Selection of an Industrial Natural-Gas-Fired Advanced Turbine System - Task 3A

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TASK 3 - GAS FUELED ADVANCED TURBINE SYSTEM SELECTION

3.0 TASK OBJECTIVES

Identify a gas-fueled turbine and steam system which will meet the program goals for efficiency and emissions.

3.1 TECHNICAL GOALS AND REQUIREMENTS

Goals for the Advanced Turbine System Program(ATS) where outlined in the statement of work for five basic categories:

- **Cycle Efficiency**

System heat rate to have a 15% improvement over 1991 vintage systems being offered to the market

- **Environmental**

No post-combustion devices while meeting the following parameter targets:

1. Nitrous Oxide (NOx) emissions to equal 8 parts per million dry (ppmd) with 15 % oxygen.
2. Carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions to equal 20 parts per million(ppmd) each.

- **Cost**

Cost of electricity to be 10 percent less when compared to similar 1991 systems.

- **Fuel Flexibility**

Have to ability to burn coal or coal derived fuels without extensive redesign.

- **Reliability, Availability, Maintainability**

Reliability, availability and maintainability must be comparable to modern advanced power generation systems.

For all cycle and system studies, analyses were done for the following engine system ambient conditions:

- Temperature 59F
- Altitude Sea Level
- Humidity 60%

For the 1991 reference system, GE Aircraft Engines used its LM6000 engine product offering for comparison of the Industrial System parameters developed under this program. The LM6000 engine parameters are listed in Table 3.1.

Table 3 3.1

(ISO) Shaft Output (MW)	40.75
Heat Rate (Btu/SHP-Hr) LHV	6,355
Simple Cycle Efficiency (%)	40.0
Exhaust Gas Flow	274
Exhaust Gas Temperature (deg F)	869
Combined Cycle Output (Mw)	52.4
Combined Cycle Efficiency (%)	51.5

3.2 CYCLE ANALYSIS

Derivatives of simple and combined cycle performance were determined with respect to gas turbine component performance and cycle parameters, turbocooler circuit airflows, and bottoming cycle performance. The results determine ATS performance sensitivity to thermodynamic inputs and highlight components and parameters critical to achieving project goals.

Cycle Variables

The derivatives were determined using the configuration shown schematically in Figure 3.2.1 with the variables indicated. This is the direct drive, turbo-cooled, 1.75 booster pressure ratio, 2700F firing temperature design. The compressor size and speed are fixed at levels consistent with GE90 sea level static operation at the 88,800 lb. thrust level. All cases were designed to constant inlet and exhaust (stack) pressure losses. LP shaft speed was held at 3,600 rpm.

Derivatives were calculated for emissions, thermal efficiency, power output and high-pressure turbine flow function (HPTFF). Emission derivatives reflect values estimated based on flame temperature only. Thermal efficiency and power output derivatives were calculated for both simple and combined cycle systems. Combined cycle derivatives are calculated from a simplified three pressure level, non-reheat, steam cycle method. Also, HPTFF derivatives were calculated, because changes in HPT size are constrained by the need to use GE90 hardware. Baseline values of the independent variables are listed in Table 3.2.1.

The derivatives were calculated with respect to independent variables, including gas turbine and combined cycle component and cycle thermodynamic parameters, turbocooler circuit airflows, and inter-turbine reheat variables. Affected components and parameters are highlighted in Figure 3.2.1. Gas turbine variables include component efficiencies, pressure losses, and parasitic flows. Component efficiencies are defined as adiabatic except the booster, which is defined as polytropic. Pressure losses are defined by the ratio of component inlet to exit total pressure. Parasitic flows are defined by a fraction of HPC inlet physical flow. In addition, high-pressure compressor (HPC) inlet guide vane (IGV) angle, which regulates HPC flow and efficiency, was evaluated. Also, an estimated derivative on steam cycle efficiency was included. Thermodynamic (cycle) variables include booster pressure ratio and firing temperature. These independent variables are defined further and their baseline values are listed in the left columns of Table 3.2.2.

Turbocooler circuit flows include burner, HPT nozzle, and HPT Stage 1 rotor-cooled cooling air and turbocooler turbine discharge air. Turbocooler independent variables are listed along with source, sink, and baseline values in the top rows of Table 3.2.4.. They are highlighted in Figure 3.2.1.

Performance derivatives were also examined for a reheat system which could be placed between the HPT and power turbine. The reheat system independent variables include burner firing temperature and pressure loss and power turbine cooling flow. These variables are listed in Table 3.2.5 and highlighted in Figure 3.2.1.

Cycle Results

The results reflect partial derivatives calculated by varying independent variables separately and resizing the engine system around a fixed HPC flow size. The derivatives reflect a delta of one point (1 point = 0.01) in independent variable as defined in Table 2.2.2, column 2, and Table 3.2.4, row 1, except for firing temperature (T41) and HPC IGV (STP25) setting. T41 derivatives are per degree Fahrenheit, and STP25 derivatives are per degree of vane angle. With these exceptions, the derivatives are defined by:

Combined and simple cycle thermal efficiency:	change in points per point
HPT flow function:	% Δ W41R per point
NOx:	Δ emission units per point
Combined and simple cycle power output:	% Δ horsepower per point

Table 2.2.4, listing derivatives with respect to turbocooler flows, contains additional data defining how the turbo-cooling system reacts to turbocooler flow changes. This is because turbocooler parameters must satisfy turbocooler operability requirements. For instance, the heat exchanger cannot function at an effectiveness greater than one, and the turbocooler turbine exit air pressure must be sufficient to re-enter the flowpath downstream of the HPT. For this reason, the following additional parameters are listed (these are not derivatives):

- PS42: Static pressure downstream of HPT exit (turbocooler turbine sink pressure)
- P80: Turbocooler turbine discharge manifold pressure (P80 is calculated such that cooled cooling flow is delivered at a manifold pressure of P3)
- ϵ HX: Heat exchanger effectiveness
- Tfuel: Temperature of fuel entering combustor

Since the above parameters are not derivatives, the result listed is due to an increase of one point in flow fraction. These parameters also are highlighted in Figure 3.2.1.

Emissions Index derivatives are defined in Tables 3.2.2 and 3.2.4. Only firing temperature, cooling flow (cooled and uncooled), and parasitic flow derivatives are nonzero: these are the only variables affecting burner fuel to air ratio. Cooled burner/vane air has a strong impact, because this air is the only dilution air between burner and HPT rotor inlet. If T41 is fixed, this air sets the combustor flame temperature, hence emission level. The remaining parasitic flows have a -order effect: if T41 and dilution airflow are constant, dilution airflow becomes a larger fraction of total burner airflow as larger parasitic flows bypass the combustor. Hence, flame temperature increases to maintain T41 and emissions increase.

Combined cycle efficiency derivatives are influenced by a variety of parameters. HPC and LPT efficiencies dominate in component efficiency effects. Pressure loss results are about even, regardless of engine location. The parasitic flow results show that the derivative is a function of port location, with high-pressure air more costly than low-pressure air. Also, the further downstream the discharge port is, the greater the loss. For example, seventh stage balance piston air is more expensive than fourth stage air, and dumping seventh stage air in the stage two HPT rotor is less costly than if it were needed to cool the LPT rotor. Booster pressure ratio and T41 derivatives are small but can have significant influence if large changes occur.

Increasing T41 and reducing booster PR have positive effects, but the selected values are dependent on other factors, such as cost, emissions, and size. The derivative on bottoming (steam) cycle efficiency simply reflects the contribution of the steam cycle to the total system power. That is, the derivative becomes stronger as steam cycle power becomes a larger fraction of total power.

Combined cycle power derivatives are impacted strongly by HPC, LPT, and gooseneck pressure loss, with other parameters having less effect. The HPC efficiency is strong due to the combined effects of reducing the HPC power requirement and dropping compressor discharge temperature (T3). Hence, these effects both provide more energy to the power turbine (HPT extracts less power) and increase burner temperature rise (T41-T3) as HPC efficiency increases. LPT performance provides for more simple cycle shaft power as LPT efficiency rises. Gooseneck pressure loss affects power output by increasing physical HPC airflow for a fixed HPC size. Hence, as pressure loss drops, airflow rises, and fuel flow (constant fuel to air ratio) and power output increase. In addition, parasitic flows affect CC power the same way they impact efficiency - high-pressure air is more costly than low-pressure air. Turbocooler circuit flows impact power in a similar way: any airflow bypassing the burner results in a loss of fuel flow, hence, power. Again, T41 and booster PR are influential but subject to other constraints.

The derivatives of simple cycle performance listed in Table 2.2.3 follow similar trends to CC derivative,s but are stronger. The derivatives are stronger, because cycle inefficiencies converted into waste heat are partially recovered in the bottoming cycle, which tends to reduce the effect of inefficiency on combine cycle performance. HPC and LPT efficiency have a strong impact on efficiency and power output. Gooseneck pressure loss drives power output, and parasitic and cooling flows drive emissions, efficiency, and power. In addition, although T41 and booster PR can have strong influences, these parameters are set by external considerations.

The HPC IGV setting derivatives show that small increases in efficiency are available but at a significant cost of power output. The baseline setting of zero degrees was picked mainly to maximize airflow and, thus, power.

Derivatives of HPTFF are also shown in Table 3.2.3, along with the corresponding influence on HPT efficiency. The idea here is that as flow function (area) deviates from its design value (about 30), HPT efficiency drops, as it becomes harder to adapt the GE90 HPT to the ATS. This effect is included in the simple and combined cycle efficiency derivatives.

The results of the reheat study are listed in Table 3.2.5. The primary benefit of reheat is it allows a higher gas turbine exit temperature (T5), which increases steam cycle efficiency. However, simple cycle efficiency falls. In addition, the reheat burner requires some sort of pressure drop, and a higher power turbine inlet temperature may require a cooled power turbine. For example, a reheat burner pressure drop of 6% requires 115 degrees of temperature rise to maintain constant CC efficiency. Two percent in cooling flow has about the same impact. This means a reheat system would require a critical balance between temperature rise, pressure drop, and cooling flows, if it is to have any benefit in system thermal efficiency. Emissions index for a reheat system was not evaluated.

Simple Cycle Recommendations

It is important to remember that these derivatives are intended to provide guidance in selecting a final cycle design: they should allow for making small tradeoffs rationally. The derivatives will be accurate for small deviations in the baseline cycle defined in Table 3.2.1. However, accuracy will deteriorate with larger deviations.

Figure 3.2.1. ATS Derivative Study Schematic and Variables

TABLE 3.2.1

Baseline ATS Preliminary Performance

E_{INOX}	6.908
η_{CC} (PTS)	58.4
$POWER_{CC}$ (MW)	97.0
W41R	32.2 (GE90 + 8%)
η_{SC} (PTS)	46.55
$POWER_{SC}$ (MW)	77.3
ϵ_{HX}	0.830
T_{fuel} (°F)	965
PS42 (PSI)	109.1
PT80 (PSI)	178.9
η_{HPT} (PTS)	92.34

TABLE 3.2.2

Engine Component Performance Derivatives For 1 Point Delta

<u>COMPONENT</u>	<u>BASELINE VALUE</u>	<u>EMISSIONS $\Delta EI/PT$</u>	<u>COMBINE CYCLE $\Delta \eta(PTS)/PT$</u>	<u>POWER $\% \Delta HP/PT$</u>
BOOSTER	$\eta_p = 0.92$	0	+ 0.063	+ 0.367
HPC	$\eta_a = 0.8536$	0	+ 0.250	+ 1.097
HPT	$\eta_a = 0.9234$	0	+ 0.197	+ 0.329
LPT	$\eta_a = 0.9405$	0	+ 0.274	+ 0.462
BC EFFICIENCY	$\eta_{ST} = 0.85$	0	+ 0.160	+ 0.269
GOOSENECK	$P/P = 0.982$	0	+ 0.115	+ 1.215
BURNER	$P/P = 0.9467$	0	+ 0.103	+ 0.173
REAR FRAME	$P/P = 0.96$	0	+ 0.102	+ 0.291
4TH STG BP AIR	$W/W_{25} = 0.0144$	+ 0.034	- 0.272	- 1.601
7TH STG BP AIR	$W/W_{25} = 0.0$	+ 0.036	- 0.356	- 1.725
HPT STG 2 AIR	$W/W_{25} = 0.0326$	+ 0.036	- 0.199	- 1.464
BOOSTER PR	$P/P = 1.75$	0	- 0.003	+ 0.196
FIRING TEMP.	$T_{41} = 2700^{\circ}F$	+ 0.033/ $^{\circ}F$	+ 0.010PTS/ $^{\circ}F$	+ 0.126/ $^{\circ}F$
HPC IGV SETTING	$STP_{25} = 0$	0	+ 0.043PTS/ $^{\circ}$	- 0.984%

TABLE 3.2.3

Simple Cycle Performance Derivatives

<u>COMPONENT</u>	<u>BASELINE VALUE</u>	<u>SIMPLE CYCLE $\Delta\eta$(PTS/PT)</u>	<u>SIMPLE CYCLE %ΔHP/PT</u>	<u>HPTFF %ΔW41R/PT</u>	<u>$\Delta\eta_{HPT}$(PTS/PT)</u>
BOOSTER	$\eta_p = 0.92$	+ 0.083	+ 0.440	+ 0.104	- 0.020
HPC	$\eta_a = 0.8536$	+ 0.344	+ 1.424	+ 0.011	- 0.088
HPT	$\eta_a = 0.9234$	+ 0.395	+ 0.850	0	-
LPT	$\eta_a = 0.9405$	+ 0.550	+ 1.183	0	0
BC EFFICIENCY	$\eta_{ST} = 0.85$	0	0	0	0
GOOSENECK	P/P = 0.982	+ 0.203	+ 1.015	0	0
BURNER	P/P = 0.9467	+ 0.208	+ 0.450	- 1.025	0
REAR FRAME	P/P = 0.96	+ 0.206	+ 0.442	0	0
4TH STG BP AIR	W/W25 = 0.0144	- 0.284	- 1.754	- 1.277	+ 0.040
7TH STG BP AIR	W/W25 = 0.0	- 0.447	- 2.078	- 1.260	+ 0.058
HPT STG 2 AIR	W/W25 = 0.0326	- 0.134	- 1.419	- 1.271	+ 0.058
BOOSTER PR	P/P = 1.75	+ 0.004	+ 0.163	+ 0.008	- 0.0016
FIRING TEMP.	T41 = 2700°F	+ 0.0036PTS/°F	+ 0.084%/°F	+ 0.020%/°F	- 0.0036%/°F
HPC IGV SETTING	STP25 = 0	+ 0.035PTS/°	- 0.533%/°	- 0.281%/°	- 0.042%/°

TABLE 3.2.4

Engine Performance Derivatives With Respect to Turbocooler Flows

PARAMETER	COOLED VANE/BURNER AIR	COOLED STAGE 1 HPT ROTOR AIR	ATC TURBINE DISCHARGE A
BASELINE W/W25	0.08	0.0252	0.021
SOURCE	ATC COMPRESSOR	ATC COMPRESSOR	ATC TURBINE
SINK	HPT NOZZLE, BURNER	HPT STAGE 1 ROTOR	LPT NOZZLE/DUCT
DERIVATIVES:			
$\Delta E/PT$	+ 0.400	+ 0.038	+ 0.037
$\Delta \eta_{CC}(PTS)/PT$	+ 0.009	- 0.280	- 0.255
$\% \Delta HP_{CC}/PT$	- 0.026	- 1.941	- 1.555
$\% \Delta W_{41R}/PT$	- 0.109	- 1.260	- 1.249
$\Delta \eta_{SC}(PTS)/PT$	+ 0.027	- 0.216	- 0.246
$\% \Delta HP_{SC}/PT$	+ 0.016	- 1.934	- 1.655
OTHER			
ϵ_{HX}	0.900	0.911	0.838
$T_{fuel} (^{\circ}F)$	1040	1052	975
PS42 (PSI)	109.2	106.8	107.0
PT80 (PSI)	157.7	157.7	261.7
$\Delta \eta_{HPT}(PTS)/PT$	- 0.001	+ 0.081	+ 0.079

TABLE 3.2.5

Reheat Burner Derivatives

<u>PARAMETER</u>	<u>R/H BURNER TEMPERATURE RISE</u>	<u>R/H BURNER PRESSURE RATIO</u>	<u>LPT ROTOR (4TH STAGE HPC COOLING FLOW</u>
BASELINE (NO REHEAT)	$\Delta T = 0$	$P/P = 1.0$	$W/W_{25} = 0$
DERIVATIVES:			
$\Delta \eta_{CC}/PT$	+ 0.005/°F	+ 0.096	- 0.341
% $\Delta HP_{CC}/PT$	+ 0.079/°F	- 0.165	- 1.196
$\Delta \eta_{SC}/PT$	- 0.007/°F	+ 0.200	- 0.544
% $\Delta HP_{SC}/PT$	+ 0.055/°F	+ 0.446	- 1.826

3.3 COMBINED CYCLE STUDIES

Using configuration 4, shown in Table 3.3.1, combined cycle studies were completed to determine combined cycle efficiency and power output. Two studies were completed with the following attributes:

	Lower Heating Value-Natural Gas	Gas Turbine Exhaust Back Pressure
Study 1	19,000 Btu/lbm.	10 in. H ₂ O
Study 2	21,515 Btu/lbm.	15 in. H ₂ O

The combined cycle analysis were made using the following assumptions:

- A standard production Rankine steam bottoming cycle with three pressure levels and no reheat.
- One steam turbine per gas turbine.
- A condenser pressure of 1.2 in. Hg.
- A generator loss of 1.2%

The results of the combined cycle studies are shown in Figure 3.3.1 compared to the combined cycle goal of 59.2% and the program emission goals. The results show that the emission goal for NO_x can be met, but there needs to be more cycle development to meet the combined cycle efficiency goal.

TABLE 3.3.1

ATS Engine Cycles Under Study

ADVANCED TURBINE SYSTEMS(ATS) PROGRAM

ATS ENGINE CYCLES UNDER STUDY

FEATURES	1*	2*	3	4	5	6	7
BOOSTER/DRIVE TURBINE	NONE	YES/LOW PRESSURE TURBINE	YES/LOW PRESSURE TURBINE	YES/LOW PRESSURE TURBINE	YES/LOW PRESSURE TURBINE	YES/LOW PRESSURE TURBINE	YES/HIGH PRESSURE TURBINE
BOOSTER DRIVE TYPE	NONE	DIRECT DRIVE	DIRECT DRIVE	DIRECT DRIVE	DIRECT DRIVE	DIRECT DRIVE	GEARED DRIVE TO 3600 RPM
PRESSURE RATIO OF BOOSTER	0	1.63	1.75	1.75	2.0	1.75	1.75
ENGINE AIRFLOW(LBS/SEC)	223	317	352	352	372	352	352
DRY LOW NO_x COMBUSTOR	YES	YES	YES	YES	YES	YES	YES
TURBOCOOLER	NO	NO	NO	YES	YES	YES	YES
NEW LOW PRESSURE TURBINE	NO-GE90	YES	YES	YES	YES	YES	YES
LOW PRESSURE TURBINE SPEED	2000 RPM	3600 RPM	3600 RPM	3600 RPM	3600 RPM	**2000/3600	3600 RPM
LOAD CONNECTION	GEARBOX	DIRECT DRIVE	DIRECT DRIVE	DIRECT DRIVE	DIRECT DRIVE	DIRECT DRIVE	DIRECT DRIVE
COMPRESSOR DISCHARGE TEMP. (°F)	912	1075	1148	1148	1176	1148	1148
TURBINE INLET TEMP. (°F)	2514	2500	2500,2600, 2700, 2800	2500,2600 2700,2800	2500,2600 2700, 2800	2500,2600 2700, 2800	2500,2600 2700, 2800
POWER OUTPUT MW	43.95	59.6	63.6,69.9, 76.4,82.9	64.4,70.8, 77.3,83.4	66.6,73.5 80.4,87.4	64.4,70.8 77.3,83.4	64.1,70.6 77.0,83.4
SIMPLE CYCLE EFFICIENCY (%)	41.873	44.53	45.0,45.7, 46.2,46.6	45.5,46.1, 46.6,46.9	46.0,46.2, 46.7,47.1	45.5,46.1 46.6,46.9	45.31,45.98 46.5,46.9

ADVANCED TURBINE SYSTEMS(ATS) PROGRAM

ATS NO_x EMISSION GOAL VERSUS COMBINED CYCLE EFFICIENCY GOAL

CONFIGURATION 4

(LM6000 EFFICIENCY GOAL REFERENCE)

Figure 3.3.1. Configuration 4 NO_x vs. Efficiency Prediction

3.4 COMBUSTOR AERO DESIGN

The combustor preliminary aero design effort during this reporting period focused in part on continued generation of flowpath layouts that accommodate the challenging performance requirements of the combustion system, yet fit into the available GE90 CDN with a minimum of mechanical modifications. In addition some supporting 3D CFD and chemical kinetics analysis were performed to get a first-cut look at the performance.

The current status of the preliminary aero layout has a combustion system, (compressor OGV trailing edge to turbine nozzle leading edge), flowpath that is approximately 1.85 inches longer than the current GE90. Figure 3.4.1 provides an illustration of the current combustor flowpath aero layout. The combustor preliminary design features a tri-dome configuration, in which there are 60 equally spaced mixer/injector assemblies in the outer two domes and 30 equally spaced mixer/injector assemblies in the inner dome. The lesser number in the inner dome is the result of circumferential spacing constraints. This is double the number of mixer/injector assemblies as featured in the LM6000 DLE combustor. This was done to allow for smaller mixer/injector assemblies, which reduced their length to better fit the overall combustion system into the limited available space of the GE90 CDN. The mixer/injector assemblies were designed using the DCARS mixer design criteria developed for the LM6000 DLE combustor. Analysis show that residence times in the mixer/injector assemblies are on the order of 0.6 to 0.8 msec. This should be low enough to prevent autoignition at all operating conditions. A similar mixer/injector dome configuration as used in the current LM6000 DLE is adopted. A tri-passage combustor inlet diffuser is also featured. This design provides for reduced length for a given area ratio and performance, and allows for better alignment of the compressor discharge flow streams into each of the three combustor domes to improve recovery and flow feed into the mixers.

A fully 3D CFD analysis of the current combustor design was performed using the CONCERT code developed at GE. CONCERT is a state-of-the-art 2D/axisymmetric or fully 3D elliptic turbulent flow code with fuel addition and combustion capability. CONCERT was developed expressly for application to gas turbine engine combustion systems and has been in production use at GE since 1987. CONCERT has been used for providing predictions of combustor exit gas temperature performance, and exhaust emissions including CO, UHC, and NO_x. CO and UHC predictions are provided via a simple 2-step reaction/eddy breakup type model, while NO_x predictions are provided by a Zeldovich mechanism. The predictions of these emissions species are not highly accurate for very lean combustor designs do to the limited chemical kinetics that can be practically used with a fully 3D calculation. CONCERT undergoes continual enhancement to improve predictive accuracy and applicability. For a typical 3D analysis, a single periodic section of the combustor is modeled. This assumption allows sufficient grid detail within limited available computer resources. This approach in essence assumes that all periodic sections of the combustor are identical. A grid network of 85 x 69 x 33 (193,545) grid points was used for this model. Figure 3.4.2 presents views of the model grid for the three principal planes. Figure 3.4.3 shows the flow splits used for the model. Boundary conditions defining the mixer/injector discharge flow characteristics into the combustor were obtained from a CONCERT axisymmetric flow analysis of the mixer/injector. A single case was run representing maximum power operating conditions. The results, (using gaseous methane fuel), are presented in Figures 3.4.4 and 3.4.5, showing as expected with essentially no cooling flow the exit profile is essentially flat. Predictions of CO and

UHC emissions at the max. power operating condition, made as part of this modeling analysis, show a CO level of 3.5 ppm and the UHC level at 1.3 ppm.

Predictions of emissions were also made utilizing the CELESTE code. CELESTE is a stirred reactor type model developed at GE. It allows for the constructing of a network of perfectly stirred and/or plug flow reactors to represent the combustor. Because there are no complex fluid mechanics involved, more detailed chemical kinetics can be used than possible with the fully 3D CFD type analysis. In the analysis performed a kinetics mechanism consisting of 154 reactions was used. CELESTE models for the max. power and 40% power operating condition were run. Figure 3.4.6 shows the simplistic network of reactors used. A natural gas representative fuel was used in these analyses. For the max. power condition the predicted emissions levels were 5.7 ppm (CO) and 10 ppm (NO_x). Given the predictive uncertainty of this model, the predicted NO_x levels are consistent with the goals for the combustor. Results with this same model at the 40% power operating condition failed to produce a combusted solution. The fuel/air mixture was below the lean extinction limit. This is in agreement with test results of the DCARS mixer/injector assembly supporting the LM6000 DLE development. This outcome suggests the need to stage the combustor to maintain stability at this operating condition. A second CELESTE model was built to represent staging the combustor, the inner dome unfueled while the outer and center domes were fueled. With staging the two fueled domes operate at a fuel/air mixture above the lean extinction limit. Flow splits for this configuration and the CELESTE model of networked reactors is shown in Figure 3.4.7. The predicted results from this revised model at the 40% power operating condition were 20 ppm for (C)] emissions and 3 ppm for (NO_x) emissions.

Figure 3.4.1. Current Combustor Preliminary Aero Layout

SIDE VIEW PLANE

END VIEW OF MODEL INLET PLANE

Figure 3.4.2. Combustor Grid Model

COMBUSTOR MODEL FLOW DISTRIBUTION (% Wcombustor)

MODEL INLET VELOCITY BOUNDARY CONDITIONS

Figure 3.4.3. CONCERT3D Model Flow/Boundary Conditions

CALCULATED VELOCITY VECTORS IN PLANE INLINE WITH MIXERS

CALCULATED GAS TEMPERATURES (R) IN PLANE INLINE WITH MIXERS

CALCULATED NON-DIMENSIONAL GAS TEMPERATURES AT EXIT PLANE

Figure 3.4.4. Combustor Flow Model Results

Figure 3.4.5. Calculated Circumferentially Averaged Exit Profiles

Figure 3.4.6. CELESTE Stirred Reactor Model for Max Power

Figure 3.4.7. CELESTE Stirred Reactor Model for 40% Power

3.5 HIGH PRESSURE TURBINE HEAT TRANSFER

Preliminary turbine cooling designs for the high pressure turbine vane and blade were developed in the previous reporting period to support the evolution of the ATS cycle and establish the design constraints necessary for a successful detailed design. In this reporting period, technical challenges were addressed pertaining to the thermal barrier coating on the HPT Stage 1 vane and cooling flow estimates were made for the HPT Stage 2 vane.

The ATS turbocooler provides cooling flow to the combustor liners and high pressure turbine airfoils and bands at reduced temperatures and increased pressures as compared to traditional CDP air cooled designs. Flow from the turbocooler cools the combustor outer liner, vane outer band, and HPT shroud individually. It also cools the HPT vane and the spent cooling air from there is used to cool the combustor inner liner, vane inner band, HPT Stage 1 blade, and forward combustor seal. A preliminary estimate of the cooling flow breakdown is as follows:

	<u>Wc (%W25)</u>
Combustor Inner Liner	1.5*
Combustor Outer Liner	1.5
HPT Vane Inner Band & Leakage	1.0*
HPT Vane Outer Band & Leakage	1.5
HPT Vane Film	3.7*
HPT Shroud	0.5
HPT Stage 1 Blade	2.2*
Forward Combustor	<u>0.4*</u>
Total	12.3

Note: All flows noted with a * pass through the HPT vane: 3.67%W25 is film and 5.1%W25 is non-film which is captured and used to cool the combustor inner liner, vane inner band, HPT Stage 1 blade, and forward combustor seal.

HPT Stage 1 Vane

Cooling flow for the high-pressure turbine vane is supplied from the turbocooler at much lower temperatures and higher pressures than the conventional vane coolant supply from CDP air. The HPT vane cooling design, as proposed in the previous reporting period, used only trailing edge film in order to minimize the cooling flow and film requirements to achieve life. The cooling circuit included two impingement inserts for increased heat transfer, but, rather than exhausting through film holes as in traditional designs, the post impingement flow is captured at the hub of the airfoil and used to cool the combustor inner liner and HPT blade. The ability to reuse the spent vane cooling air is only possible due to the increased pressures and lower cooling temperatures supplied by the Turbocooler. Typical impingement/film cooled vane designs are limited by backflow margins ($P_{coolant}/P_{gas}$) at the leading edge of the vane to prevent gas ingestion. This is not a restriction for the ATS design; only the cooling air pressure supplying the combustor inner liner, which is the vane cooling air exhaust pressure, is a design constraint.

The TBC surface temperatures proposed for the ATS vane were much higher than our previous experience on either aircraft or military and industrial applications. There was a concern that the TBC would sinter and that the TBC thermal conductivity would increase at these temperatures. Therefore, based upon the recommendations of our material technologists, TBC outer surface temperatures were limited to 2350F, and TBC bond coat interface temperatures were limited to 1920F. These design constraints dictated that the vane design should be modified to include additional film cooling. Only 10 mils of TBC are required to achieve these temperature limits, however, which also reduces the technical challenge of thicker TBC. Five mils of TBC are not atypical on today's airfoils, although up to ten mils have been tested for limited periods.

A listing of the ATS vane parameters is as follows:

	<u>ATS</u>
Hot Streak Temperature (F))	3075
Coolant Temperature (F)	719
Pcoolant/Pgas	1.10
TBC Thickness (mils)	10
Wc (%W25)	8.77
Film (%W25)	3.67
NonFilm (%W25)	5.10
Life (cycles)	10,000

The non-film cooling flow which cools the ATS vane impinges on the airfoil and goes on to cool the combustor inner liner and HPT blade; of the remaining film flow. 1.12%W25 film flow exhausts through the trailing edge slots and 2.55%W25 is used as pressure and suction side film. Figure 10 indicates the ATS film geometry and flow distribution. Preliminary metal and TBC temperatures are shown in Figure 11. Additional concepts are still under consideration for further iterations on the cooling design of the vane.

HPT Stage 2 Vane

The coolant supply for the ATS HPT Stage 2 Vane is supplied from the exhaust from the Turbocooler turbine. Cooling air is furnished at temperature and pressure levels similar to the GE90 design conditions which is fed with 7th stage bleed as shown below.

	<u>ATS</u>
P3 Design Point	588.2
Ps Vane 2 Source	299.1
Gas Temperature (F)	2488
Coolant Temperature (F)	948
TBC Thickness (mils)	4/7/10
Wc (%W25)	2.50
Forward	1.13
Aft	0.15
Trailing Edge	1.22
Life (cycles)	10,000

The life limiting location of the ATS HPT Stage 2 vane is the trailing edge. In order to achieve the ATS life requirements, the trailing edge temperatures will have to be reduced ~100F below GE90 temperatures. This can be accomplished with increased pressure side film and trailing edge flow. A listing of the ATS flows are shown in Figure 3.5.3. Figure 3.5.4 indicates the TBC distribution and the life-limiting temperatures for the ATS.

Technology/Testing Needs

Vane Impingement with Crossflow Test:

The HPT vane cooling design relies upon impingement air providing enhanced coolant side heat transfer coefficients. Rather than film cooling the airfoil, the flow is captured at the hub of the airfoil and reused as combustor liner or HPT blade cooling. Intercepting the flow implies that some of the benefit of higher impingement heat transfer coefficients will be reduced due to cross-flow. The vane design will be dependent upon optimization of the internal cooling concept.

Three configurations have been tested for vane impingement with crossflow - a baseline and two variations.

Technology Challenges

TBC provides a technical challenge in many arenas: spallation of the TBC is not fully known; temperatures through the TBC as well as the maximum temperature of the TBC are areas of concern for the ATS life requirements.

Figure 3.5.1. Stage 1 Vane Film Geometry and Flow Distribution

Figure 3.5.2. Stage 1 Vane Preliminary Metal and TBC Temperatures

Figure 3.5.3. ATS Stage 2 Vane Cooling Flows

TBC Thickness Distribution

**$T_{\text{max}} = 1929\text{F}$ @ airfoil trailing edge
10000 cycles**

Figure 3.5.4. Stage 2 Vane TBC Distribution and Life-Limiting Temperatures

3.6 TURBOCOOLER SYSTEM

An internal preliminary design of the turbocooler (Turbocooler) system has been completed, using as a base the Allied Signal compressor and turbine maps provided for another application.

The current size accommodates an increased primary cooling flow requirement of 12.35% W25, up from the 10.52% Proposal value, due to TBC temperature limits.

A preliminary layout of the system was used to estimate the system pressure losses is shown in Figure 3.6.1. Pressure distribution in the system at full power is shown in Figure 3.6.2.

Current pressure drops are higher than Proposal values for both the turbocooler turbine and turbocooler compressor circuits. Effects of the pressure drop estimates on the system include an increase in the required turbocooler compressor pressure ratio from 1.2 to 1.29, and an attendant increase in the fuel sink utilization to maintain turbocooler primary coolant supply temperature of 700F. The available air side pressure drop in the heat exchanger was reduced to partially compensate the increased extraction and feed losses.

In the current design, the turbocooler turbine exhaust is directed to and provides cooling for the engine HPT second-stage vane, replacing the HPC (high-pressure compressor) interstage coolant for this purpose. The resultant increase in turbocooler turbine exit pressure (relative to the proposed system) reduces the available head, requiring an increase in extraction for the purpose of driving the turbocooler compressor. There is more air available for downstream (secondary) cooling, but it will necessarily be hotter than the HPC interstage source. The increased primary flow and pressure requirements, noted above, and the increase in pressure loss in the turbocooler turbine circuit also contribute to an increase in turbocooler turbine extraction levels.

Meeting the primary cooling requirements (HPT vane and blade, burner liner and HPC shaft) at the baseline required-to-run fuel flow results in a fuel temperature at the burner of 1049F. (Column A below). Fuel temperature at the burner can be maintained at 1000F only by reducing the primary coolant 0.75% W25 (B), or increasing its supply temperature by 36F. Column D provides a comparison with the original proposal system.

	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
Primary coolant (%W25)	12.35	11.60	12.35	10.5
Supply temperature (F) @ HPT Stage 1 vane	700	700	736	700
Fuel temperature at burner (F)	1049	1001	1000	893
HX volume (ft ³)	1.78	1.4	1.32	0.8
Turbocooler wheel diameter (in.)	6.18	6.	6.23	6.34
Turbine exit temperature (F)	1003	1003	1003	735
Turbocooler wheel diameter (in.)	5.3	5.1	5.25	11.1
Turbocompressor speed (rpm)	46,840	48,590	47,220	37,650
Turbocooler pressure ratio	1.29	1.29	1.29	1.19
Turbocooler pressure ratio	1.58	1.58	1.58	4.35

Figure 3.6.1. Estimated Pressure Distribution in ATS Turbocooler at Full Power

Turbocooler

Figure 3.6.2. Turbocooler Pressure Distribution

3.7 LOW PRESSURE TURBINE DESIGN

Mechanical Design

The ATS power turbine is a five-stage design that drives both the low-pressure booster and the power output shaft. The mechanical design is based on the GE90 LPT philosophy with the intention to utilize the maximum amount of GE90 hardware. The turbine cross-section is shown in Figure 3.7.1.

The power turbine uses the GE90 flowpath with new vanes and blades. The GE90 LPT secondary flows and temperatures were used for the preliminary estimate of the ATS turbine flows and temperatures which were used for component sizing. The disks have been sized for ATS operating conditions (3600rpm) and 100,000 hours creep life.

The turbine mid frame and the rear frame have been adopted for the GE90 design with minimum modification. To ensure the use of the GE90 LPT case, the axial distance between the two frames has not changed. Instead, spacers have been added to the flowpath, because the ATS turbine has one fewer turbine stage than the GE90.

The bearing sump and rotor thrust balance design is similar to the GE90 design with the exception that an additional bearing has been incorporated to support the new power output shaft.

Turbine Airfoil Material Selection

For initial assessment of the material requirements for the LPT blades, the stress and temperature regime for each stage was established and compared to the 0.2% average creep life capability for a series of candidate turbine airfoil alloys. The goal life for LPT blades is 50,000 hours minimum, a period of time for which materials data does not exist for most of these alloys; this required extrapolation and estimation to project the long time materials capability. Based on prior experience, the physical metallurgy of these materials, and the temperature range of the estimate, we expect these estimates to be accurate.

The 0.2% creep requirement is a standard, but conservative, criteria first step design assessment which, if met, provides a product component with substantial deformation margin (is not deformation limited) which usually lasts the product lifetime or is refurbished due to long time environmental effects. If the criteria is not met, then the designer moves to another step and conducts further analytical work to calculate detailed creep deformation for the airfoil and assess this result against configuration requirements; tuning the airfoil configuration to reduce stress in limiting areas may be part of this step in the process. Typically, for a machine this size, total radial creep of 20 mils for Stage 1 to 30 mils for Stage 2 represent acceptable limits. This report covers only the initial step in this life assessment process.

ADVANCED TURBINE SYSTEMS(ATS) PROGRAM

Figure 3.7.1. LM9000 Power Turbine

Table 3.7.1

LPT Blades - Temperature Study Regime and Stress Requirements

X - Denotes Temperature Regime

<u>Stage</u>	<u>Stress</u> <u>(Ksi)</u>	<u>1800F</u>	<u>1700F</u>	<u>1600F</u>	<u>1500F</u>	<u>1400F</u>	<u>1300F</u>	<u>1200F</u>	<u>1100F</u>	<u>1000F</u>	<u>900F</u>
1	17	X	X	X							
2	30		X	X	X						
3	37			X	X	X					
4	39					X	X	X			
5	43								X	X	X

LPT Blades Temperatures (F) for 2700F T41 and 2600F T41

<u>Stage</u>	<u>Stress (Ksi)</u>	<u>2700F T 41</u>	<u>2600F T41</u>
1	17	1700	1600
2	30	1560	1450
3	37	1420	1320
4	39	1230	1140
5	43	1090	990

A range of temperatures was studied to correlate with the various ATS cycles under study and display the influence of varying temperature and stress on component life as shown in Table 3.7.1. Material capability in terms of 0.2% creep life was assessed for cast nickel-based turbine blade alloys used by GE. These alloys are listed below:

<u>Alloy</u>	<u>Form</u>
R77	Conventionally Cast
R80	Conventionally Cast
In738	Conventionally Cast
GTD111	Conventionally Cast
R125	Conventionally Cast
R108	Directionally Solidified - Multi Grain
R142	Directionally Solidified - Multi Grain
RN4	Directionally Solidified - Single Crystal
RN5	Directionally Solidified - Single Crystal
RN6	Directionally Solidified - Single Crystal

Average 0.2% creep lives were calculated for each alloy for the temperature regime (3 x 100F increments) and stress condition of each LPT Blade Stage, plotted as bar charts and compared with the 50,000 hour life goal for these components. The following four charts present the results of the analysis for Stages 1 through 4, respectively. The Stage 5 analysis indicated lives greater than 1,000,000 hours for all the alloys considered for temperatures of 1100F and lower and no chart is presented for this situation.

Review of the chart for the Stage 1 LPT blade indicates at 1800F none of the alloys meet the 50,000 hour 0.2% creep criteria. At 1700F, RN6 comes close with 42,000 hour capability, and at 1600F, both RN5 and RN6 exceed the requirement. The chart for Stage 2 shows that, although the temperature regime is lower, the increased stress level causes a similar situation as Stage 1, with no alloys meeting the criteria at both 1700F and 1600F, but RN5 and RN6 satisfy needs at 1500F.

Review of the chart for the Stage 3 stress again shows the deformation-free criteria not to be met by any alloy until the temperature is around 1500F, where RN6 would be fully satisfactory. For Stage 4, conventional cast alloys should be capable of meeting the deformation free criteria with the temperature below 1300F at 2700F T41. Stage 5 is not creep limited with any of the alloys.

The overall conclusions are that for the low pressure turbine design:

1. LPT Stages 1, 2, 3 are creep deformation limited and may require DS/Single crystal alloys to meet life along with detailed deformation analysis and stress tuning to maintain an uncooled LPT airfoil system.
2. LPT Stages 4 and 5 material capability requirements can be satisfied with conventionally cast materials.

3.8 OVERALL SUMMARY/CONCLUSIONS

After continued studies, a cycle configuration that had the potential to achieve the required program goals was obtained. Key differences of this cycle compared to Configuration 4, which was studied earlier, are as follows:

- Intercooling- Added to allow higher cycle pressures while minimizing the increase in compressor discharge temperature while helping to increase the power output needed to meet the program economic goals.
- Higher cycle pressure ratio which helps to achieve a higher simple cycle efficiency
- Reduced cooling flows, which are a result of lower compressor discharge temperatures.

Based on the changes as noted, an intercooled, turbocooled gas turbine design was carried into Task 6 for concept development. Figures 3.8.1 and 3.8.2 outline the key attributes of this new cycle.

Steam Cycle

The steam cycle used for the calculation of the combined cycle performance has the following characteristics:

- A three-pressure boiler with reheat and hydrogen cooling.
- Fuel lower heating value (LHV) of 19,000 Btu/lb.

The overall combined cycle performance is shown in Table 3.8.1. The schematic for the steam cycle is shown in Figure 3.8.3.

GE ADVANCED INTERCOOLED ATS CYCLE

Figure 3.8.1. Advanced Intercooled ATS Cycle

GE ADVANCED INTERCOOLED ATS CYCLE

AUXILIARY TURBOCOOLER CIRCUIT

TEMPERATURES = DEGREES F
PRESSURES = PSIA
FLOW = LBM/SEC OF GAS

Figure 3.8.2. Auxiliary Turbocooler Circuit

TABLE 3.8.1

ATS Combined Cycle Performance Summary

<u>Item</u>	<u>Units</u>	<u>Value</u>
Gross Gas Turbine Shaft Power	KW	134,279
Gross Steam Turbine Shaft power	KW	28,937
Gross Shaft Power	KW	163,216
Gross Generator Power	KW	160,236
Gas Turbine Heat Consumption	Mbtu/hr	895.89
Gross CC Heat Rate	Btu/KW-hr	5,591
Gross CC Efficiency	%	61.04%
Equipment and BOP Auxiliaries	KW	1,600
Net Generator Power	KW	158,835
Net CC Heat Rate	Btu/KW-hr	5,647
Net CC Efficiency	%	60.43%

Notes:

- (1) Includes heating of feedwater to 210.33F by gas turbine intercooler air.
- (2) Includes addition of 2,471 Btu/sec of heat to feedwater from fuel heating / cooling air cooling system.
- (3) Includes addition of 226 Btu/sec of heat to feedwater from air turbocooler exhaust gas cooling system.
- (4) Assumed generator loss for both turbines is 1.76%
- (5) Fuel pumping losses for the gas turbine fuel is not included.

MHB Model for a 3Pr Reheat Combined Cycle System

HEAT RECOVERY STEAM GENERATOR (HRSG)

Figure 3.8.3. Steam Cycle Schematic

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