NASA/CR—2005-213972

System Study

Technology Assessment and Prioritizing

General Electric Aircraft Engines
Cincinnati, Ohio

October 2005

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1.0 Executive Summary

1.1 Task Objectives

The objective of this NASA funded project is to assess and prioritize advanced technologies required to achieve the goals for an "Intelligent Propulsion System" through collaboration among GEAE, NASA, and Georgia Tech. Key GEAE deliverables are parametric response surface equations (RSE's) relating technology features to system benefits (SFC, weight, fuel burn, design range, acoustics, emission, etc…) and listings of Technology Impact Matrix (TIM) with benefits, debits, and approximate readiness status. TIM has been completed for GEAE and NASA proposed technologies. The combined GEAE and NASA TIM input requirement is shown in table 1. In the course of building the RSE's and TIM, significant parametric technology modeling and RSE accuracy improvements were accomplished. GEAE has also done preliminary ranking of the technologies using Georgia Tech/GEAE USA developed technology evaluation tools. System level impact was performed by combining beneficial technologies with minimum conflict among various system figures of merits to assess their overall benefits to the system. The shortfalls and issues with modeling the proposed technologies are identified, and recommendations for future work are also proposed.

1.2 Study Results

Figures 13 to 19 shows the impact of each proposed technology on new engines in terms of SFC, fuel burn, design range, noise, emission, fan diameter, and total propulsion weight relative to the QAT baseline using TIES One-on and One-off methods. The impact of HPT clearance control on deteriorated engines is also shown in the same figure. On the left side of the figures, the technology list is shown, consistent with table 1. The technology numbering (simplified as "T" followed by a number) listed in table 1 will be referred throughout the report unless otherwise indicated. Throughout this study, SFC refers to specific fuel consumption at mid cruise point, and fuel burn refers to the fuel burn at 5600 nautical mile (NM) mission.

Notice that the top ten technology rankings for SFC, fuel burn and design range are listed at the bottom of these figures for both One-on and One-off methods. The top ten remain the top ten for both methods, although the order changed slightly. T13 (Intelligent HPT rotor cooled cooling), T19 (Active tip clearance control using high temperature SMA), T20 (Variable area fan nozzle via high temperature SMA), T5 (HPT blade cooling flow modulation), T15 (Shape changing airfoil) have relatively significant impact on SFC, fuel burn and design range. T14 (Smart Containment System), which reduced engine weight, has minimum impact on SFC, however, it reduces fuel burn and significantly increases design range.

Among the acoustic technologies T1 (Steady fluidic injection), T2 (Synthetic jet actuators), T3 (Shape memory alloy), T4 (Active liners), T1 and T2 have the best acoustic benefits while T2 has minimum impact on fuel burn and design range. Among the emission technologies, T16 (GEAE Intelligent combustor) reduces NO_x by 50 percent from the baseline QAT level, equivalent to 15 percent additional reduction from 1996 ICAO limit. In other words, the QAT baseline goal is 70 percent below 1996 ICAO limit while the P21 goal is 85 percent below 1996 ICAO limit. NASA's active combustion control (T21) retains the same NO_x level as the QAT baseline.

The engine system level impact was estimated by selecting the best technologies among the incompatible technologies and including all the beneficial technologies. The final system contains all the proposed technologies except for T1, T3, T15, T21, and T22. The engine system level impacts from combining all the technologies are shown in table 3. With respect to the QAT Baseline, SFC was improved by delta 1.7 percent, fuel burn improved by delta 2.0 percent, design range improved by delta 1.9 percent, Noise (cumulative margin) improved by 3.3 EPNdB, NO_x reduced by 50 percent, and propulsion system weight reduced by 73 lbs.

All the above technology evaluation results, except for T23 and T24, are based on new engine designs. In modeling the benefits of the proposed technologies, the new engine was resized to obtain the maximum benefit while retaining the same cycle parameters as the QAT baseline. The QAT baseline engine was designed with an optimized cycle that minimizes fuel burn with balanced noise and Engine Related Operating Cost (EROC).

For deteriorated engine cases, T23 and T24 and their system impacts are shown in yellow in figures 13 to 19. T23 and T24 are two different methods to achieve HPT clearance control. T23 is based on elastic stretch, smart materials or advanced thermal systems. T24 uses more traditional mechanical actuators. Both T23 and T24 target to recover deteriorated HPT adiabatic efficiency. The difference is that T24 requires more HPT chargeable cooling flow (G31W42) than T23 from having more leakage passages from its segmented hardware. As shown in figures 13 to 15, T23 achieves better SFC, fuel burn and design range than T24.

1.3 Conclusions

For the Intelligent Engine System (Propulsion 21) system study, each technology was evaluated to determine the impact to SFC, fuel burn, design range, acoustics, emissions, fan diameter, and propulsion system weight. The optimum combination of technologies and their overall benefits to the system were also performed, resulting in improvement potential of 3.3 EPNdB Cumulative margin, 2 percent fuel burn and 50 percent NO_X reductions from the QAT baseline. All the technology evaluations, except T23 and T24, were based on new engines where the engine was resized to obtain the maximum system benefit while maintaining the same cycle parameters as the QAT baseline. The impact of HPT clearance control on deteriorated engines, T23 and T24, were also evaluated.

Recommendations for future system study work include, but not limited to, adding manufacturing cost, maintenance cost, and customer value analysis as figures of merits beside SFC, fuel burn, design range, emission and acoustics. Long-term system study goals include improving and enhancing the life prediction model and adding thermal dynamic/transition analysis modeling capabilities.

2.0 Project Overview

2.1 Program Work Scope

Propulsion 21 overall is a NASA funded task with the objective to develop technologies that will enable commercial gas turbine engines to produce reduced fuel burn, fewer emissions and less noise while increasing reliability. The engine entry into service (EIS) date is in the timeframe of 2008 to 2012. The System Study is a work element of the overall Propulsion 21 task. The focus of this system study is to assess and prioritize advanced technologies so that these technologies can be carefully integrated to achieve the best balance of system benefits between dissimilar and contradictory figures of merits.

The work scope defined in the original contract for system study includes the following tasks for both GEAE and GT:

(1) Define engine and aircraft technology baselines;
(2) Define Technology Impact Matrix (TIM) and Technology Audit Datasheets (TAD) of Proposed Technologies;
(3) Perform One-Off Technology Ranking;
(4) Perform Engine System Level Impact;
(5) Identify Modeling Shortfalls and Make Recommendations for Future Efforts.

To facilitate the collaboration, GEAE proposed the work scope definition shown in figure 1, leveraging each partner's strength, and agreed to by NASA and GT. The plan was for GEAE to build the latest QAT/UEET engine and aircraft models using GEAE internal tool PREDATER to construct the response surface equations. The response surface equation is to be used in TIES for technology evaluation.

Key GEAE deliverables are parametric response surface equations (RSE's) relating technology features to system benefits (SFC, weight, fuel burn, design range, acoustics, emission, etc…) and listings of Technologies Impact Matrix (TIM) with benefits, debits, and approximate readiness status.

Upon completion of the system study, GEAE met the deliverables of constructing response surface equations and transmitting them to GT. In addition, GE delivered results beyond the original work scope. GE completed the TIM for GEAE proposed technologies and coordinated GE expert evaluation of NASA TIM. The combined GEAE and NASA TIM input requirements are shown in table 1. In the course of building the RSE's and TIM's, significant parametric technology modeling capability enhancement and RSE accuracy improvements were accomplished and substantial effort spent on validating the NASA TIM. GEAE completed preliminary ranking of the technologies using Georgia Tech/GEAE USA developed technology evaluation tools. System level impact was also performed by combining technologies with minimum conflict in order to assess the overall system benefits. The shortfalls and issues with modeling the proposed technologies were identified, and recommendations for future work are proposed.

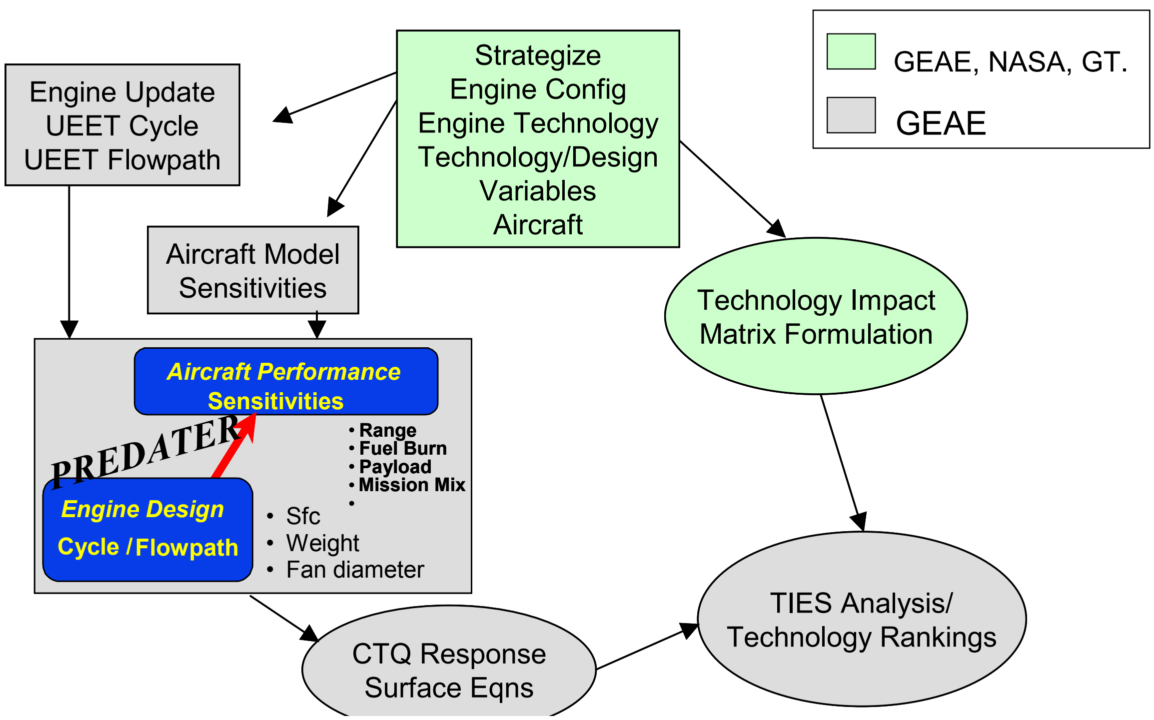


Figure 1.—Roles and responsibilities.

TABLE 1.—COMBINED GEAE AND NASA TIM INPUT REQUIREMENTS

	GEAE Technology list	ΔFPR	ΔOPR	ΔT41(F)	ΔTca(F)	Δ EGT adder	Δ ED12	ΔED25	Δ ED41	ΔG31W41	ΔG31W42	ΔG27W42	ΔSG31W42	Δ SG27W42	Δ Weight	Power	Bleed	System
		p/p	p/p	DegF	DegF	DegC	pt	pt	pt	%WR25	%WR25	%WR25	Mod Cool SF	Mod Cool SF	lbs	Horsepower	lbs/sec	Impact
	Active noise reduction																	Noise, FB
T1	–Steady Fluidic Injection																	
T2	–Synthetic Jet Actuators																	
T3	–Shape memory alloy																	
T4	–Active Liners																	
	Thermal management and advanced cooling																	FB, Reliab.
T5	HPT blade cooling flow modulation																	
T6	HPT vane cooling flow modulation																	
T7	HPT smart TE cooling																	
T8	HPT smart tip cooling																	
T9	HPT film optimization																	
T10	Active internal cooling																	
T11	Rotor purge control																	
T12	HPT shroud																	
T13	Intelligent HPT rotor cooled cooling																	
T14	Smart containment system																	FB, Reliab
	–Advanced Structure & Containment Fab																	
	–Advanced Nanofiber diagnostics																	
T15	Shape Changing Airfoils																	FB
T16	Intelligent combustor																	50% (15% 96 ICAC
T17	HPT clearance control																	FB, Reliab
	NASA Technology list																	
T18	Active Flow Control Via Hi Temp Piezoelectric ceramics																	
T19	Active tip clearance control using Hi Temp SMA																	
T20	Variable area fan nozzle via Hi Temp SMA																	
T21	Active Combustion Control																	
	Combustor fuel nozzle control via Hi Temp SMA																	
	LDI Combustor Technology																	
	Active Combustion Control																	
	Passive Acoustic Tomography																	
	Ceremic Thermocouple																	
T22	Magnetic bearing technoloy																	
	GEAE: deteriorated engine																	
	HPT clearance control (deteriorated engine)																	FB, Reliab
T23	–Elastic Stretch –Smart materials –advance thermal systems																	
T24	–Mechanical actuators																	
	Malfunction &Operation error reduction																	Reliab
	Disk life meter																	Reliab
	Sub system health management																	Reliab
		FPR	OPR	T41(F)			ED12	ED25	ED41	G31W41	G31W42	G27W42	SG31W42	SG27W42	ropSysWeight			
	Baseline (engine)																	

2.2 Baseline Selection

Baseline engine and aircraft selection for the system study was discussed among GEAE, NASA, and GT. It was agreed by NASA, GEAE, and GT to use the QAT type aircraft and the balanced Noise-EROC QAT engine as the baseline for the Propulsion 21 system study. The QAT Balanced Noise-EROC engine was developed as a "derivative" of the UEET medium size engine.

The QAT/UEET represents an advanced aircraft and engine system with the best fit for the Propulsion 21 system study. The QAT/UEET engine was flown on the QAT/UEET aircraft in a typical aircraft mission to determine the fuel burn, design range, acoustics, and emissions.

GEAE's UEET engine concept was designed to revolutionize the state of the art in propulsion technology with the biggest reduction in aircraft fuel burn (CO_2), emissions (NO_x), noise and Engine Related Operating Cost (EROC) relative to a baseline engine. Multi functional revolutionary engine technologies were carefully integrated to achieve the best balance between challenging and contradictory program goals with an EIS of 2015. The UEET engine features technology advancements that will revolutionize the commercial propulsion engine state of the art for the next 15 to 20 years in the area of emissions, performance, noise, and cost of ownership.

These features include:

- Ultra low noise, low speed counter rotating swept fan blades
- Counter rotating vaneless booster
- 6 stage HPC, all blisk rotors with advanced materials
- Ultra low emissions TAPS combustor with CMC liners
- Non deteriorating, low leakage seals
- Two stage HPT with advanced materials
- Robust, high DN HP rotor bearings
- Simplified main engine frames and architecture
- Counter rotating, vaneless LPT
- Intelligent Propulsion Controls

3.0 Response Surface Equation Creation

3.1 Approach

3.1.1 Approach for constructing response surface equations

The approach for constructing response surface equations involves three steps. The first is to build parametric engine design model using GEAE parametric engine design tool PREDATER. The second is to run design of experiment using PREDATER by varying key control parameters such as fan pressure ratio (FPR), component efficiencies, cooling flows and obtaining the response of the system metrics, such as SFC, fuel burn, range, noise, emission, and propulsion system weight. This process is shown in figure 2. The third step is to post process the responses to obtain the response surface equation using a commercial statistic tool.

Since GEAE parametric engine design tool PREDATER plays an important role in this system study, below is a more detailed introduction of this tool.

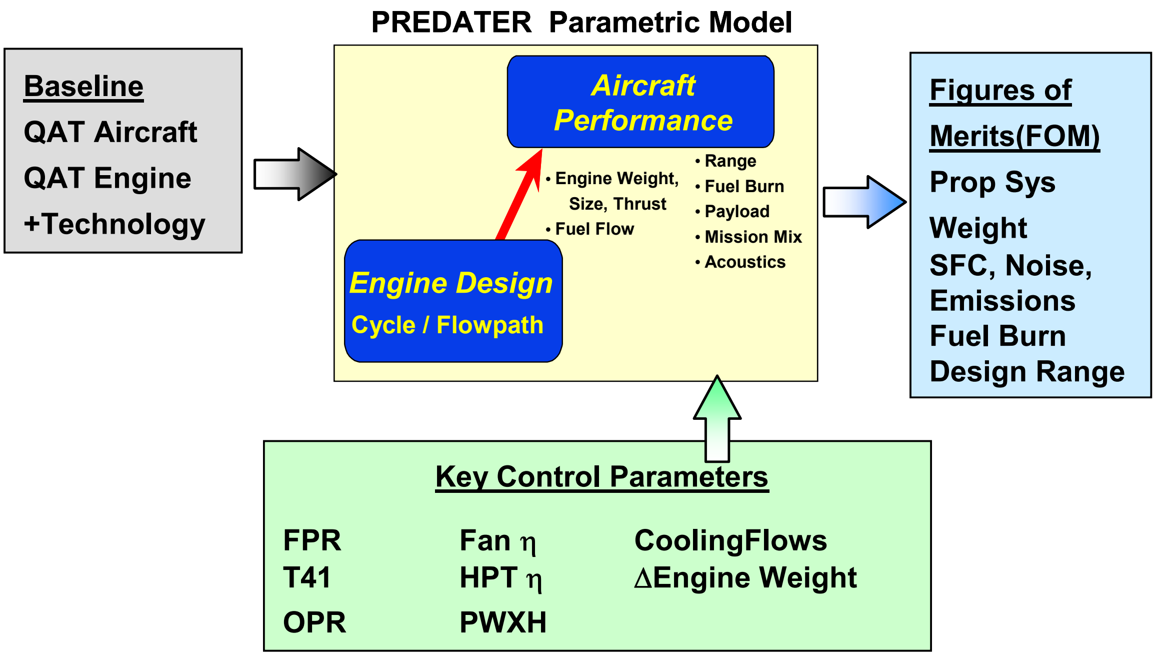


Figure 2.—Approach for constructing response surface equations.

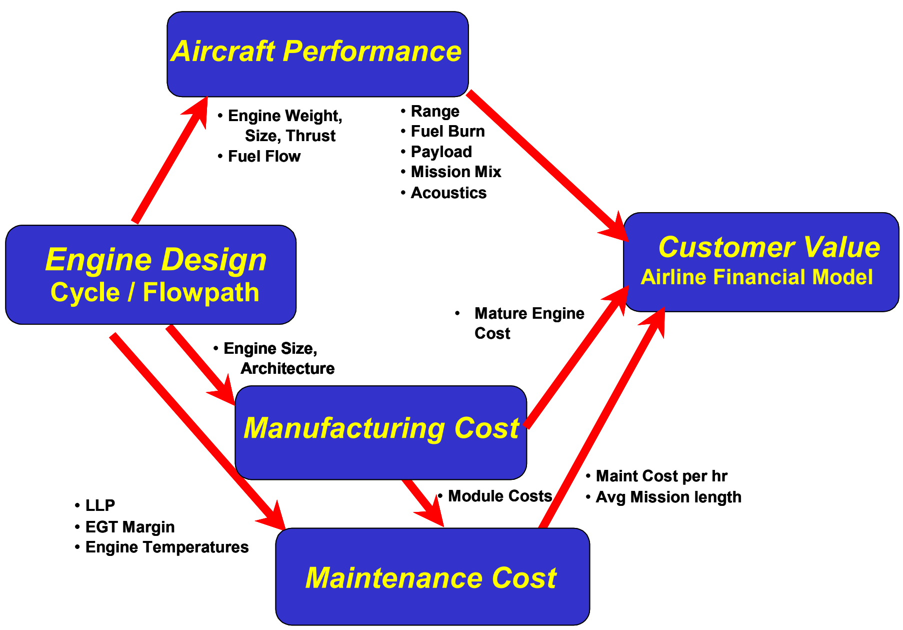


Figure 3.—PREDATER engine design evaluation process.

3.1.2 Primary tool: PREDATER

PREDATER is a GEAE linked computer analysis tool that combines parametric engine design with aircraft performance analysis, system cost assessment, airline economic analysis and ultimately customer economic value per figure 3. An engine design model, aircraft performance model, and manufacturing cost model were built and integrated into the PREDATER system. Maintenance cost modeling and airline economic modeling were also incorporated. PREDATER has the capability to call modules assessing engine manufacturing cost; maintenance cost and customer value analysis, although for this study, they were not used. The full system was run and checked out to ensure proper communication between the modules.

PREDATER has Design of Experiments (DOE) capability, which allows the rapid investigation of wide design space. The factors that varied in the DOE study are key control parameters, and they are component performance and architecture characteristics. In general, key component characteristics assessed include, but not limited to, compressor pressure ratio, overall pressure ratio, fan pressure ratio, T41, T3, all HPT and LPT chargeable and non chargeable flows, all components (fan, HPC, LPC, HPT LPT) efficiencies, customer bleed, power extraction, weight and more. In summary, PREDATER covers the spectrum required for technology evaluation focused on system benefits.

3.2 Validation

Before doing the full-scale design of experiment (DOE) and constructing the response surface equations, the system and methodology were validated. The purpose of the validation was two folds: Validate the tool and validated the accuracy of the RSE.

(1) Validation of commercial tool JMP. For this purpose, JMP was compared to PEZ, an internally developed GEAE tool with vigorous statistics algorithm which is widely used and thoroughly tested inside GEAE. JMP is a commercial software developed by SAS Institute Inc. It has good plotting and visualization capability and the response surface equations generated from JMP can be easily read by TIES, which is the technology evaluation tool using the response surface equations as input.

For validation purpose, 3 factor DOE was conducted. The 3 factors are: Fan Pressure Ratio (FPR), Design Overall Pressure Ratio (OPR), nd Maximum turbine inlet temperature (T41). It turns out JMP and PEZ give exactly the same response surface equations and regression accuracy. The response surface equations shown in figure 4 exhibits reasonable physical trend.

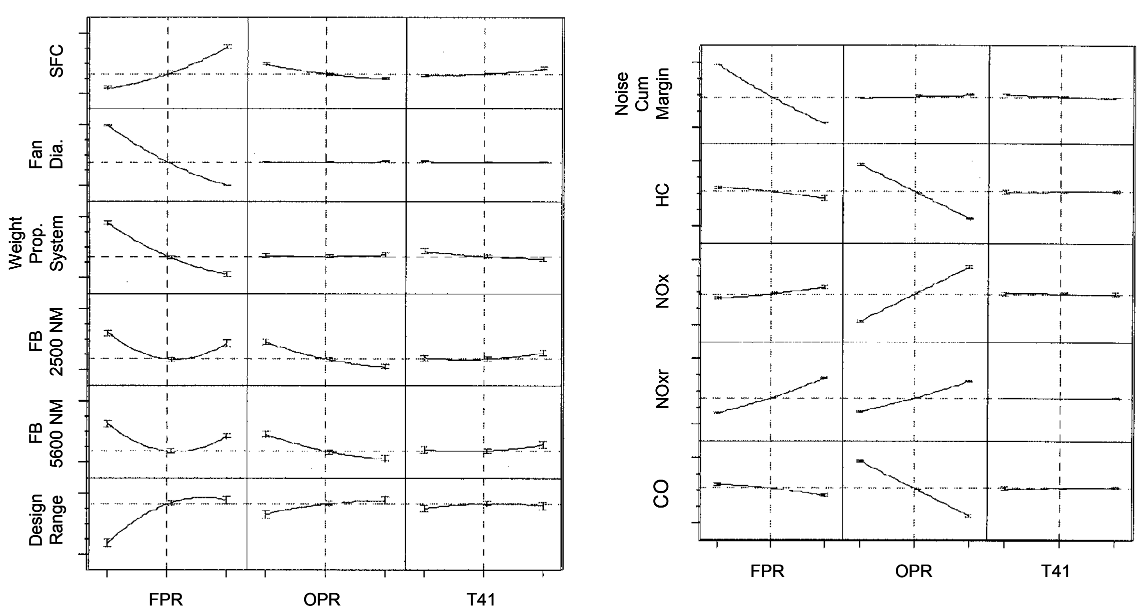


Figure 4.—Response surface equations from 3 factors design of experiments.

(2) Validating the accuracy of response surface equations (RSE) by comparing actual data with predicted value based on response surface equations. Figure 5 shows the comparison for SFC at mid-cruise point and fan diameter. These two parameters have very smooth trend and RSE fits into the actual runs very well. Figure 6 shows the comparison for propulsion system weight and design range. The RSE, which always has smooth trend, leave space for further improvement.

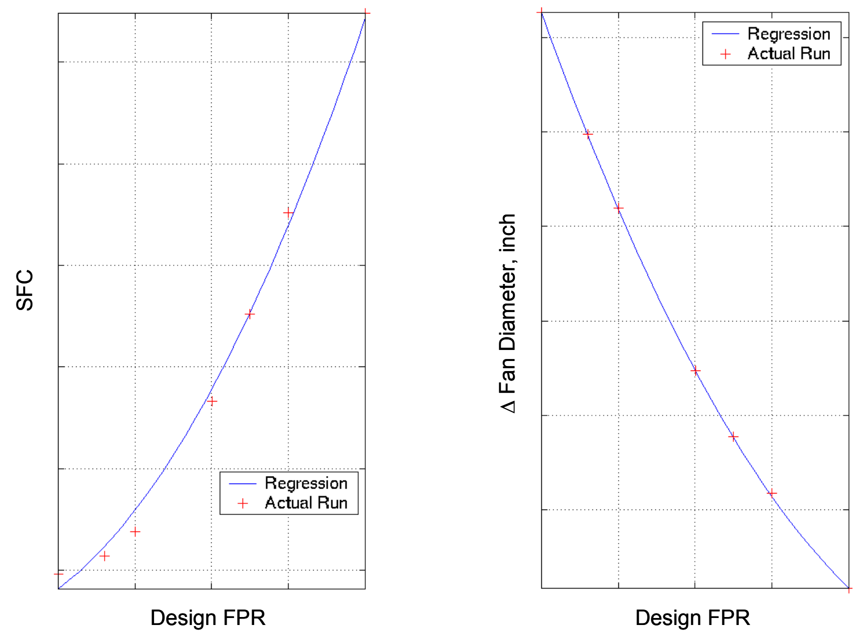


Figure 5.—Comparison between response surface equation and actual runs.

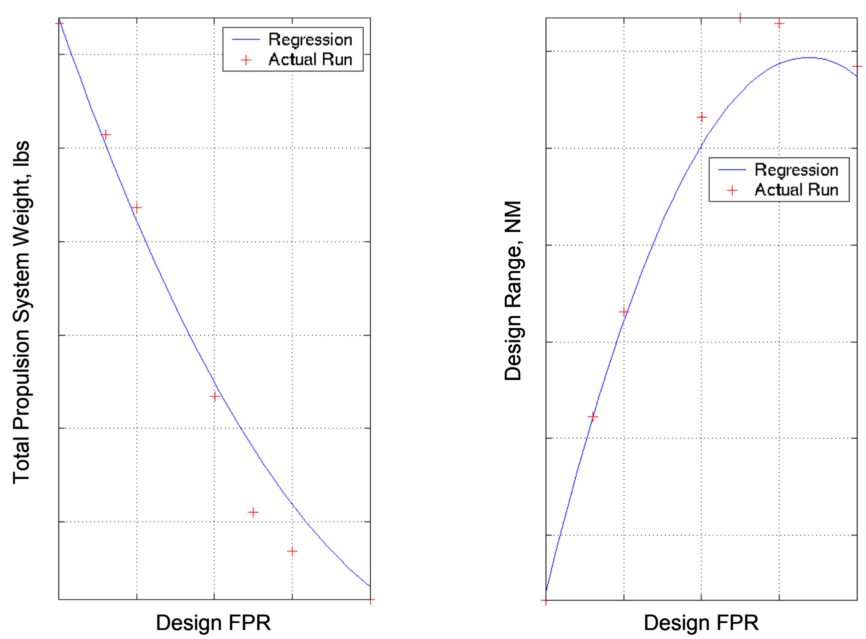


Figure 6.—Comparison between response surface equation and actual runs.

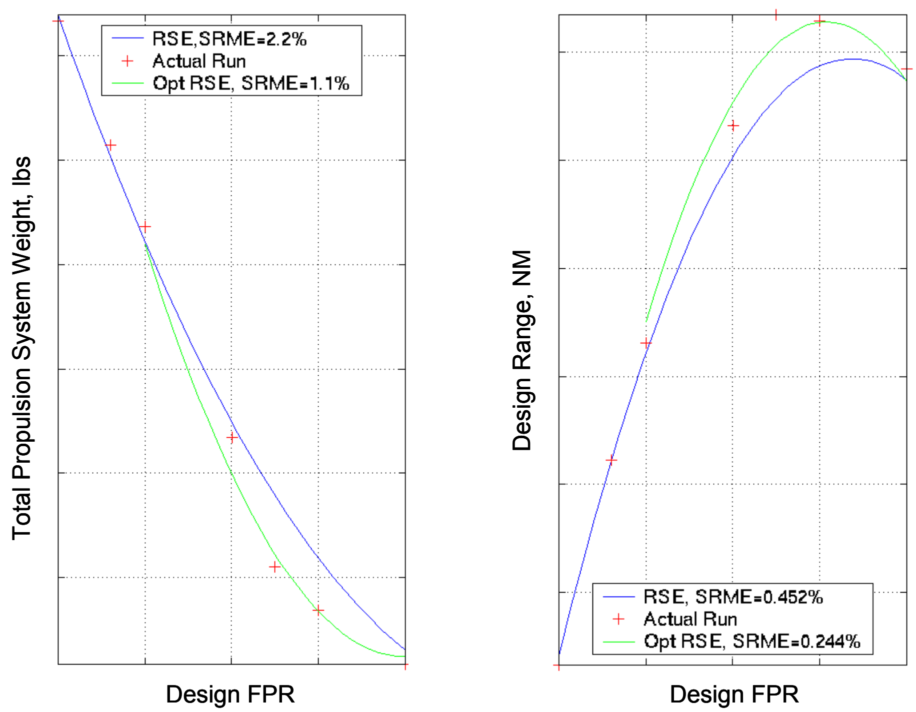


Figure 7.—Comparison between RSE and actual runs: original versus improved.

By changing FPR range, the RSE error can be reduced by half as shown in figure 7. The difference between RSE and actual runs are indicated by square root of mean percent error (SRME) as shown in the formula below ("Act" stands for actual values, "RSE" stands for predicted values based on response surface equations, "n" stands for the number of points. In figure 7, "RSE, SRME" and "Opt RSE, SRME" are original and improved SRME numbers respectively):

$$SRME = \sqrt{\left(\sum_{1}^{n}[(Act - RSE)/Act]^2\right)/n}$$

4.0 Technology Impact Matrix and Technology Modeling

4.1 GEAE and NASA Technology Impact Matrix (TIM)

To assess the impact of proposed technologies, the first step is to compile the Technology Impact Matrix (TIM). TIM serves as a listing of the benefits/detriments/enabling relationships each technology is expected to produce. The TIM provides the inputs to modify the engine design for each technology alternative.

The combined GEAE and NASA TIM were completed for technologies shown in table 1. Listed in the first row are the key control parameters. Shown in the first column are the technology reference number simplified as "T" followed by a number. The second column list 17 GEAE and 5 NASA technologies/suite for new engines. In addition, 2 technologies for deteriorated engines are tabulated. These technologies are two different approaches to attain HPT active clearance control. One uses smart materials/elastic stretch/advanced thermal systems, and the other uses mechanical actuators. It is worth mentioning that the impact of HPT clearance control are three folds: (1) Improve cruise SFC, fuel burn and design range for new engines, however, this benefit is already included in the QAT baseline and will not be considered in this study; (2) Reduce EGT overshoot for new engines, and this impact is evaluated and listed as T17; (3) Improve cruise SFC, fuel burn and design range for deteriorated engines and this is evaluated through T23 and T24.

Tabulated in the body of the TIM table are key control parameter deltas representing the change relative to the QAT baseline for each technology item. As supplement to the TIM table, the acoustic benefits model and emission benefits model, which are not listed in the TIM table due to limited space, are shown.

4.1.1 Acoustic benefits model

Acoustic assessment was carried out utilizing a preliminary-design method based on correlation of propulsion system component noise levels. The component noise metric output of this method is Effective Perceived Noise Level or EPNL, in decibels. Each of the component contributions to the total propulsion system EPNL have their own separate correlation methodology, based on cycle parameters and certain basic geometric definitions. The following components were considered in the assessments:

1. Combustor/Core Noise
2. Fan Exhaust Noise
3. Fan Inlet Noise
4. Jet Mixing Exhaust Noise
5. Airframe Noise

The correlation used in estimating the component EPNL values were developed under GE internal programs over a period of several years, and are based on an accumulated data base from engine test decompositions from CF6, CFM56, CF34, E^3, and GE90 engine families. Use was also made of published Advanced Ducted Propulsion (ADP) data and QCSEE engine test data.

As part of the UEET study, a counter-rotating fan was evaluated, and it showed significant potential for reducing fuel consumption, propulsion system weight, and direct operating cost. It was estimated that the counter-rotating fan (CRF) concept could also provide a noise benefit as well. Therefore, a preliminary-design level estimation procedure was developed to evaluate this concept in the context of previous baseline UEET/QAT study. The same methodology was adopted in this study. It should be noted that the conceptual reason for a CRF being quieter than a single rotating fan (SRF) is based on the notion that fan noise varies as some high power of fan tip speed, and that each stage of a CRF runs at a significantly lower tip speed that the SRF equivalent. Each stage of a CRF produces roughly a pressure ratio that is the square root of the total fan pressure ratio, and hence can run at significantly lower tip speed to produce the required pressure ratio. When the noise levels from each of the two stages are summed (anti-logarithmically), the sum is still less than that of the equivalent single-stage fan.

This noise benefit model is build into PREDATER to calculate the overall engine cumulative noise margin. Shown in figure 8 are cumulative noise margin for the four acoustic technologies.

4.1.2 Emission benefits model

There are two emission related technologies, T16, GEAE Intelligent Combustor and T21, the NASA Active Combustion Control. The NASA combustion technology emission level will remain the same as QAT baseline while the Propulsion 21 combustion technology targets to reduce the emission by 50 percent from QAT baseline. Shown in figure 9 are GEAE emission benefits model for QAT and P21 (indicated as “Intel Comb). This model is built into PREDATER to calculate the LTO NO_x level.

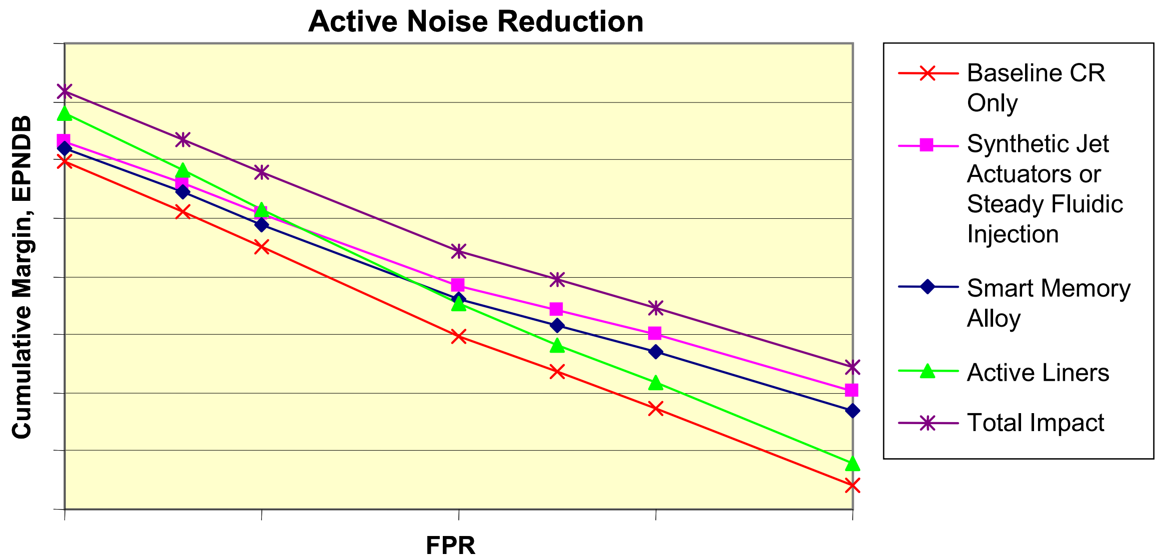


Figure 8.—Cumulative noise margin for acoustic related technologies.

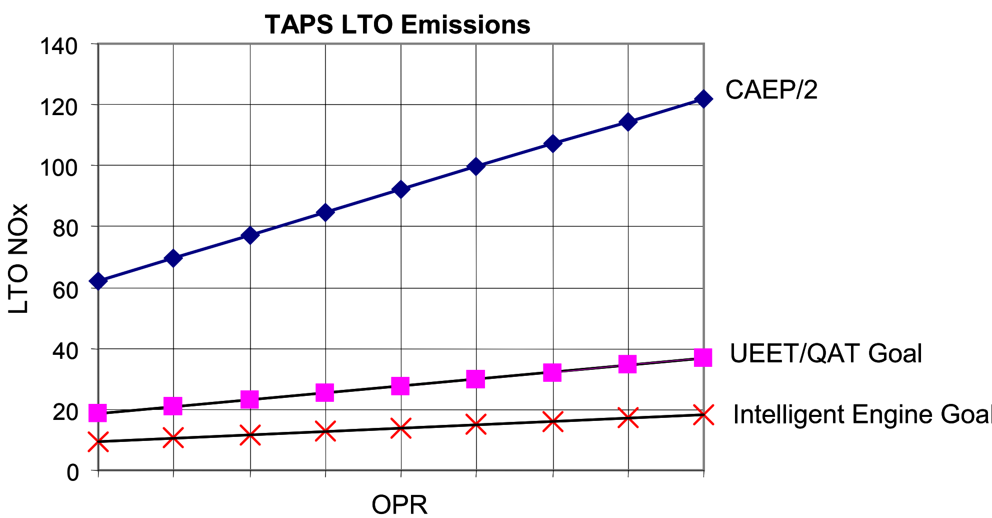


Figure 9.—GEAE PREDATER emission model.

4.1.3 Some comments on T15

The Shape Changing Airfoil Technology T15 was assessed using inputs from the Shape Changing Airfoil project technical effort to assess the system level impact of implementation. Due to the early stage of development of this technology and several unknowns that had not yet been explored, several assumptions were made to enable an overall assessment. Only preliminary assessment of this configuration could be performed under the scope of the Shape Changing Airfoil concept assessment effort and this configuration is not considered to be optimum.

A fan efficiency improvement was determined based on the ability to modify the baseline QAT blade camber into the optimum mission cruise stage blade configuration while keeping the standard baseline blade shape under take-off and climb conditions.

Assessment of the risks associated with the Shape Change Airfoil technology for QAT fan blade applications suggest that there are significant design, performance, safety, and material constraints which would have to be addressed in order to move forward with this technology as it applies to QAT fan blades and the overall QAT mission cycle. It is critical that these issues be assessed to determine the feasibility of implementing such a system.

4.2 GEAE TIM: Selected Technology Modeling

One critical step for constructing Response Surface Equations (RSE) is to build the modeling capabilities for each technology to accurately model the impact of each technology. The GE special technologies here refer to these technologies that are seldom or never modeled in past studies. Examples are modulated cooling (T5 and T6) and cooled cooling (T13) under the technology suite of Thermal management and advanced cooling; the HPT clearance control benefit from reduced EGT overshoot (T17) and the benefit for deteriorated engines (T23 and T24). By enhancing the modeling capabilities for these technologies, significant parametric technology modeling and RSE accuracy improvements were accomplished

4.2.1 Modulated cooling

T5 (HPT blade cooling flow modulation) and T6 (HPT vane cooling flow modulation) are two technologies employing the modulated cooling concept. The benefits are reduced fuel burn and increased design range. An example is shown in figure 10. In this example, the same cooling level reduction is applied to HPT cooling flows at cruise off-design. The X-axis, labeled as "Cooling Scale at Cruise," is the ratio of reduced cooling level at cruise off-design versus the design cooling level. The model has the capability to apply different modulation level to the HPT and LPT chargeable and non-chargeable cooling flows.

4.2.2 Cooled cooling

The concept of cooled cooling is to reduce the cooling air temperature so that the amount of cooling required will be reduced, hence reduced fuel burn and increased design range. The use of fan air as a heat sink to reduce the temperature of the turbine cooling air was evaluated here. Shown in figure 11 is an example of cooling flow versus reduced cooling air temperature. It indicated that significant cooling flow level could be reduced as cooling air temperature is reduced.

4.2.3 HPT ACC for reduced EGT overshoot

Two different approaches are used to model the benefit of EGT overshoot for HPT clearance control. The first approach increases T41 while fixing cooling flow. The second reduces exhaust gas temperature (EGT) stack adders.

Both approaches give similar benefits. However, the first approach requires fixing cooling flow while the rest of the technologies do not. The second approach is much easier to implement in the Design of Experiment environment. Due to these reasons, the second approach was used in constructing the response surface equations to evaluate the benefits for T17.

To model the impact of HPT ACC on deteriorated engines, it is assumed that the HPT ACC can improve the deteriorated HPT adiabatic efficiency. The approach was to apply HPT adiabatic efficiency improvement to a deteriorated engine model so that the HPT efficiency could be recovered to the original baseline level up to a maximum deteriorated level.

The deterioration model was built based on CFM56-7B engine deterioration model. The CFM56-7B deterioration model was constructed based on field experience of the CFM56-7B engine with 20000 flight hours. The QAT deterioration model is a scaled version of the CFM56-7B model. SFC, fuel burn and design range are all improved due to enhanced HPT adiabatic efficiency from T23, while additional cooling flow required minimizes T24 benefit.

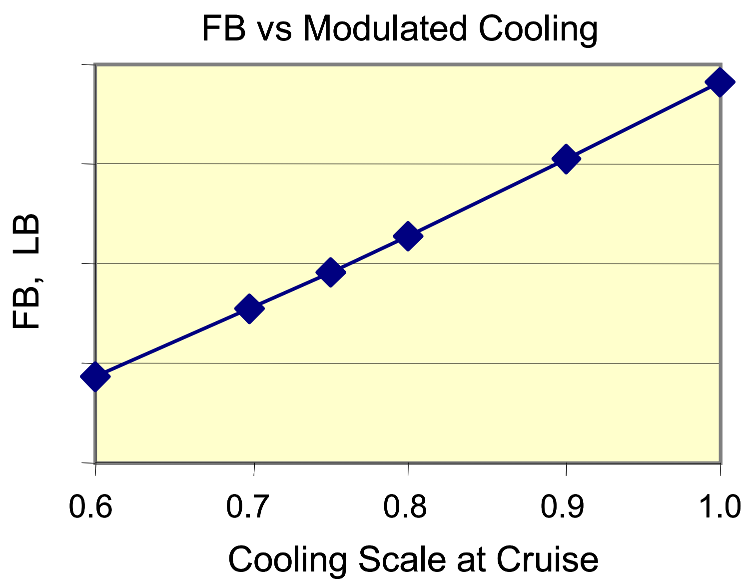


Figure 10.—Impact of modulated cooling on fuel burn.

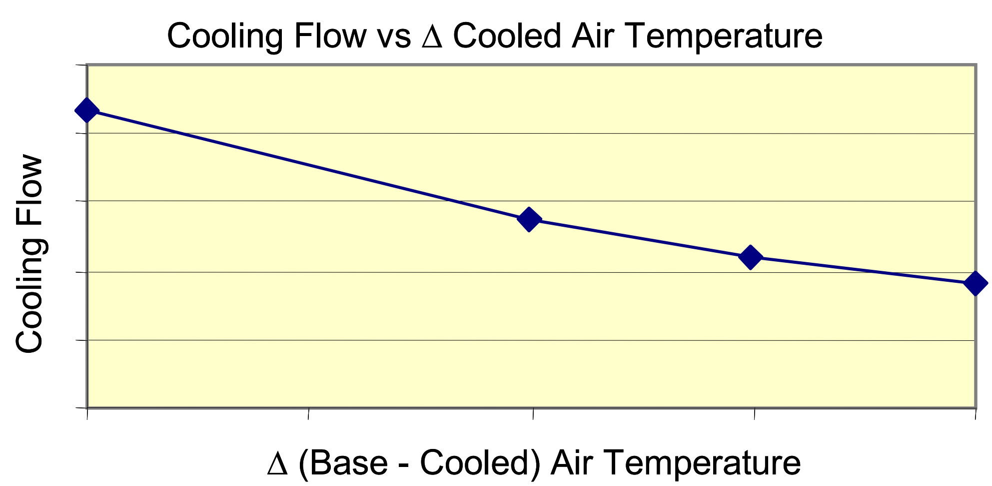


Figure 11.—Impact of cooling air temperature reduction on cooling flow.

4.3 NASA TIM: Construction Considerations and Results

GEAE received a draft version NASA's TIM from GA Tech and spent substantial work effort evaluating and validating the technology estimated effects. A series of meetings were held with NASA technologies owners to better understand the technology and its readiness level. Table 2 shows NASA TIM after the first screening. Some numbers were deleted and others added to the original NASA TIM based on GEAE technologist's expert advice on best-projected system impact for these technologies. Furthermore, GEAE design tools were employed to estimate the system impact as an input to the TIM. The final version of NASA's TIM is jointly listed with GEAE's in table 1. There were significant delta changes from the original to the final TIM versions. Some technologies were grouped together and others not included in the final TIM. The following explains the rationale behind the assessment of each technology listed in table 2. Within this section, for the convenience of discussion, the technology numbering refers to the number in table 2 instead of the final combined GEAE/NASA TIM in table 1.

Deleted
Added

TABLE 2.—ORIGINAL NASA TIM AFTER FIRST ITERATION

NASA IPSFT Technology Applications		ΔFPR	ΔOPR	ΔTIT	$\Delta\eta_{fan\ tip}$	$\Delta\eta_{fan\ hub+LPC}$	$\Delta\eta_{HPC}$	$\Delta\eta_{HPT}$	$\Delta\eta_{LPT}$	ΔHPT NC (CDP)	ΔHPT C (CDP)	ΔHPT C	ΔLPT NC	ΔLPT C	ΔCf_{fan}	ΔCf_{core}	ΔCd_{fan}	ΔCd_{core}	Weight	ΔLeng	ΔWbare	ΔWmech	ΔWnozz	ΔSMfan	ΔFanLoad	ΔHPCLoad
Tech No.		%	%	°F	pt	pt	pt	pt	pt	% Corr. Flow	% Corr. Flow	% Corr. Flow	% Corr. Flow	% Corr. Flow	pt	pt	pt	pt	%	%	%	%	%	ND	%	%
T1	Active Tip Clearance Control Using Hi Temp SMA																									
T2	Noise Control via Synthetic Jets and Piezoelectric Ceramics																									
T3	Active Flow Control via Hi Temp Piezoelectric Ceramics																									
T4	Active Blade Damping (e.g. Hi Temp Piezoelectric Ceramics)																									
T5	Active Blade Damping via Magnetic Bearing Technology																									
T6	Magnetic Bearing Technology																									
T7	Variable Area Core Nozzle via Hi Temp SMA																									
T8	Variable Area Fan Nozzle via Hi Temp SMA																									
T9	Compressor Inlet Guide Vane Control via Hi Temp SMA																									
T10	Combustor Fuel Nozzle Control via Hi Temp SMA																									
T11	LDI Combustor Technology																									
T12	Active Combustion Control (includes Ceramic Thermocouple & Passive Acoustic Tomography)																									

4.3.1 Combustion related technologies:

In the original NASA TIM, there were four technologies related to combustion: Combustor fuel nozzle control via Hi Temp SMA (T10); LDI combustor technology (T11), active combustion control (T12), ceramic thermocouples and passive acoustic tomography (T12). Based on the information provided by NASA technology owners, T10 and T11 were considered actuation methodology, T12 control methodology and T12 sensing methodology. Since system performance is the evaluation target, it was natural to group all the four technologies into one and call this suite the Active Combustion Control, which is listed in the final NASA TIM in table 1.

The potential benefits include:

(1) Reduced HPT non-chargeable cooling flow
(2) Reduced NO_x emission
(3) Reduction in combustor weight.
(4) Increased combustor/turbine life from reduced hot spot temperature. Life related benefit was not modeled or addressed in this study.

The potential negative impacts include:

(1) Need a fail/safe design criteria;
(2) Increased wiring, plumbing, cost, maintenance and control requirements.

4.3.2 Active tip clearance control using Hi Temp SMA (T1)

Based on GEAE technologist input, this technology was considered more applicable to fan blade tips because of its feasibility, more space, environment, and easier access to the fan area. Based on fan aero database and technologist input, an aggressive benefit for SMA fan clearance reduction is an increase in fan efficiency. This is based on the aggressive assumption of reducing fan clearances by 50 percent.

The potential negative impact on weight is minimum. Power requirement is minimum assuming this technology can be realized using thin wire SMA structure which does not require too much power.

4.3.3 Variable area core nozzle via Hi Temp SMA (T7)

Based on design tool study, varying core nozzle area (A8) for the QAT cycle, could find no significant benefit.

4.3.4 Variable area fan nozzle via Hi Temp SMA (T8)

Based on design tool study, varying fan nozzle area (A18) for the QAT cycle could result in a potential increase in fan efficiency (ED12) and engine weight increase.

Note that variable A18 technology is not additive with the SMA fan airfoil. All the results of varying A8 or A18 are very cycle dependent. In other words, existing engines might benefit more or less from these technologies.

4.3.5 Active flow control via Hi Temp piezoelectric ceramics (T3)

The potential benefit for this technology includes weight reduction from a short transition duct. However, the QAT baseline already assumes a short transition duct, and the weight reduction benefit does not apply. Another benefit could be stall margin improvement. Based on HPC rig result**,** for the HPC stall margin technology (piezoelectric), assumed an improvement in stall line and corresponding increase in operating line, which translates into improvement in HPC efficiency based on new engine design experience.

4.3.6 Magnetic bearing technology (T6)

The potential benefits for this technology is two folds: First, lower overall vibration level, which could improve reliability and life. However, as previously stated for this study, life related benefit was not modeled. Second benefit is the higher DN capability. However, the QAT new engine design is not limited by DN; hence there is no immediate impact from higher DN capability.

The shortcomings for aircraft engine applications are listed:

(1) Weight penalty is huge plus magnetic bearings need auxiliary bearings to handle blade-out load and as safety backup.
(2) Offset bottom case clearance grind to allow rotor drop during shut down;
(3) Cooling flow requirement under hot section;
(4) Extra power requirements.

GEAE conducted an ideal case assessment for magnetic bearing technologies attempting to minimize the above mentioned disadvantages. This ideal case assessment is based on the following assumptions:

- An innovative magnetic bearing concept will be designed to support counter rotating rotors;
- Magnetic field will be transmitted through the counter rotating rotors;
- These advanced magnetic bearings will not require back up bearing and lube systems;
- A concept will support the rotors during engine off and fan blade out conditions.

All the mentioned technologies were taken into consideration for evaluation. However, the following two technologies were not included because GEAE technologists could not estimate a benefit over existing systems or a practical method to implement:

4.3.7 Active blade damping (T4)

The concerns on this technology are two folds: First, the target TRL 9 date is 2017 while the Propulsion 21 EIS is 2008 to 2012 or 2015 at the latest. Secondly and most important, is the implementation of this technology in a rotating structure and its effect on LCF life.

4.3.8 Compressor IGV control via Hi Temp SMA (T9)

The concerns on this technology are two folds: First using SMA will not provide additional benefit to the current rotor actuator. Secondly and most important, SMA is an on-off switch while IGVs need continuous and instant actuation control.

5.0 Response Surface Equation Construction Results

For this study, a 12-factor Design of Experiment (DOE) table, with central composite design of 281 runs, was generated as input to the PREDATER analysis and results from the DOE were post processed using the commercial statistical tool JMP to obtain the response surface equations. The RSE are shown in figure 12. The 12 factor key control parameters and the 12 responses representing the system figures of merits are listed.

12 Factors:

(1) **ZFPRD**: Fan Pressure Ratio
(2) **EGTadder**: EGT stack adder reduction
(3) **DTE1C2**: Cooled delta air temperature from baseline
(4) **ED12**: Fan efficiency

(5) **ED25**: HPC efficiency
(6) **ZSWC42**: Cooling flow scalar
(7) **ZSWC43**: Cooling flow scalar
(8) **SG31W42**: Modulated cooling scalar
(9) **SG27W42**: Modulated cooling scalar
(10) **DELWT**: Delta weight to propulsion system weight
(11) **ZPWXH**: Power extraction
(12) **ZWB**: Customer bleed

12 Responses:

(1) **SFC_MP**: SFC Mid Cruise
(2) **DIT2A**: Fan diameter
(3) **WTTWAV**: Propulsion system weight
(4) **FUEL7**: Fuel burn at 5600 NM
(5) **RANGE10**: Design range
(6) **CR_CUM_MARG**: Baseline cumulative acoustic margin
(7) **CR_SFI**: Baseline + SFI (T1) or SJA (T2) cumulative acoustic margin
(8) **CR_SMA**: Baseline + SMA (T3) cumulative acoustic margin
(9) **CR_AL**: Baseline + Active Liners (T4) cumulative acoustic margin
(10) **P21_CUM_MARG**: P21 cumulative acoustic margin
(11) **NOXQAT**: Baseline NO_x, same for NASA Active Combustor (T21) NO_x
(12) **NOXP21**: GEAE Intelligent Combustor (T16) NO_x

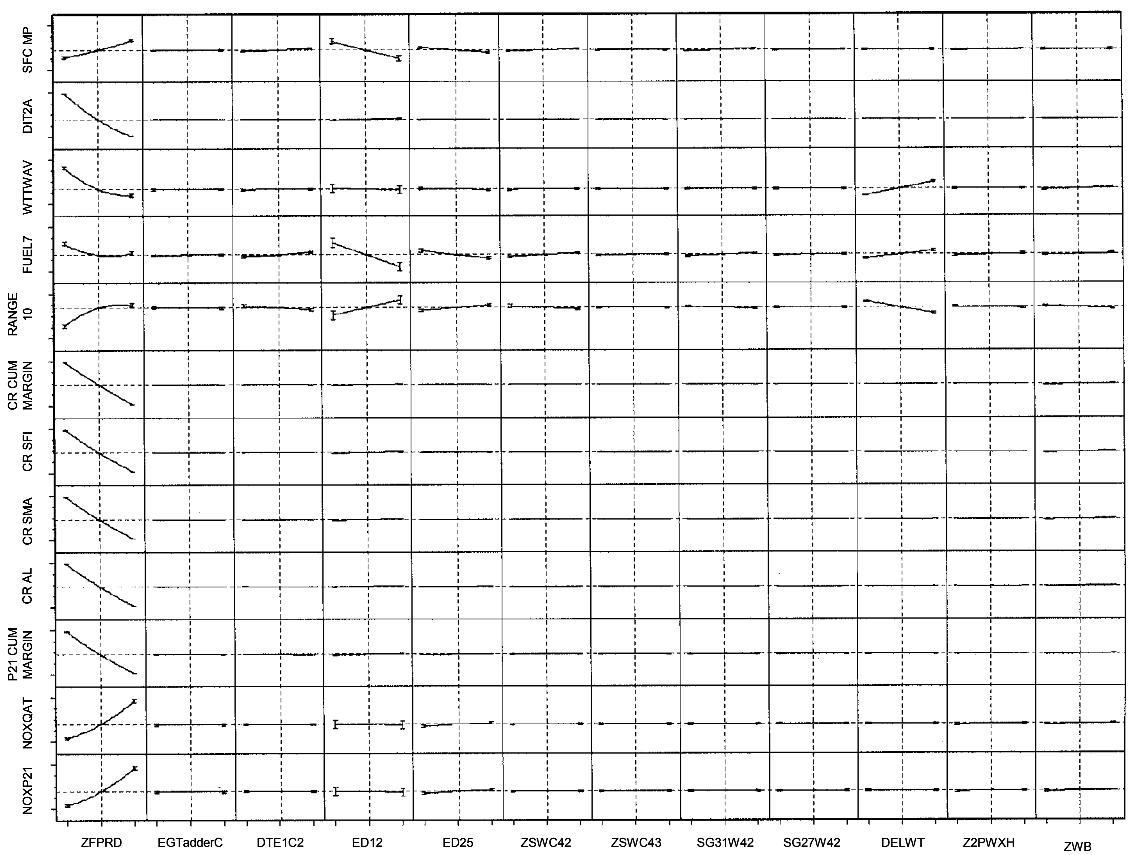


Figure 12.—Response surface equations.

6.0 Technology Ranking and System Benefits

6.1 Individual Technology Evaluation

The purpose of the technology benefits assessment was to determine the individual or technology groups that provide the greatest benefit to the engine platform. In this study, GEAE evaluated the internally suggested technologies as well as NASA suggested technologies. GEAE PREDATER was used to construct the response surface equations, and the Georgia Tech Technology Impact Evaluation System, TIES was used to conduct the technology assessment for all the new engine technologies. The deteriorated engine technologies T23 and T24 were not included in the TIES One-on and One-off study because they were not applied to new engines while the rest of the technologies were. Instead, the results from PREDATER for T23 and T24 were directly used and they are plotted with the rest of new engine technologies, indicated as yellow bars in figures 13 to 19.

TIES is a disciplined methodology that combines expert technology impact assessment with a physics based description of the engine design space. The TIES method was developed by Georgia Tech and was used in cooperation as part of a larger Industry-University Partnership that GEAE has with Georgia Tech. In this study, the two methods in TIES, One-on and One-off were used. For one-on, the baseline is the QAT engine with no additional technology on, and then added only one technology at a time. For One-off, the baseline is the QAT engine plus all technologies on, and then technology removed one at a time. Figures 13 to 19 show the impact of each proposed technology on new engines, except T23 and T24, in terms of SFC, fuel burn, design range, noise, emission, fan diameter, and total propulsion weight relative to the QAT baseline using TIES One-on and One-off methods. Shown on the same charts is the impact of HPT clearance control on deteriorated engines. Throughout this study, SFC refers to specific fuel consumption at mid cruise point, and fuel burn refers to fuel burn at 5600 Nautical Mile (NM) mission. Note that all the technology evaluation charts are shown as deltas or delta percent values from their own baseline.

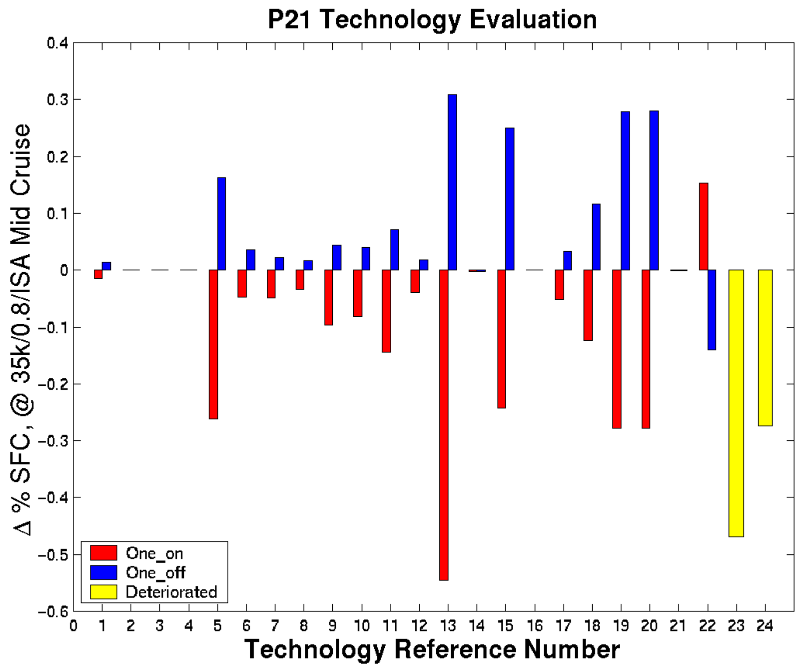
6.1.1 SFC, fuel burn, and design range

The top ten technology rankings for SFC, fuel burn and design range are listed at the bottom of these figures for both One-on and One-off methods. The top ten remain the top ten for both methods, although their order changed slightly. T13 (Intelligent HPT rotor cooled cooling), T19 (Active tip clearance control using high temperature SMA), T20 (Variable area fan nozzle via high temperature SMA), T5 (HPT blade cooling flow modulation), T15 (Shape changing airfoil) have significant impact on SFC, fuel burn and design range. T14 (Smart Containment System), which reduces engine weight, has minimum impact on SFC; however, it reduces fuel burn and significantly increase design range.

6.1.2 Acoustic Assessment

Among the acoustic technologies, T1 (Steady fluidic injection), T2 (Synthetic jet actuators), T3 (Shape memory alloy), and T4 (Active liners), T2 has most acoustic benefits with minimum impact on fuel burn and design range.

		GEAE Technology list
	Active noise reduction	
T1		–Steady Fluidic Injection
T2		–Synthetic Jet Actuators
T3		–Shape memory alloy
T4		–Active Liners
	Thermal management and advanced cooling	
T5		HPT blade cooling flow modulation
T6		HPT vane cooling flow modulation
T7		HPT smart TE cooling
T8		HPT smart tip cooling
T9		HPT film optimization
T10		Active internal cooling
T11		Rotor purge control
T12		HPT shroud
T13		Intelligent HPT rotor cooled cooling
T14	Smart containment system	
		–Advanced Structure & Containment Fab
		–Advanced Nanofiber diagnostics
T15	Shape Changing Airfoils	
T16	Intelligent combustor	
T17	HPT clearance control	
		NASA Technology list
T18	Active Flow Control Via Hi Temp Piezoelectric ceramics	
T19	Active tip clearance control using Hi Temp SMA	
T20	Variable area fan nozzle via Hi Temp SMA	
T21	Active Combustion Control	
		Combustor fuel nozzle control via Hi Temp SMA
		LDI Combustor Technology
		Active Combustion Control
		Passive Acoustic Tomography
		Ceremic Thermocouple
T22	Magnetic bearing technology	
		GEAE: deteriorated engine
	HPT clearance control (deteriorated engine)	
		–Elastic Stretch –Smart materials
T23		–advance thermal systems
T24		–Mechanical actuators

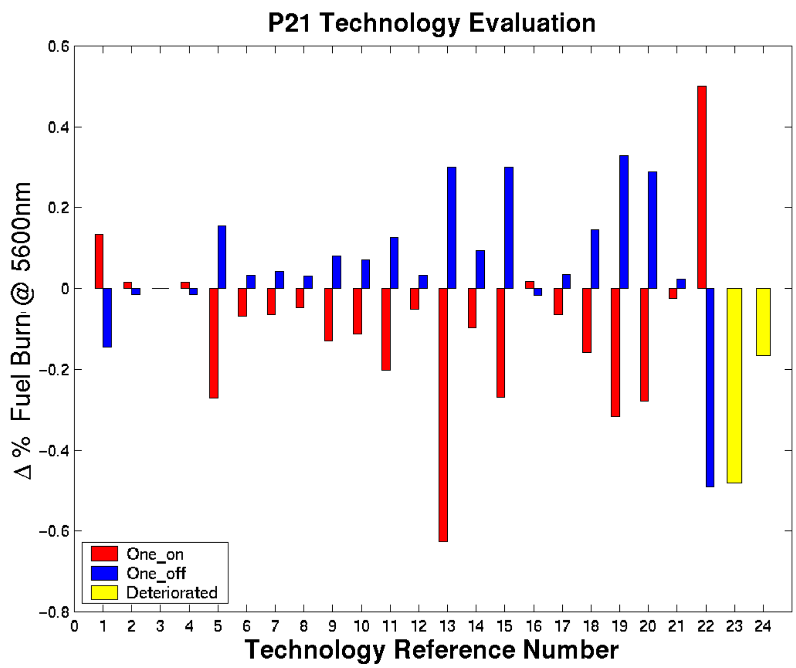


Top Ten SFC

Tech #	13	19	20	5	15	11	18	9	10	6
One_on	1	2	3	4	5	6	7	8	9	10
One_off	1	2	3	5	4	7	6	9	10	8

Figure 13.—Technology evaluation: SFC.

		GEAE Technology list
	Active noise reduction	
T1		–Steady Fluidic Injection
T2		–Synthetic Jet Actuators
T3		–Shape memory alloy
T4		–Active Liners
	Thermal management and advanced cooling	
T5		HPT blade cooling flow modulation
T6		HPT vane cooling flow modulation
T7		HPT smart TE cooling
T8		HPT smart tip cooling
T9		HPT film optimization
T10		Active internal cooling
T11		Rotor purge control
T12		HPT shroud
T13		Intelligent HPT rotor cooled cooling
T14	Smart containment system	
		–Advanced Structure & Containment Fab
		–Advanced Nanofiber diagnostics
T15	Shape Changing Airfoils	
T16	Intelligent combustor	
T17	HPT clearance control	
		NASA Technology list
T18	Active Flow Control Via Hi Temp Piezoelectric ceramics	
T19	Active tip clearance control using Hi Temp SMA	
T20	Variable area fan nozzle via Hi Temp SMA	
T21	Active Combustion Control	
		Combustor fuel nozzle control via Hi Temp SMA
		LDI Combustor Technology
		Active Combustion Control
		Passive Acoustic Tomography
		Ceremic Thermocouple
T22	Magnetic bearing technoloy	
		GEAE: deteriorated engine
	HPT clearance control (deteriorated engine)	
		–Elastic Stretch –Smart materials
T23		–advance thermal systems
T24		–Mechanical actuators

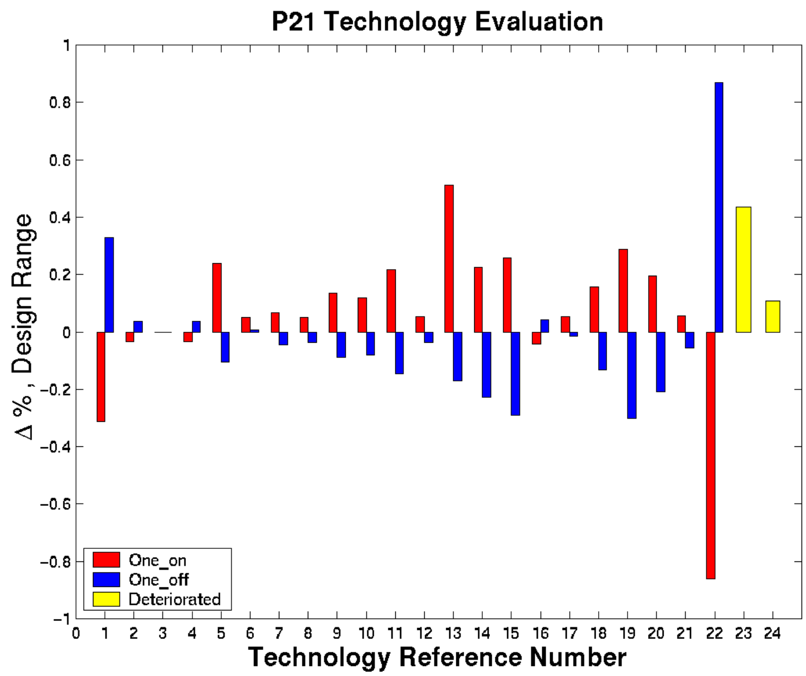


Top Ten FB

Tech #	13	19	15	20	5	11	18	9	10	14
One_on	1	2	3	4	5	6	7	8	9	10
One_off	2	1	4	3	6	7	5	9	10	8

Figure 14.—Technology evaluation: Fuel burn at 5600 NM.

	GEAE Technology list
	Active noise reduction
T1	–Steady Fluidic Injection
T2	–Synthetic Jet Actuators
T3	–Shape memory alloy
T4	–Active Liners
	Thermal management and advanced cooling
T5	HPT blade cooling flow modulation
T6	HPT vane cooling flow modulation
T7	HPT smart TE cooling
T8	HPT smart tip cooling
T9	HPT film optimization
T10	Active internal cooling
T11	Rotor purge control
T12	HPT shroud
T13	Intelligent HPT rotor cooled cooling
T14	Smart containment system
	–Advanced Structure & Containment Fab
	–Advanced Nanofiber diagnostics
T15	Shape Changing Airfoils
T16	Intelligent combustor
T17	HPT clearance control
	NASA Technology list
T18	Active Flow Control Via Hi Temp Piezoelectric ceramics
T19	Active tip clearance control using Hi Temp SMA
T20	Variable area fan nozzle via Hi Temp SMA
T21	Active Combustion Control
	Combustor fuel nozzle control via Hi Temp SMA
	LDI Combustor Technology
	Active Combustion Control
	Passive Acoustic Tomography
	Ceremic Thermocouple
T22	Magnetic bearing technoloy
	GEAE: deteriorated engine
	HPT clearance control (deteriorated engine)
	–Elastic Stretch –Smart materials
T23	–advance thermal systems
T24	–Mechanical actuators



Top Ten Range

Tech #	13	19	15	14	5	11	20	18	9	10
One_on	1	2	3	4	5	6	7	8	9	10
One_off	5	1	2	3	8	7	4	6	9	10

Figure 15.—Technology evaluation: Design range.

	GEAE Technology list
	Active noise reduction
T1	–Steady Fluidic Injection
T2	–Synthetic Jet Actuators
T3	–Shape memory alloy
T4	–Active Liners
	Thermal management and advanced cooling
T5	HPT blade cooling flow modulation
T6	HPT vane cooling flow modulation
T7	HPT smart TE cooling
T8	HPT smart tip cooling
T9	HPT film optimization
T10	Active internal cooling
T11	Rotor purge control
T12	HPT shroud
T13	Intelligent HPT rotor cooled cooling
T14	Smart containment system
	–Advanced Structure & Containment Fab
	–Advanced Nanofiber diagnostics
T15	Shape Changing Airfoils
T16	Intelligent combustor
T17	HPT clearance control
	NASA Technology list
T18	Active Flow Control Via Hi Temp Piezoelectric ceramics
T19	Active tip clearance control using Hi Temp SMA
T20	Variable area fan nozzle via Hi Temp SMA
T21	Active Combustion Control
	Combustor fuel nozzle control via Hi Temp SMA
	LDI Combustor Technology
	Active Combustion Control
	Passive Acoustic Tomography
	Ceremic Thermocouple
T22	Magnetic bearing technoloy
	GEAE: deteriorated engine
	HPT clearance control (deteriorated engine)
	–Elastic Stretch –Smart materials
T23	–advance thermal systems
T24	–Mechanical actuators

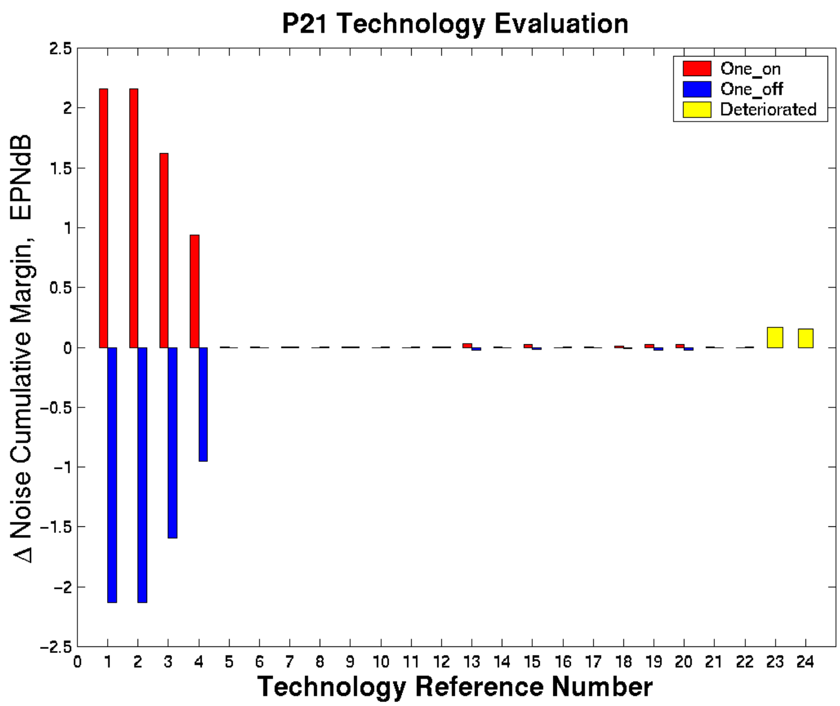


Figure 16.—Technology evaluation: Noise.

		GEAE Technology list
	Active noise reduction	
T1		–Steady Fluidic Injection
T2		–Synthetic Jet Actuators
T3		–Shape memory alloy
T4		–Active Liners
	Thermal management and advanced cooling	
T5		HPT blade cooling flow modulation
T6		HPT vane cooling flow modulation
T7		HPT smart TE cooling
T8		HPT smart tip cooling
T9		HPT film optimization
T10		Active internal cooling
T11		Rotor purge control
T12		HPT shroud
T13		Intelligent HPT rotor cooled cooling
T14	Smart containment system	
		–Advanced Structure & Containment Fab
		–Advanced Nanofiber diagnostics
T15	Shape Changing Airfoils	
T16	Intelligent combustor	
T17	HPT clearance control	
		NASA Technology list
T18	Active Flow Control Via Hi Temp Piezoelectric ceramics	
T19	Active tip clearance control using Hi Temp SMA	
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		LDI Combustor Technology
		Active Combustion Control
		Passive Acoustic Tomography
		Ceremic Thermocouple
T22	Magnetic bearing technoloy	
		GEAE: deteriorated engine
	HPT clearance control (deteriorated engine)	
T23		–Elastic Stretch –Smart materials –advance thermal systems
T24		–Mechanical actuators

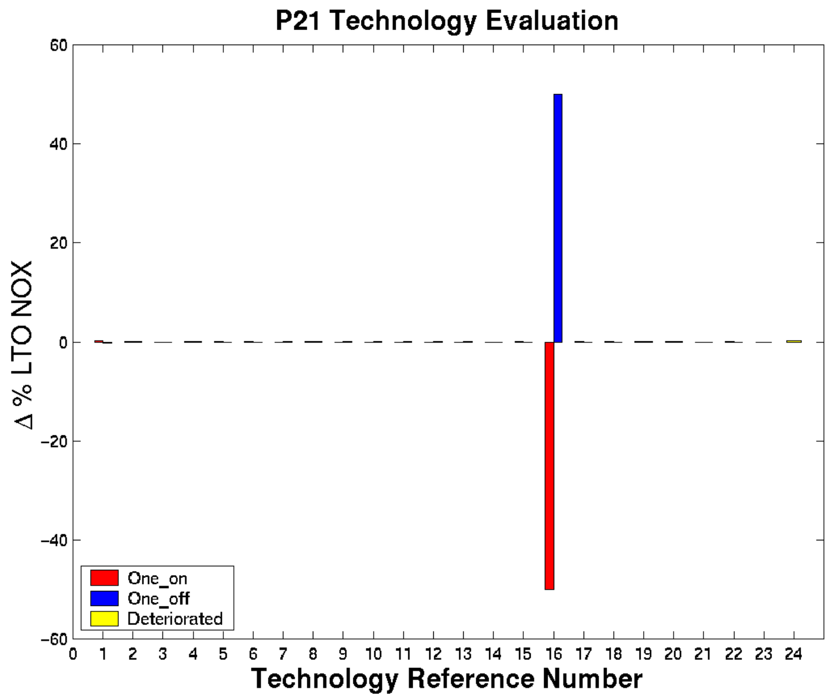

Figure 17.—Technology evaluation: LTO NO_x.

6.1.3 Emissions

The LTO NO_x assessment is shown in figure 19. The predicted LTO NO_x data for T16 (GEAE Intelligent combustor) reflects the potential benefit of the TAPS design to meet the program goal of reducing NO_x by 50 percent from baseline QAT level, equivalent to 15 percent additional reduction from 1996 ICAO limit. NASA's active combustion control (T21) will remain the same NO_x level as the QAT baseline.

6.1.4 Fan diameter and propulsion system weight

Engine fan diameter, propulsion system weight and SFC are engine characteristics that have significant impact to aircraft fuel burn and design range. Weight is also considered an indicator of engine cost and engine manufacturers are always looking at ways to reduce weight in new designs. For this reason the fan diameter and propulsion system weight are included as system figures of merits. The technology evaluation for fan diameter and propulsion system weight are shown in figures 18 and 19.

		GEAE Technology list
	Active noise reduction	
T1		–Steady Fluidic Injection
T2		–Synthetic Jet Actuators
T3		–Shape memory alloy
T4		–Active Liners
	Thermal management and advanced cooling	
T5		HPT blade cooling flow modulation
T6		HPT vane cooling flow modulation
T7		HPT smart TE cooling
T8		HPT smart tip cooling
T9		HPT film optimization
T10		Active internal cooling
T11		Rotor purge control
T12		HPT shroud
T13		Intelligent HPT rotor cooled cooling
T14	Smart containment system	
		–Advanced Structure & Containment Fab
		–Advanced Nanofiber diagnostics
T15	Shape Changing Airfoils	
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		Combustor fuel nozzle control via Hi Temp SMA
		LDI Combustor Technology
		Active Combustion Control
		Passive Acoustic Tomography
		Ceremic Thermocouple
T22	Magnetic bearing technoloy	
		GEAE: deteriorated engine
	HPT clearance control (deteriorated engine)	
		–Elastic Stretch –Smart materials
T23		–advance thermal systems
T24		–Mechanical actuators

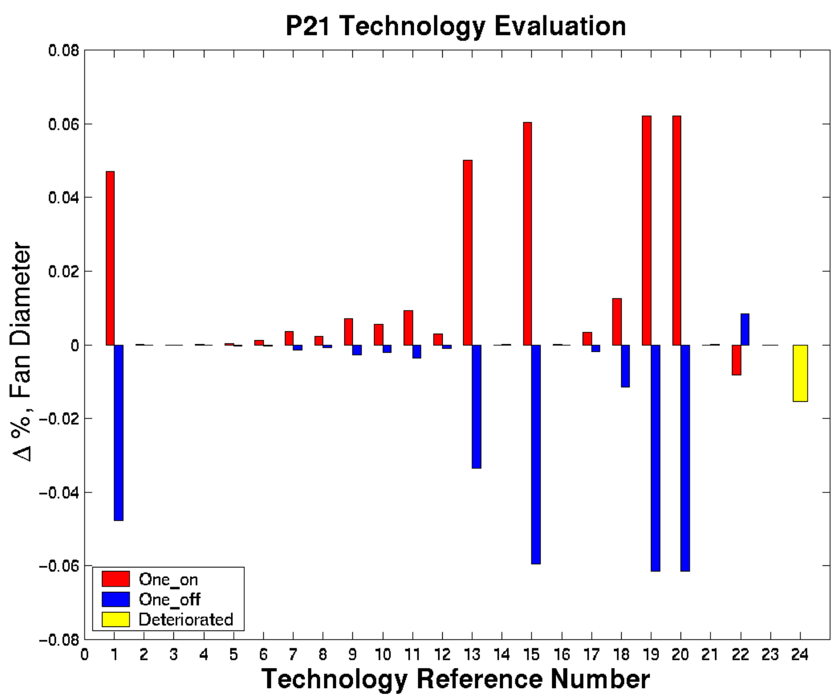

Figure 18.—Technology evaluation: Engine fan diameter.

	GEAE Technology list
	Active noise reduction
T1	–Steady Fluidic Injection
T2	–Synthetic Jet Actuators
T3	–Shape memory alloy
T4	–Active Liners
	Thermal management and advanced cooling
T5	HPT blade cooling flow modulation
T6	HPT vane cooling flow modulation
T7	HPT smart TE cooling
T8	HPT smart tip cooling
T9	HPT film optimization
T10	Active internal cooling
T11	Rotor purge control
T12	HPT shroud
T13	Intelligent HPT rotor cooled cooling
T14	Smart containment system
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	–Advanced Nanofiber diagnostics
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T22	Magnetic bearing technoloy
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	–Elastic Stretch –Smart materials
T23	–advance thermal systems
T24	–Mechanical actuators

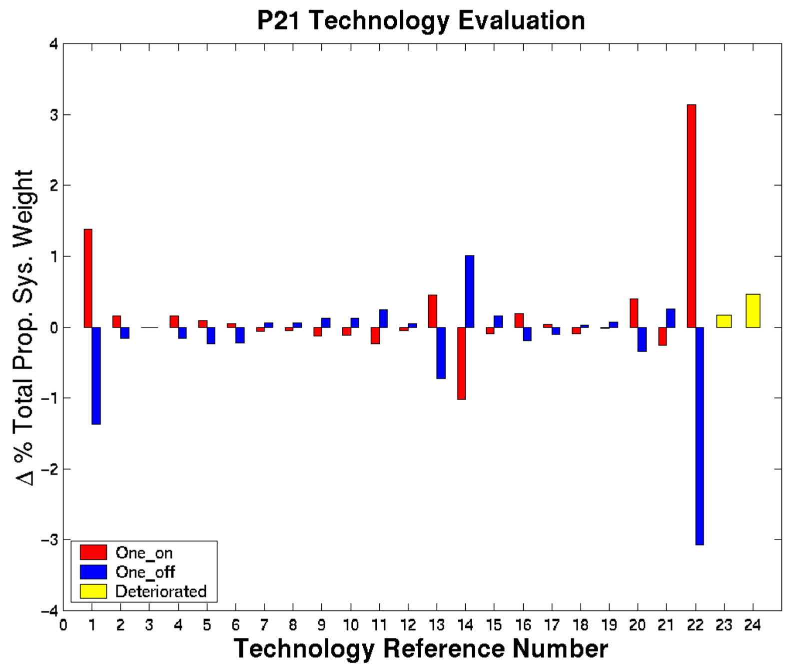

Figure 19.—Technology evaluation: Total propulsion system weight.

6.2 Engine System Level Impact: Combined Technologies

The engine system level impact was estimated by selecting the best technologies, among the incompatible technologies, and including all the beneficial technologies. There were three steps involved:

Step (1): Selecting the best technology out of the incompatible ones based on the individual technology evaluation

(a) Incompatible Acoustic related technologies: T1, T2, T3:
T1 and T2 have the best acoustic benefits, while T2 has minimum impact on fuel burn and design range compared to T1. Selected T2.

(b) Incompatible fan flow related related technologies: T15, T20

The Shape Changing Airfoil (T15) uses SMA to change fan airfoil shape. The Variable Area Fan Nozzle via High Temperature SMA (T20) uses SMA to change fan nozzle area. These two technologies are not additive due to the following reasons:

1. The SMA fan airfoil reduces the loss associated with off design operation by changing the blade camber.
2. Variable fan nozzle area (A18) does not change the blade shape, but it does change the fan operating line. Opening A18 at part speed may also reduce the incidence loss.
3. Based on the individual technology evaluation results, these two technologies have almost identical benefits. T15 is slightly better on design range, but more risky. For evaluation purpose, selected T20.

(c) Combustion related technology: T16 and T21.

T16 has 50 percent reduction on NO_x while T21 has the same as the QAT baseline. Selected T16.

Step (2): Excluding technologies with no system benefit within modeling capability. Excluded T22 (magnetic bearing technology)

Step (3): Combining all the selected technology to evaluate potential engine system level impact. The final system contains all the proposed technologies except T1, T3, T15, T21, and T22. The system level impacts based on the response surface equations are shown in table 3. With respect to the QAT baseline, SFC was improved by 1.7 delta percent, fuel burn improved by delta 2.0 percent, design range improved by delta 1.9 percent, Noise (cumulative margin) improved by 3.3 EPNdB, NO_x reduced by 50 percent, and propulsion system weight reduced by 73 lbs.

TABLE 3.—ENGINE SYSTEM LEVEL IMPACT

SFC	**-1.7%**	Delta percent from baseline
Fuel Burn (at 5600NM)	**-2.0%**	Delta percent from baseline
Design Range	**1.9%**	Delta percent from baseline
Noise cumulative margin	**3.3**	Delta EPNdB from baseline
NOX	**-50%**	Delta percent from baseline
Propulsion System Weight	**-73**	Delta from baseline (lbs)

7.0 Conclusions

7.1 Deliverables Met

For the Propulsion 21 system study, the following tasks were accomplished within the original work scope:

- Reached agreement with NASA and Georgia Tech regarding work scope and baseline engine/AC definition;
- Completed TIM for GEAE technology list;
- Validated Response Surface Equations using JMP and PEZ tools;
- Improved RSE fit accuracy based on Design Space Study;
- Built the system model using the QAT as baseline AC and engine;
- Generated response surface equations and transmitted to Georgia Tech.

7.2 Additional Deliverables

Additional results were delivered beyond the original work scope. These include:

- Coordinated GE evaluation of NASA TIM;
- Enhanced modeling capability for special technologies, including modulated cooling, cooled cooling, HPT ACC for EGT overshoot and deteriorated engines;
- Evaluated/ranked individual new engine technology using One-on and One-off methods;
- Evaluated deteriorated engine technology impact for HPT clearance control;
- Estimated overall system impact by optimally combining technologies;
- Compiled Technology Readiness Level;

7.3 Engine System Level Impact

The engine system level impact was estimated by the optimal combination of technologies, resulting in potential 3.3 EPNdB cumulative noise margin improvements, 2.0 percent fuel burn reduction and 50 percent NO_x emissions reduction from the QAT baseline.

7.4 Modeling Shortfalls and Improvement Needs

Some technologies were not assessed to their full potential benefits due the modeling capability; while other technologies could have been evaluated to higher accuracy with improvement on the tools. The following are modeling shortfalls or future improvement needs:

(1) The model used did not consider life related benefits. This impact the assessment for magnetic bearings, combustion control, malfunction and operation error reduction, disk life meter, sub system health management, as all these technologies have the potential for hardware life related benefits.
(2) The model did not have the capability for thermal dynamic/transition analysis. This capability will be ideal for EGT overshoot analysis.
(3) Need to better understand future NASA technologies, especially the implementation techniques and feasibilities, in order to better simulate and include in future evaluations.

8.0 Recommendations for Future Work

Recommendations for future work include short term and long-term items. These include, but not limited to:

(A) Short term

Add the following figures of merits to the system study beside SFC, fuel burn, design range, emission and acoustics:

(1) Manufacturing cost,
(2) Maintenance cost,
(3) Customer value analysis

(B) Long term

(1) Validate, improve and enhance the life prediction model;
(2) Add the thermal dynamic/transition analysis modeling capabilities.
(3) Further investigate NASA technologies showing significant performance improvement and/or noise and emission reduction
(4) Potential improvements to cycle/systems modeling that would aid deterioration modeling and deterioration technology impact assessment. Types of deterioration include

Increased tip clearances
Open seal clearances
Airfoil surface roughness
Blade leading edge damage (FOD)
Bushing, shroud leakage
Airfoil/other hardware dirt buildup

Linking these effects via some physics based models to cycle component/systems modeling is the key to assessing deterioration reduction technologies. The deterioration reduction technologies (intelligent and other....) then must be characterized consistent with the physics based model inputs.

9.0 Work Element Schedule

Figure 20 shows the detailed schedule for the system study work element.

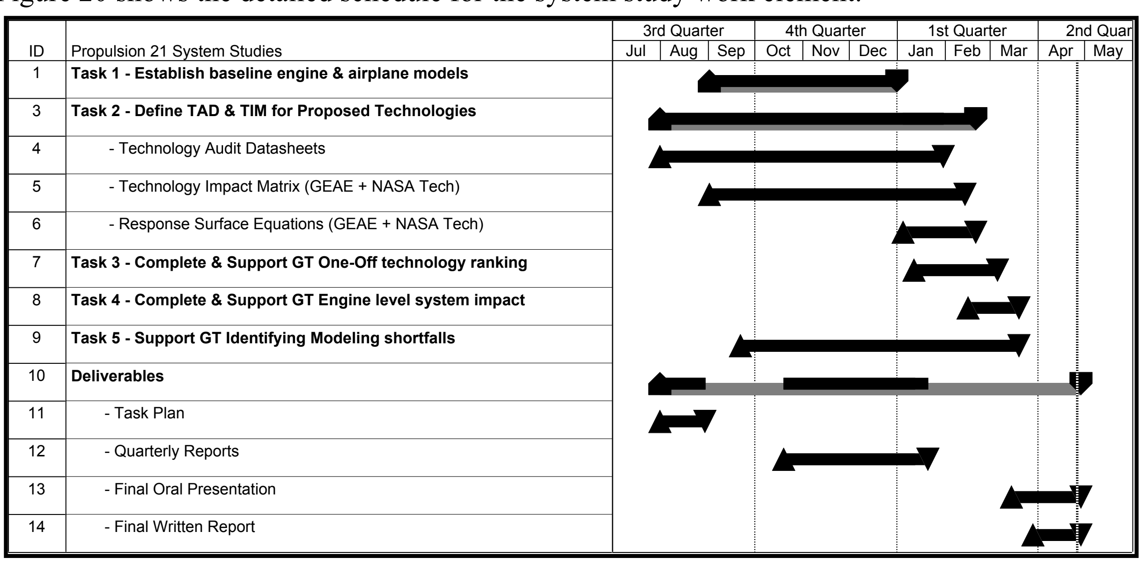

Figure 20.—Schedule plan.

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13. ABSTRACT *(Maximum 200 words)*

The objective of this NASA funded project is to assess and prioritize advanced technologies required to achieve the goals for an "Intelligent Propulsion System" through collaboration among GEAE, NASA, and Georgia Tech. Key GEAE deliverables are parametric response surface equations (RSE's) relating technology features to system benefits (sfc, weight, fuel burn, design range, acoustics, emission, etc…) and listings of Technology Impact Matrix (TIM) with benefits, debits, and approximate readiness status. TIM has been completed for GEAE and NASA proposed technologies. The combined GEAE and NASA TIM input requirement is shown in Table.1. In the course of building the RSE's and TIM, significant parametric technology modeling and RSE accuracy improvements were accomplished. GEAE has also done preliminary ranking of the technologies using Georgia Tech/GEAE USA developed technology evaluation tools. System level impact was performed by combining beneficial technologies with minimum conflict among various system figures of merits to assess their overall benefits to the system. The shortfalls and issues with modeling the proposed technologies are identified, and recommendations for future work are also proposed.

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