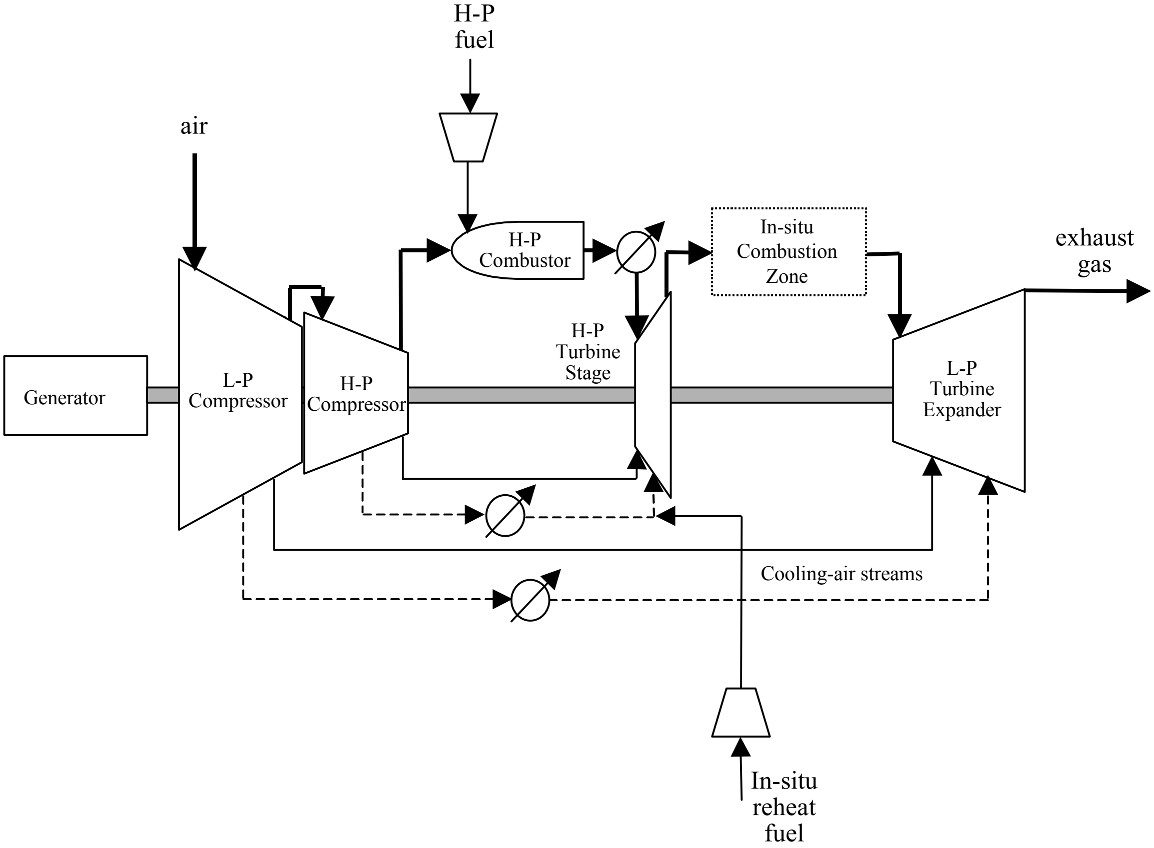

Figure 3 – Reheat Turbine Configuration with *In-situ* Reheat Combustion

Low-NO_x versions of the *in-situ* combustors have been conceived, but are still in early laboratory development. It is conceptualized that the *in-situ* reheat combustor may be more compact, lower in cost, and have lower pressure drop than the sequential combustion reheat combustor. A schematic comparison of the turbine layouts with sequential combustion reheat and with *in-situ* reheat is shown in Figure 4. The ability to complete combustion between the high-pressure stage and the low-pressure turbine, while avoiding overheating of airfoils, has not been demonstrated.

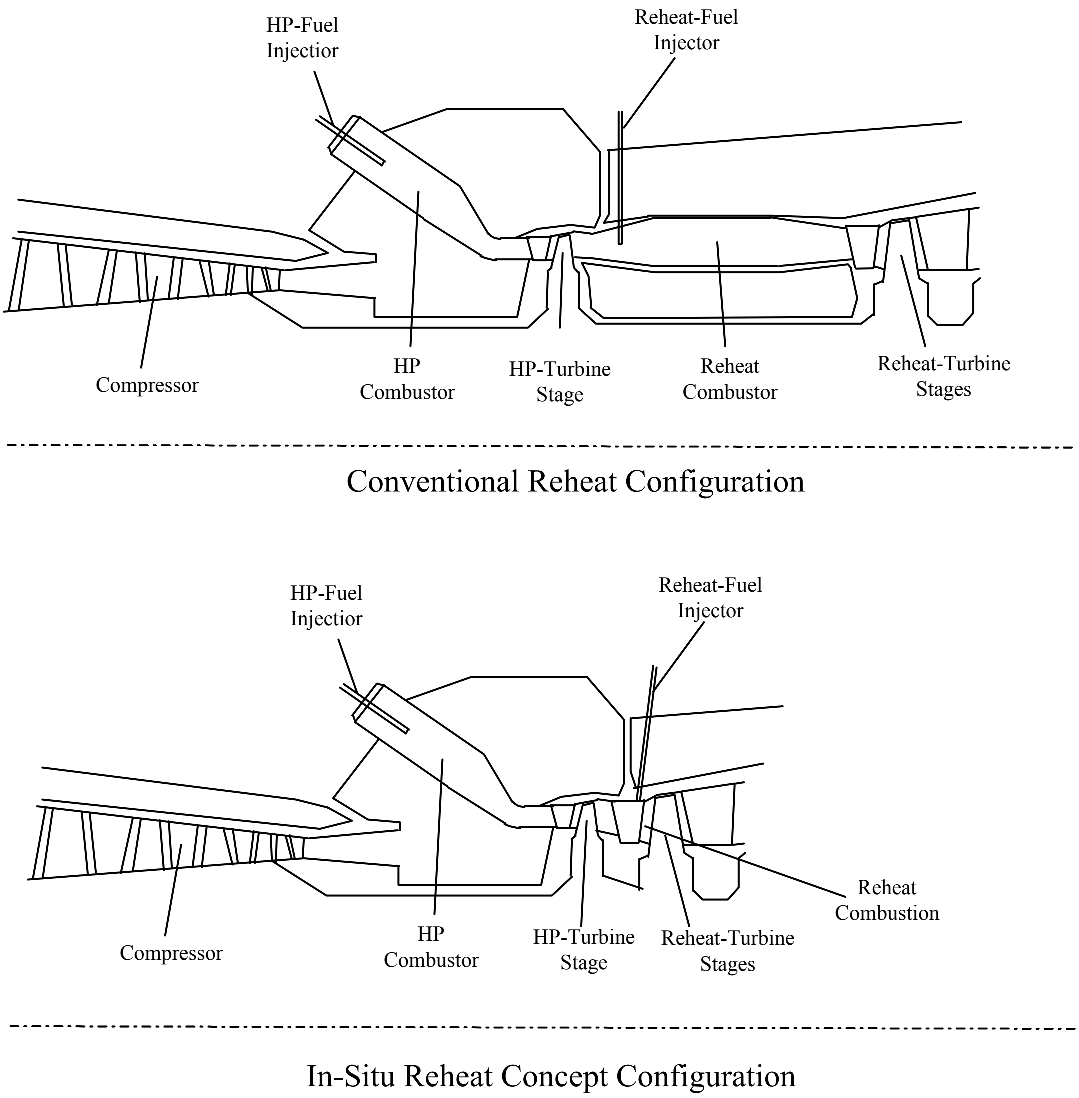

Figure 4 – Comparison of Conventional and *In-situ* Reheat Structures

The results listed in Table 3 for sequential combustion reheat are then also comparable to the results expected if *in-situ* reheat combustion were used, with possible small additional performance gain due to lower pressure drop over the *in-situ* reheat combustors. It can also be concluded that only a single *in-situ* reheat stage will be beneficial. Note that optimum pressure ratios for the simple-cycle and combined-cycle cases were not identified; so further performance improvements might be possible.

2.4 Fractional Reheat

In this approach a lesser degree of *in-situ* reheat is employed for moderate degrees of reheat in an existing turbine. The concept applies the existing compressor and expander design and adds a small amount of fuel into the first-stage vane (vane cooled by an air-fuel mixture). The gas flowing past the first vane is heated by this limited *in-situ* combustion approximately back up to the temperature that would have existed with no first-vane cooling. Fractional reheat can also be applied over the stage-1 rotor and stage-2 vane. The concept is illustrated in Figure 5.

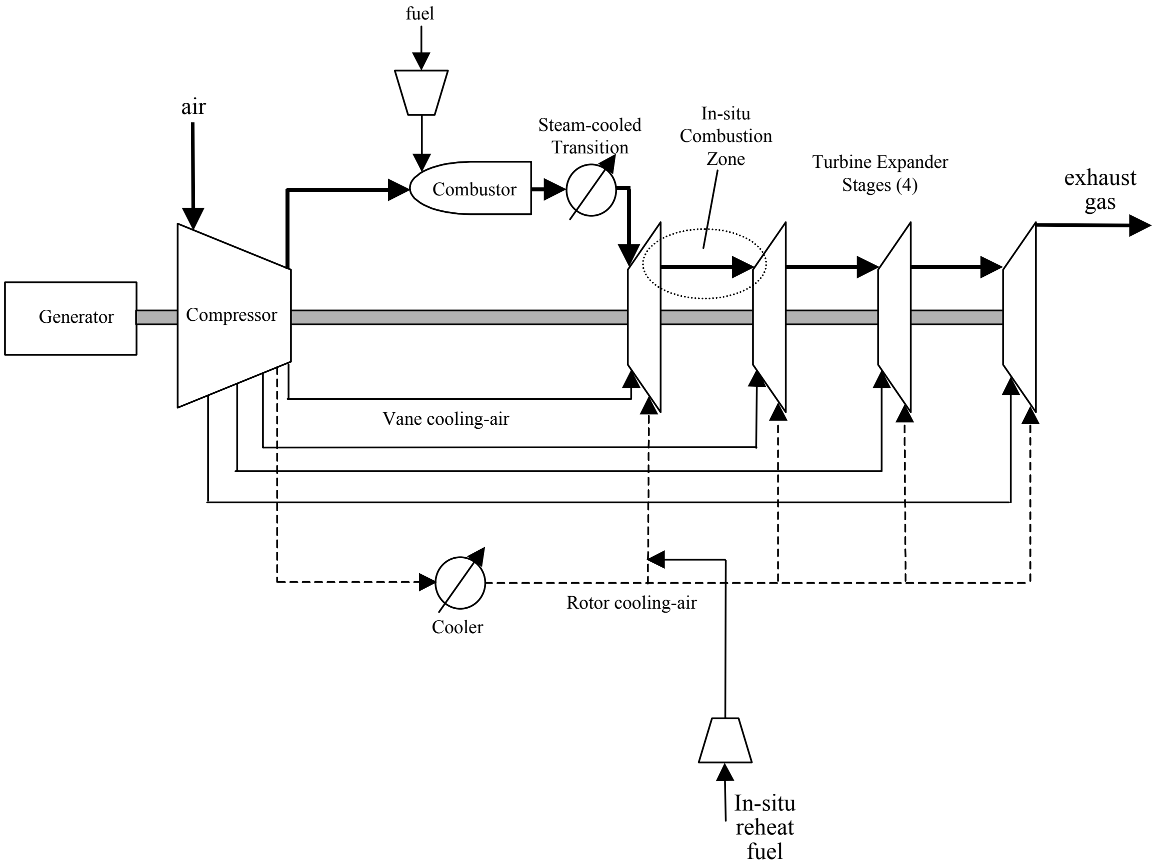

Figure 5 – Fractional *In-situ* Reheat Configuration

The cycle performance was simulated for an F-class application using GateCycle software. A design model of the engine was first generated and then modified to an off-design model to perform the simulation. A compressor map was utilized in the simulation that was not really representative of this compressor, so the off-design compressor simulation is not strictly accurate, but does show appropriate trends. Fractional reheat was roughly simulated in the GateCycle by placing a zero pressure drop reheat burner between the first and second expander stages and looking at the relative benefits of performing a small amount of reheat vs. the additional cooling air needed for cooling the subsequent airfoils. These heat transfer calculations are incorporated into the gate cycle program. The fuel flow is so small that it cannot replace significant cooling air or provide significant cooling of the airfoil.

At each level of fractional reheat, the compressor extraction control valves would need to be adjusted to accommodate the needed additional airfoil cooling. The primary combustor fuel rate and air rate were fixed at constant values throughout the range of reheats evaluated to give the same combustion temperature and turbine inlet conditions. The compressor surge margin must be sufficient to accommodate the increased air mass flow and expansion ratio for cooling the second-stage, and subsequent stages, which operate at higher temperatures with reheat.

Performance is listed in Table 4. The primary fuel rate is fixed at 21.925 lb/s. The compressor exit air rate is fixed at 894.9 lb/s, resulting in a turbine inlet temperature of 2581.5°F. The normal first-stage vane cooling air rate is 83.0 lb/s at 754°F and the first-stage rotor cooling air rate is 38.2 lb/s at 392°F. As the fractional reheat fuel input increases, the turbine simple-cycle power increases. The turbine simple-cycle efficiency initially increases, but then drops as the turbine exhaust temperature becomes too large. The compressor inlet air rate increases as the reheat fuel input increases due to increased airfoil cooling needs.

Table 4 – Fractional Reheat Simulation Results Using F-class Conditions (Simple-Cycle)

Reheat Fuel (lb/s)	**Turbine Power (MWe)**	**Turbine Efficiency (%, LHV)**	**Turbine Exhaust Temp (°F)**	**Compressor Pressure Ratio**	**Compressor Inlet Air Flow (lb/s)**	**2nd Stage Inlet Temp (°F)**	**2nd Stage Cooling Air Flow (lb/s)**
0	189.5	38.09	1097	16	1008.7	2050	55.1
0.1	190.5	38.13	1099	16	1009.9	2056	55.4
0.2	191.6	38.17	1101	16	1011.2	2063	55.8
0.3	192.7	38.21	1104	16	1012.4	2069	56.1
0.4	192.9	38.08	1108	16	1014.6	2078	56.6
0.5	193.9	38.12	1112	16	1016.8	2085	56.9
0.75	195.5	38.02	1119	16	1020.1	2104	57.9
1.0	197.7	38.02	1126	16	1023.7	2121	58.7
1.5	201.8	38.0	1140	16	1031.2	2159	60.5
2.0	205.3	37.8	1156	16	1038.9	2196	62.1
5.0	229.3	37.5	1243	16	1077.4	2408	70.8
10.0	269.9	37.3	1382	16.2	1129.4	2744	82.0

The table indicates that the maximum gain in simple-cycle efficiency is about 0.1 percentage points, or a 0.3% increase. The maximum gain in plant power is about 2.3% before the simple-cycle efficiency starts to drop. Fractional reheat results in greater cooling need after the turbine reheat stage(s) due to higher than normal subsequent-stage inlet temperatures. The higher turbine exhaust temperatures will also result in significant increases in combined-cycle power.

2.5 Partial Oxidation Reheat

Natural gas can be partially oxidized at high pressure by substoichiometric air to generate a low heating-value fuel gas and this is an important technology used to produce syngases for chemical synthesis. This fuel gas can be partially expanded across a high-pressure expander to generate power and to simultaneously cool the gas, and then applied for turbine reheat. The concept is illustrated in Figure 6. Steam is mixed with the preheated natural gas fuel to eliminate carbon formation in the partial oxidation burner. The generated fuel gas, having high hydrogen and carbon monoxide contents, has medium heating value and potential low-NO_x combustion behavior. It differs from the sequential combustion reheat cycle because 1) the H-P turbine expands a fuel gas rather than a combustion gas, and 2) the high-pressure expander is open-loop, steam cooled. The reheat is performed with combustor baskets, and the reheat combustor is much like a combustor used for medium heating value fuel gases in IGCC applications. This cycle was previously evaluated with 100% of the HRSG steam being added to the PO burner and found to have potential performance advantages [2].

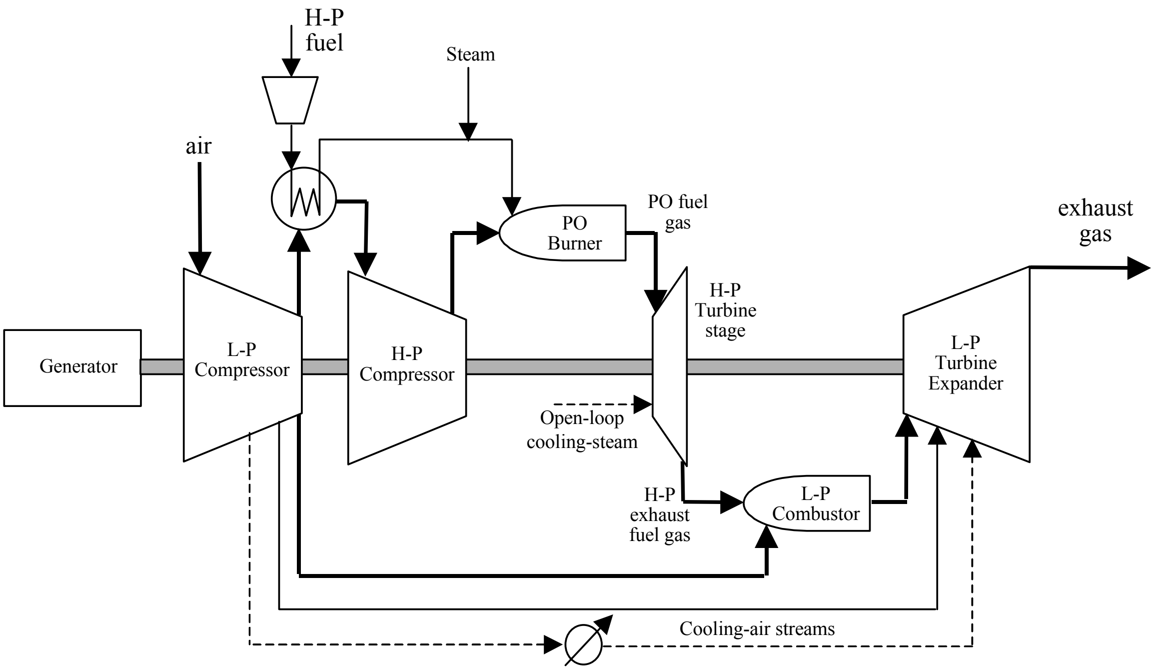

Figure 6 – Partial Oxidation Turbine Reheat Concept

If reheat is performed by *in-situ* reheat combustion, the airfoil coolant air in the reheat stages can also provide the oxidant needed for combustion of the fuel gas. The steam consumption can be minimized to levels needed for soot protection so that greater combined-cycle performance is achieved. Steam for the PO burner is generated by inter-cooling the H-P compressor. The fuel-rich nature of the partial oxidation combustors has the potential to improve cycle performance and reduce NO_x emissions. A multiple *in-situ* reheat configuration is illustrated in Figure 7. A partial oxidation burner is followed by a high-pressure expander and then three *in-situ* combustors before reaching the low-pressure turbine. The cooling air requirement for each reheat stage must be compatible with the reheat combustion needs on the subsequent stage.

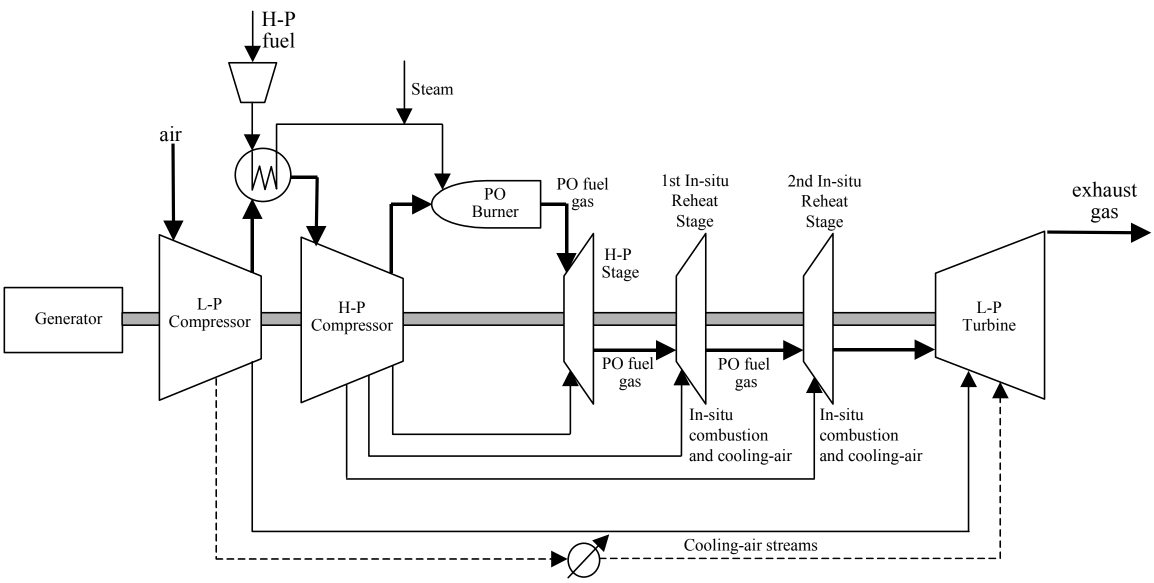

Figure 7 – Partial Oxidation with Multiple *In-situ* Reheat Stages

The results in Table 5 are for a Figure 7 configuration with 2 H-P turbine stages. They show that the performance for the partial oxidation reheat concept using a PO burner, followed by a H-P turbine (2 stages) having one *in-situ* reheat stage, with an expansion ratio of about 6.0, is better than sequential combustion reheat . The H-P turbine is followed by an *in-situ* reheat combustor integrated into an L-P turbine whose design is conventional. The PO burner outlet gas and the H-P turbine exhaust gas are medium heating-value gases having acceptable hydrogen content and the combustion of the H-P turbine gas in the L-P turbine should result in low NO_x emission:

Table 5 – ChemCad PO-Reheat Turbine Simulation Results

	F-class Two PO Expanders
Fuel input (10^9 Btu/hr)	2.48
Fuel input (lb/hr)	120,000
Water input (lb/hr)	200,000
HP-PO Turbine TIT(°F)	2590
HP-PO turbine RIT (°F)	2450
Reheat-turbine TIT(F)	2590
Reheat-turbine RIT (F)	2429
H-P turbine exhaust (lb/hr)	1,635,140
L-P turbine exhaust (lb/hr)	3,957,383
Exhaust temperature (°F)	1132
Exhaust O_2 (vol%)	8.0
Compression ratio	103
H-P turbine power (MW)	93.3
Total GT shaft power (MW)	318.5
Fuel compressor (MW)	6.3
GT generator eff (%)/ loss (MW)	98.5 / 4.8
Net GT power (MW)	307.5
ST power (MW)	115.5
Aux. and BOP losses (MW)	7.6
Net plant power (MW)	415.4
Net C-C efficiency - LHV (%)	57.1
Net S-C efficiency - LHV (%)	42.2

	PO burner gas	H-P turbine gas
H_2 (vol%):	14.33	9.00
CO	7.41	5.39
CO_2	4.34	5.20
H_2O	27.13	28.45
N_2	46.20	51.29
Ar	0.60	0.67
Heating value (10^4 Btu/lb-mole)	1.88	1.05

2.6 Conclusions

The following conclusions and recommendations can be drawn for the alternative reheat technologies:

- The sequential combustion reheat cycle can improve the performance (power output and efficiency) of both the simple-cycle and combined-cycle turbine power plant. A single reheat stage, with total turbine pressure ratio of about 30 may represent the upper limit of performance gains. Sequential combustion reheat requires major changes in compressor design, combustor design, reheat combustor design and turbine casing design.

- The *in-situ* reheat stage, with reheat fuel injected through the airfoils and into the expansion gas in the airfoil wakes, has the potential to provide a more compact turbine design than the sequential combustion reheat basket design, with comparable or better performance gains. The *in-situ* reheat design requirements, combustion behavior, and NO_x emission potential have not yet been established. Cycle studies indicate that *in-situ* reheat should also be limited to a single reheat stage, with multiple-reheat stages providing only limited additional benefits.

- The fractional reheat cycle applies a form of *in-situ* reheat combustion, with an air-fuel mixture used as airfoil coolant and reheat combustion occurring in the airfoil wakes. The level of reheat is limited so that minimal equipment modifications are possible. Fractional reheat can provide moderate benefits of increased power and efficiency that are limited by maximum reheat temperature limits and the compressor surge margin. It could be a low cost alternative to improve the performance of the standard turbine cycle.

- Partial oxidation *in-situ* reheat expands a partial oxidation fuel gas through the turbine, using airfoil cooling air for inter-stage, *in-situ* reheat combustion. It can utilize multiple reheat stages and can have performance superior to the sequential combustion reheat cycle. The concept has the potential for low plant NO_x emission, but carbon (soot) formation may be a technical issue. Design requirements and the ability to control the local temperature distribution have not been established.

- All of the reheat alternatives show performance merits, and differ in their relative complexity and technical risks. Small-scale testing of all of the reheat concepts is needed to advance the technologies to the state where technical feasibility potential can be judged, with parallel cycle evaluations being applied to assess design features, operation, control, and performance.

3. CONCEPTUAL DESIGN

The results of this Task 4 study and of Task 1 (Blade Path Aerodynamics, q.v. topical report) and of Task 2 (Combustion and Emissions, q.v. topical report) are consistent in concluding that *in-situ* reheat as applied to the vane 1 trailing edge of an existing large turbine is the preferred design. In this conceptual design, combustion can be completed, efficiency and power gains are most significant, and emissions increments are smallest. Based on the results in the Task 2 Topical Report, each vane 1 tailing edge would have 24 holes of diameter 1.8 mm (0.07 in) on each vane.

The three Task results for vane 2 reheat after vane 1 reheat are also consistent. Combustion can be completed, but in this case vane 2 holes would need flameholders in the form of bluff bodies. The specific design optimum found is to use 8 holes of diameter 3.2 mm (0.125 inch) on the trailing edge of each vane 2.

These designs are shown in Figure 8. The counter bores are used only for vane 2 reheat after vane 1 reheat. Since the burnout zone for vane 1 reheat is downstream of the injection point, no material changes would likely be needed. For vane 2 reheat, the Task 2 Topical Report shows that optimized design can also push the burnout zone for the stabilized flames off the metal.

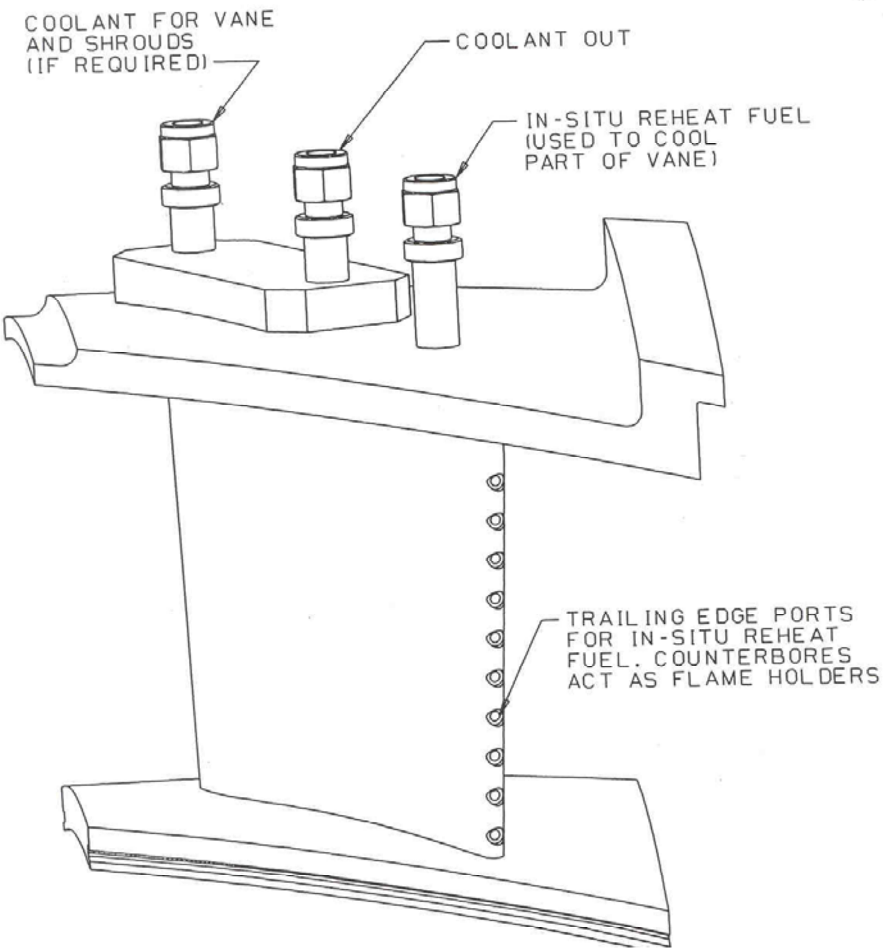

Figure 8 – Vane 1 and Vane 2 Trailing Edge Conceptual Designs

4. DEVELOPMENT PLAN

This program has used CFD; detailed chemical kinetics; high-pressure, high-temperature, full Mach number, sub-scale testing, and power cycle evaluation software to identify a preferred approach for *in-situ* reheat. The detailed kinetics suggests moderately increased emissions. Consequently, *in-situ* reheat development requires further experimental verification, scale-up verification, and theoretical and experimental looks at more design options.

Consequently the following development plan is proposed, prior to any detailed engine engineering:

- Parametrics. There are many parameters still to be explored using detailed kinetics, CFD, and testing. These include: leading edge or mid-span fuel injection; injection at an angle different from the local turbine gas angle; possible dilution of fuel to reduce NOx; injection mods to permit more rapid mix-out of injected fuel. All options are aimed at finding optimum designs that allow burnout of CO at low enough temperatures not to form NOx.

- Alternative fuels. Perform similar calculations and tests on reformed fuels, or hydrogen -containing fuels. There will be a possible increase in combustion rate with seeding of fuel with hydrogen. Also, advanced reheat cycles featuring integrated synthetic fuel technologies might offer efficiency benefits, so cycle evaluations are needed.

- Testing of stabilized flames. The flameholder model used in the Task 2 topical report must be experimentally verified.

- Verify results on larger scale. Verification of the small-scale tests in Task 3 of this program should be done on the now-completed (Siemens-owned) higher flow test facility.

- Verify with realistic rotors and stators. The next step is the experimental investigation of a scaled down, one-and-a-half stage turbine combustor. This experimental investigation would provide critical data on the interaction between the *in-situ* reheat, the rotor/stator interaction and the combustor hot streaks. This experiment would also provide the apparatus necessary to investigate different approaches for fuel injection and blade cooling. The experiment can be done at the blow down facility of the Texas A&M University. This facility provides approximately 10 kg/sec at 44 bar for approximately 5 minutes. If necessary, the mass flow rate can be increased by reducing the operating time.

5. REFERENCES

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