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Advanced Controls for Airbreathing Engines

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Allison Gas Turbine

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1.0 SUMMARY

This report provides quantified measures of performance and operability improvement resulting from the application of advanced control technologies to an airbreathing engine as part of the ongoing Advanced Propulsion Concept (APC) program. The model aircraft of study was a 39-passenger civil tiltrotor based on the military V-22 Osprey, which utilizes two Allison T406 engines. A takeoff point and a maximum cruise point were selected from an expected civil mission profile to simplify this first-pass quantitative analysis. The engine performance and operability parameters examined were specific fuel consumption (SFC), engine weight, engine acquisition cost, maintenance, emissions, and safety.

Concepts were examined to reduce emissions in anticipation of stringent FAA regulations. Critical combustor design conditions are idle and maximum power conditions since carbon monoxide (CO) and unburned hydrocarbons (UHC) tend to be high at idle while nitrogen oxides (NOx) are high at maximum power. Current fixed-combustor design yields acceptable emissions at maximum power yet much improvement is needed at the idle point. By controlling combustor fuel/air ratio, via variable geometry, reductions of CO by 53% and UHC by 69% were calculated at idle with no effect on the maximum power conditions.

Concepts were examined for improved SFC. Massachusetts Institute of Technology (MIT) has done studies with regard to surge inhibitor technology which enable operating the engine nearer the surge line. Reducing the surge margin, through compressor variable geometry vane settings, by 5% it was seen that a 0.7% decrease in SFC resulted. Incorporating gas generator turbine variable geometry, to allow varying flow by 10%, an improvement to SFC of 1.3% was achieved. Implementation of hardware allowing active cooling control also yielded a 1.3% improvement to SFC.

Concepts were examined for improved one-engine-inoperative (OEI) capability, an important safety design criteria. At high compressor corrected speeds, 0.5% increase in horsepower was attainable while power turbine-turbine variable geometry yielded a 5.8% increase or 400 horsepower. The benefit of this concept provides either an increase of safety margin or a dynamic potential for downsizing the engines yielding less weight for the same power.

A concept was examined to control combustor pattern factor. An actively controlled fuel nozzle system would allow for control of combustor circumferential pattern factor control. It was found that with 36% reduction in pattern factor the maximum burner outlet temperature could be reduced by at least 100°F. This relates to an increase in turbine component life in excess of 100% which reduces maintenance cost. Alternatively, the engines could be run hotter, thus providing additional power output.

Performance seeking control (PSC) was studied as not only an engine controller but as an outer loop for combining airframe and engine in the optimization analysis. Although beyond the scope of this report to quantify, PSC is expected to improve any other APC performance benefit as well as optimize the coordination of any combination of implemented APCs.

Resizing the engine to reduce weight as a trade-off to SFC benefits was examined. Weight and cost deltas for each APC are presented whereas quantified measures of maintenance were deemed beyond the scope of this report. For this commercial application the effects of APC implementation were summed as sensitivities to direct operating cost. This is not intended to be a final ranking of the APCs but simply one method of recording the results. It is recommended that a downselect process be performed on the basis of this report and that further, more detailed analysis be conducted by way of computer simulation and if appropriate, eventual engine implementation and testing.

2.0 INTRODUCTION

The application of advanced controls technologies to airbreathing engines offers potential for significant improvement of performance and operability. Detailed studies are planned by NASA as a part of the APC program to provide detailed quantified measures of such improvement for engine control features. Task 3 of the Unique Systems Analysis program, entitled Advanced Control for Airbreathing Engines, successfully completed a preliminary screening of some 27 APCs against three model aircraft. From the results of Task 3, Task 6 (Phase II) continues the study, in greater detail, of the eight most promising APCs against a single model aircraft. The purpose of Task 6, under same title as Task 3, was twofold: provide a starting point for quantifying the benefits of each APC and gain insight into the best methods of further detailed studies.

This program was divided into the following five tasks:

- Task 1: Define Aircraft—The results of Task 3 led to the selection of the Civil Tiltrotor because of it's common interest to NASA and Allison and because of it's excellent potential for future demonstration programs. The mission profile was already well-defined such that operation points could be easily chosen, with technical baseline information readily available. Specific aircraft/engine details can be found in Section 3.1 of this report.
- Task 2: Establish Evaluation Criteria—To obtain an evaluation criteria for ranking the net benefit of each APC, two types of information were considered, namely, aspects which could be easily quantified and those which could not. Specific fuel consumption benefits could be determined fairly easily with quantified numerical approximations. However, isolating the effects of individual hardware maintenance on overall aircraft maintenance costs, for example, is a difficult, costly process beyond the scope of this effort. So, whenever possible, an impact to direct operating cost (DOC) is shown and the other effects are described as best as possible. Details on the evaluation criteria can be found in Section 3.2 of this report.
- Task 3: Engineering Effort—Assistance was obtained from throughout the variety of engineering disciplines to obtain information for each APC. The concepts were reassessed and reshaped, preliminary drawings were generated, and technical information required for evaluation was gathered. Details of this work, the bulk of this report, can be found in Section 3.0 of this report.
- Task 4: Evaluation Analysis—With concepts more clearly developed and the technical information defined, a net benefit for each APC was approximated. Each APC's impact on the evaluation criteria were tallied to show what level of benefit might be expected if pursued by future, larger-funded studies such as engine implementation or simulation analysis. This material is also found in Section 4.0 of this report.
- Task 5: Reporting—The results of the work to be presented orally and in written form.

Allison's effort for Phase II began in late January of 1991 and continued through June of the same year. Boeing has been very helpful in providing required airframer information with regard to the model aircraft and future endeavors could easily take place with further funding. Similar relationships have developed with experts inside and outside of Allison, related to the other topics herein, which provide the foundation of the study at hand and the potential for success in further, more detailed studies.

3.0 ANALYTICAL MODEL

3.1 REFERENCE MODEL AIRCRAFT

The tiltrotor aircraft, with its combination of vertical takeoff/landing (VTOL) operation and turboprop comfort, speed, and cruise efficiency, has attracted the interest of commercial operators. Tiltrotor development has progressed over the past decade from the successful XV-15 flight demonstrator program to the current V-22 full-scale development program. Although these programs are military, studies of civil application have utilized the existing database for development purposes. The technologies which translated from military to civil applications include: all-composite structure; triply redundant, digital, fly-by-wire (FBW) control system; single-fail-operational, dual fail safe flight control system; 5,000 psi hydraulic system; advanced electronic multifunction cockpit display; and integrated digital avionics system. Studies have presented five different passenger-size concepts for the various VTOL intercity transport needs (see Figure 1).

A standard mission profile was conceived as a 600-nmi mission range with full IFR reserves for intercity VTOL operations. This was based on surveys of potential operators early in the studies. The mission profile included taxi, takeoff, climb, cruise, and descent as shown (see Figure 2). IFR reserve fuel was provided for 45 minutes of cruise at the long-range cruise speed and normal cruise altitude. Additional fuel was provided for a 50-nmi alternate, including 0.5 minute hover at each end and climb and descent legs within alternate fuel calculations. Each vehicle's VTO design gross weight (DGW) was determined based on its full passenger load and fuel for the 600-nmi range plus alternate and reserve fuel. The propulsion system was then sized to provide hover out of ground effect with one engine inoperative (OEI) at the VTO GW. The vehicles were designed around the high-density intercity passenger market, cargo operations, offshore oil and gas platforms, corporate and executive transport, and public service such as police, Coast Guard, fire, drug enforcement, and disaster relief.

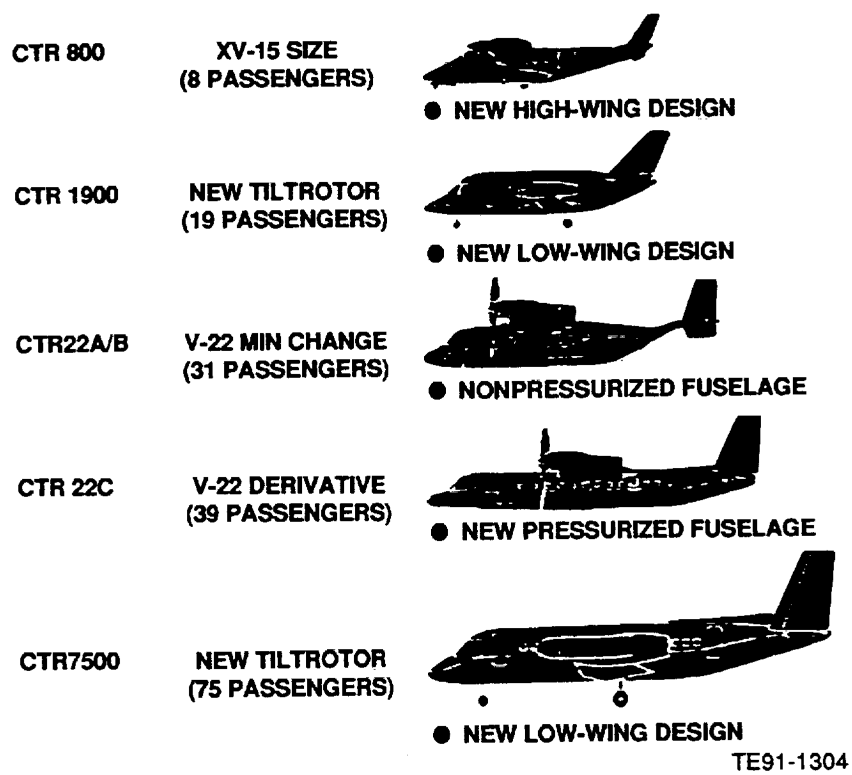


Figure 1. Potential civil tiltrotor designs.

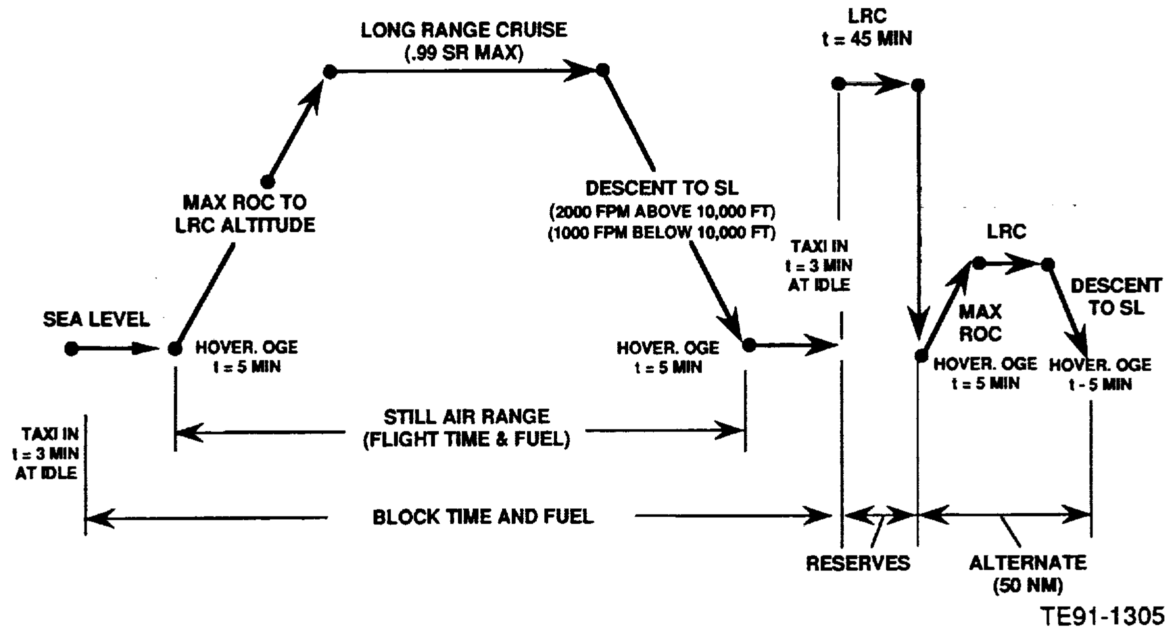


Figure 2. Civil tiltrotor mission profile.

The CTR-22C is a 39-passenger derivative of the V-22. It uses the V-22 wing and propulsion system with a new, pressurized fuselage. The original V-22 fuselage converted to a civil version was volume-limited to only 31 passengers (see Figure 3). This was below the capacity of the wing and rotor system, which gave birth to the new fuselage for increased seating. This vehicle retains the basic V-22 high-wing configuration, but has the wing set low to the fuselage to minimize contour fairing and associated weight and drag. The wing is also set at a 6-deg incidence to keep a level fuselage attitude during cruise conditions, 300 knots at 18,000 ft altitude. This reduces cruise drag and also provides a more comfortable body attitude for low-speed climb and landing approach.

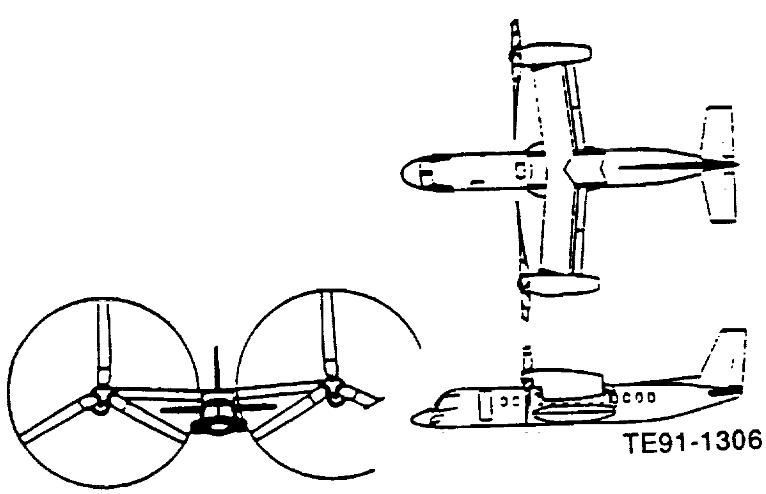


Figure 3. CTR-22C.

The V-22 Allison T406-AD-400 (Allison Gas Turbine Division of General Motors) engine was used as the basis for power available and specific fuel consumption of the CTR-22C aircraft. The engine torque limit is relaxed, being consistent with the assumption of a new, civil 30-second OEI power rating. The drive system ratings are the same as the V-22, however, it is considered that some redesign of the main transmission input spur gears and housing may be required. Fuel system design was based on a wet-wing approach yielding capacity of 1423 gallons. The digital FBW flight control system, hydraulics and actuators were left identical to those in the V-22, including the nacelle tilt actuators.

3.2 EVALUATION CRITERIA

To determine the net benefit, if any, of each APC, a method of evaluation was developed. This method needed to be: consistent with current practices associated with the application; relevant to the concepts being studied; and intelligible as a first-pass of quantifying net benefits. An approach was needed which would show all major impacts on the baseline model in a way that would allow for direct comparisons.

For a commercial application the key issues are profit and federal regulations. Profit can be shown to be impacted by the direct operating cost (DOC), a familiar term in the commercial arena. Federal regulations play an important role in areas of emissions, safety and noise. The future environmental concerns will continue to increase and commercial manufacturers will be forced to find new technologies to meet stricter requirements. Hence, the development of all evaluation criteria for APCs evolved from these two very important elements. Boeing Helicopters' personnel were very instrumental in the development of the evaluation criteria including weighing specific values of DOC sensitivity.

After discussions with Allison and Boeing personnel, it was determined that the most obvious items of concern related to DOC were the following:

- SFC—Engine model runs were completed to determine the delta Specific Fuel Consumption impact on the DOC.
- EW—An Engine Weight delta was approximated for the added hardware of concept implementation.
- EAC—The impact of the technology on Engine Acquisition Cost was approximated based on development and hardware costs.

Impact on the baseline due to emissions were calculated where pertinent. Safety issues were considered via the scope of OEI/hard accel cases. Noise considerations were eventually eliminated as an evaluation criteria because of the difficulty in assessing the impact on the evaluated systems. Early in the investigation it was found that an engine maintenance cost (EMC) impact study would easily consume the entire present funding in itself, hence, qualifying statements concerning the subject are made accordingly. DOC sensitivities and listing of the other studied criteria are found in Table I.

3.3 MISSION PROFILE STUDY POINTS

To obtain worthwhile information while maintaining simplicity, it was deemed necessary to view the mission from two select operation points key to the overall mission profile. The two points chosen were a takeoff point and a maximum (typical) cruise point. All APCs were to be evaluated at both points assuming that the full range of benefit versus penalty would be approximated. Table II shows the mission points and the pertinent parameters.

Table I.
Evaluation criteria.

1. Direct operating cost sensitivities*

ΔDOC/Δ Specific fuel consumption	= 2.75%/10.0%	baseline SFC = 0.423
ΔDOC/ΔEngine weight	= 0.04%/10.0%	baseline engine weight = 1,991 lb baseline gross A/C weight = 46,240 lb
ΔDOC/Δ Engine acquisition cost	= 2.50%/10.0%	baseline cost = 3.4M/engine (25% of A/C cost of 13,455M)
ΔDOC/ΔEngine maintenance cost	= 2.20%/10.0%	did not use
ΔDOC/ΔEngine dimensions	= no effect	

2. Emissions

3. Safety (OEI-conditions)

*For individual DOC sensitivities, see Figure 23.

Table II.
Mission profile study points.

	Cruise	Takeoff
Shaft horsepower/engine	3520	6150
Temperature day	ISA	59°F
Altitude	20,000 ft	Sea level
Mach number	303 knots	--

4.0 CONTROLLABLE ADVANCED PROPULSION CONCEPTS

4.1 COMBUSTOR VARIABLE GEOMETRY CONCEPT FOR AIR-BREATHING ENGINES

Advanced air-breathing engine applications will demand more efficient and higher power engines compared to the present designs. The operational range of future gas turbines is expected to be stretched in both speed and altitude demands as civil/commercial transports cross over from advanced subsonic to supersonic speeds at altitudes above 50,000 ft above sea level. The wide operational envelope, in turn, demands high performance at all operating conditions. Combustion systems with fixed geometry (conventional designs) are therefore designed to operate efficiently in a limited flight envelope, therefore becoming an undesirable design for future applications. As the combustion system operational capabilities are stretched, the thermodynamic performance (at higher and/or lower operating condition) is less than optimum, thereby losing efficiency and increasing the pollutant exhaust emissions.

The thermodynamic performance of the combustion section in a gas turbine engine depends on the proper mixture of fuel and air. Consequently, inefficiencies caused by incomplete combustion and high temperature reactions can form carbon monoxide (CO), nitrogen oxides (NOx), unburned hydrocarbons (UHC), and soot formation (smoke). These gas emissions are becoming an increasing concern in polluting the environment, therefore encouraging technology to produce gas turbines with more restrictive emission requirements.

Therefore, an important design criteria in the development of advanced gas turbine designs consists of operating the combustion chamber at or near stoichiometry at all performance conditions to minimize these inefficiencies. Unfortunately in fixed geometry combustors, at low operating conditions, operating at low fuel/air ratios, CO and UHC production is high and NOx production is low, and the reverse occurs at high operating conditions where the operating conditions have fuel/air ratios closer to the stoichiometric value. Therefore, a good combustor design achieves a good compromise to minimize all emissions throughout the operating range.

A variable geometry combustion liner can be used to change the overall air distribution to the combustor, thereby varying the primary zone and dilution zone fuel/air ratios. With this variable geometry concept (see Figure 4), the combustor airflow admitted to the front end is increased to enhance the mixture of air and fuel at the higher operating conditions to reduce smoke and lower the overall flame temperature to reduce NOx. Similarly, the variable geometry can be adjusted to permit less air in the primary zone (front end) of the combustor at lower operating conditions to allow increased stability and reduce the production of CO and UHC by burning the fuel at a richer fuel/air mixture.

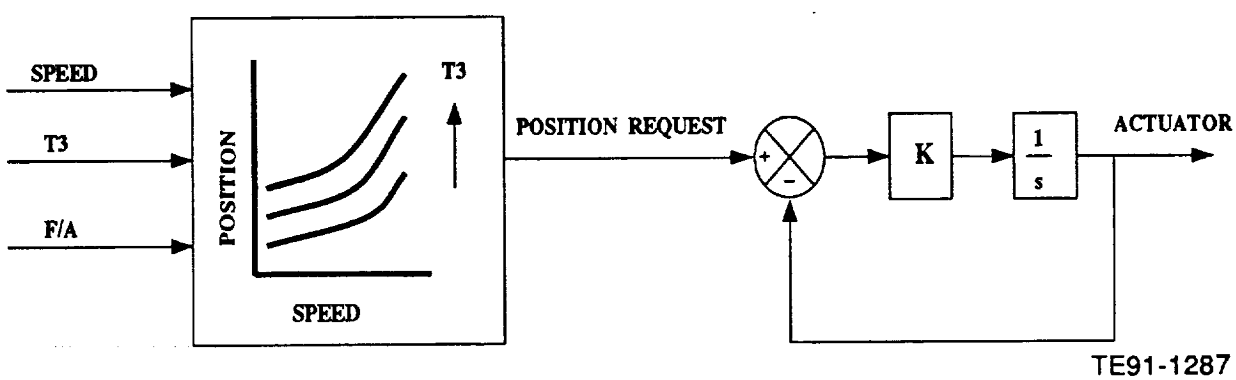


Figure 4. Combustor variable geometry block diagram.

The fuel/air ratio at the primary zone is considered to be crucial in the production and consumption of the gas emissions. The fuel/air ratio (f/a) is significantly changed by selectively controlling the amount of air entering through the primary zone jet orifices. The critical design conditions are idle and maximum power conditions since CO and UHC tend to be high at idle while NOx is higher at maximum power due to the high temperature combustion interior environment. The emissions of the baseline reference combustion system (T406) is acceptable at or near the maximum operating condition (takeoff); however, idle emissions could be significantly improved, especially for commercial/civil applications where Environmental Protection Agency (EPA) operation cycles are applied.

In the T406 combustion system, the idle operating primary zone equivalence ratio (defined as the f/a for the primary zone divided by the stoichiometric f/a) is 0.444. The equivalence ratio at stoichiometry is 1.00. The CO and UHC emissions from a T406 engine operating at idle are significantly high, considering that the typical EPA landing-takeoff cycle demands an idle operation time of 26 minutes. The currently proposed variable geometry combustor design applied to the T406 annular combustor can increase the primary zone equivalence ratio to 0.576 if the primary zone jets are totally blocked. This would effectively decrease the idle CO emission by 53% and reduce the UHC emission by 69% over those produced by the baseline T406 current design. The predicted NOx emission indicated a 1% increase compared with the T406 value at idle. In addition, no significant change was produced in the smoke signature compared to that of the T406 baseline. These values were obtained by using Allison-derived empirical correlations based on extensive test data on the T406 engine. These empirical correlations are complex equations which depend on combustor volume, fraction of air to the primary zone, temperature in the primary zone, inlet pressure, liner wall pressure drop, fuel spray droplet size, fuel droplet evaporation rate, stoichiometric temperature, fuel, and air properties.

The variable geometry would therefore change the current T406 design by blocking the primary zone jets totally or partially to lower the emissions at the idle conditions. Similarly, the variable geometry would revert back to the original T406 configuration to obtain the good emission signature of the current T406 at or near maximum power.

The variable geometry control in the combustor is performed by varying the orifice area of the primary and dilution zone holes located in the side wall of the combustion liner. The dilution zone holes are simultaneously changed along with the primary zone holes to maintain equal pressure drop through the combustion liner since this significantly affects the pattern factor. The variable geometry hardware design is shown in Figure 5. The hole size is effectively changed by sliding tabs over the hole, thereby increasing or decreasing the blockage area. The controls for the primary and dilution zone holes are linked to a master control which allows the primary holes to reduce while the dilution zone holes are increased and vice versa. The mechanical drive is provided by a digital stepping motor with a position control. The correct position of the variable geometry at different operating conditions will be determined by establishing a flame temperature curve in the primary zone of the combustion system. The flame temperature in the engine control feedback unit is determined using the measured compressor discharge temperature (T3), combustor fuel/air ratio (f/a), and gas generator rotor speed (Ng) as inputs to the ideal temperature rise relations for a specific fuel. The combustor airflow rate needed for the F/A will be calculated using the measured Ng using empirically determined compressor performance relations. Therefore, the relation between the variable geometry (VG) position and Ng, F/A, and T3 will be processed by the computer logic which will actuate the stepping motor via a digital indexer driver. The driver, in turn, sends the proper signal to the stepping motor using a position sensor as feedback to indicate the location of the VG mechanism. Additional work is required to detail the concept of the mechanical control to actuate the blocker rings blocking the primary and dilution zone holes.

The weight of the variable geometry actuation mechanism is estimated to increase the baseline combustion liner weight by 8%, and an overall baseline engine weight increase of 1.40%, with all hardware included. The cost of the variable geometry design has been estimated to increase the overall engine acquisition cost by 1.90%. The proposed components listing is given in Table III.

In summary, the variable geometry combustor design can significantly decrease the emission CO and UHC signatures of the baseline T406 combustion system with little change in the NOx emissions. This is potentially advantageous for civil/commercial aircraft applications which, due to the increase in airport traffic, require long term operation at idle.

Table III.
Combustor variable geometry components list.

	Unit Volume –in.^{3}	Unit Density –lb/in.^{3}	Unit weight –lb	Quantity	Total weight –lb
Actuator	4.40	0.28	1.23	2	2.46
Actuator hardware			1.50	2	3.00
Actuator plumbing			2.00	2	4.00
Torque rod			0.25	2	0.50
Link	0.10	0.28	0.03	2	0.06
Rocker arm	0.05	0.28	0.01	6	0.08
Outer forward ring	1.19	0.28	0.33	1	0.33
Outer aft ring	1.48	0.28	0.41	1	0.41
Inner forward ring	0.62	0.28	0.17	1	0.17
Inner aft ring	0.25	0.28	0.07	1	0.07
Outer forward retainer	0.48	0.28	0.13	4	0.54
Outer aft retainer	0.48	0.28	0.13	4	0.54
Inner forward retainer	0.48	0.28	0.13	4	0.54
Inner aft retainer	0.48	0.28	0.13	4	0.54
Fasteners			0.15	4	0.60
Total					13.85

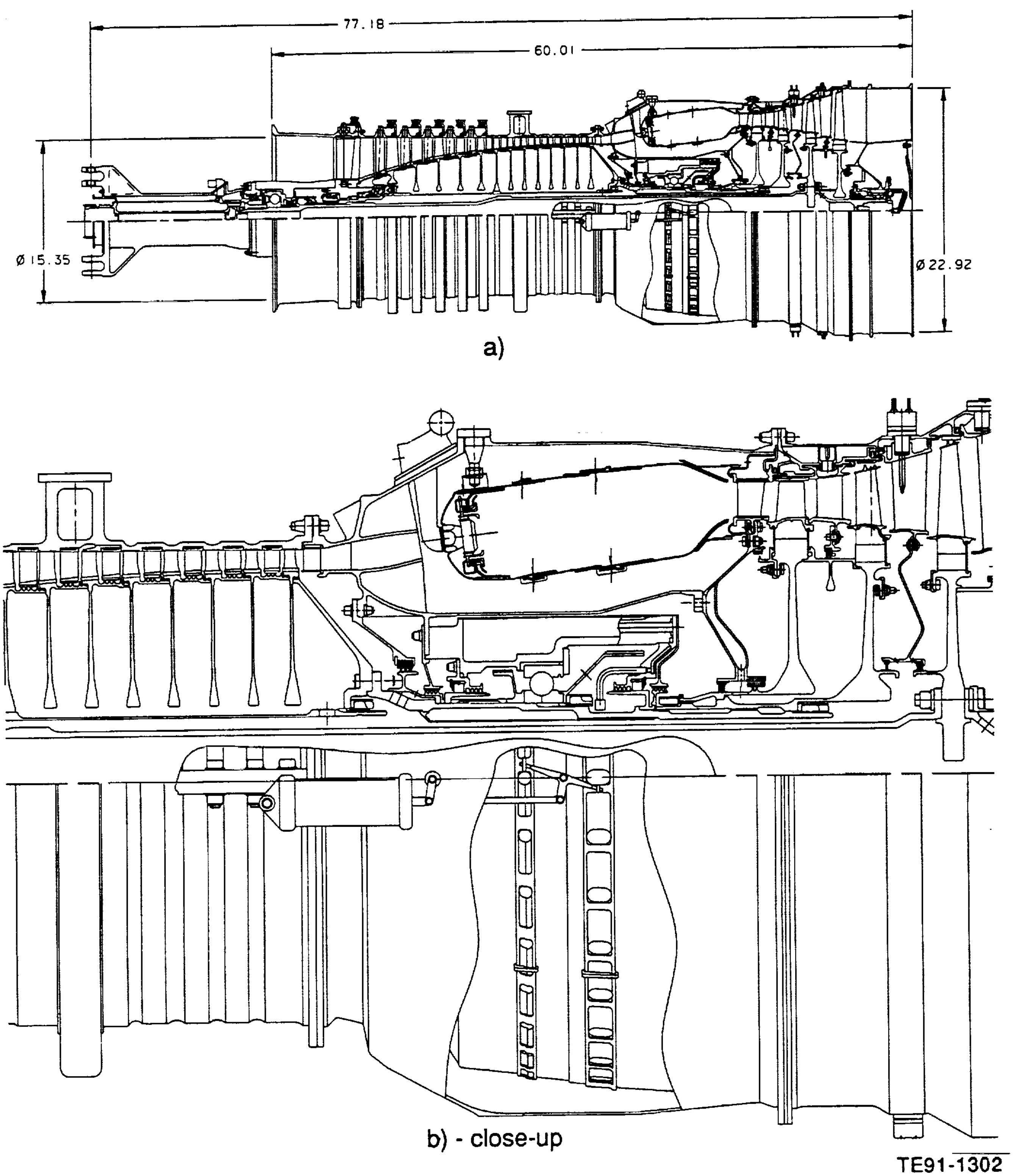


Figure 5. Combustor variable geometry.

4.2 COMPRESSOR VARIABLE GEOMETRY

Compressor variable geometry was examined for expected benefits of power increase during max accels/OEI and for benefits of SFC when utilizing reduced surge margin concepts. Figure 6 shows a simplified block diagram depicting the concept. This figure also depicts the need for modulating cooling air to control blade tip clearance. The concepts of surge margin control and OEI depicted here with CVG and wiggling vanes requires extensive work in the area of sensing. The benefits are shown from an open-loop, "avoidance" approach.

4.2.1 One-Engine-Inoperative

Additional compressor airflow capacity at high corrected speeds, with minimal loss in efficiency and surge margin, can be obtained in existing compressors with variable geometry by opening inlet stator vanes somewhat beyond optimum. The additional flow capacity may be useful in providing extra power capability at very high compressor corrected speeds and airflow such as OEI or maximum climb conditions.

OEI is an emergency engine rating which may be used to keep an aircraft airworthy after a failure of one engine in a multi-engine aircraft. Maximum climb power requirements generally allow for maneuver capability at high altitude (cold outside ambient temperatures) and high compressor corrected speeds. A study using the T406 engine for the V-22 tiltrotor aircraft yielded 0.5% shp potentially available at

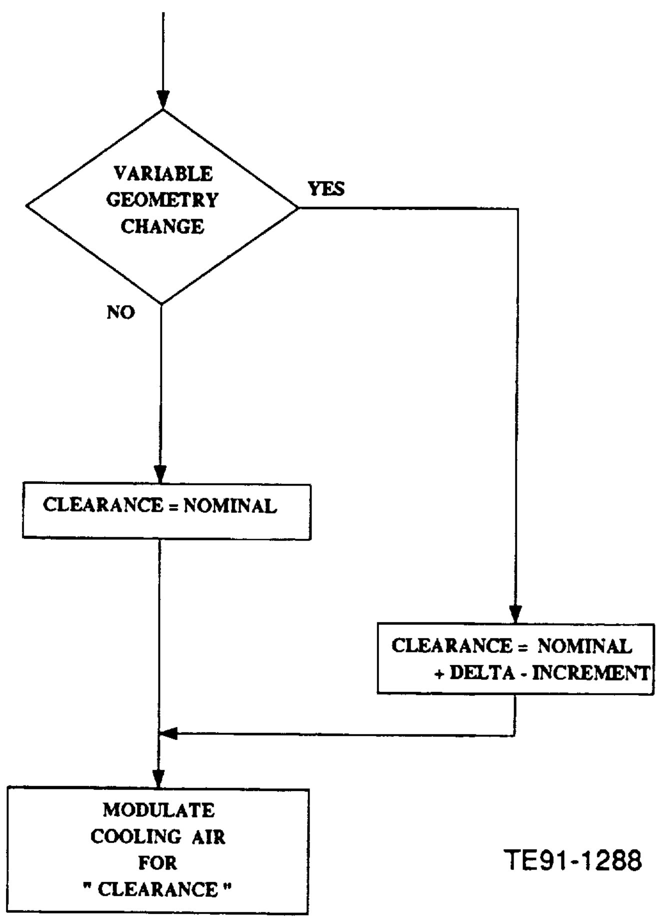


Figure 6. Compressor variable geometry block diagram.

OEI and 1.6% at the maximum climb rating condition. As noted, this benefit is only available at high compressor corrected speed.

These potential improvements in OEI/max climb do not lend themselves to any SFC benefit but do, however, address serious safety and power requirements.

4.2.2 Reduced Surge Margin

Compressor variable geometry can also show performance benefits by reducing design surge margin. Compressors are normally designed with at least 15% surge margin. This surge margin covers a number of effects which work to either move the surge line closer to the operating line (Reynolds number, distortion, compressor-compressor variations, variable vane schedule inaccuracies) or the operating line closer to the surge line (engine deterioration, acceleration requirements). Normally these effects are combined in a worse-case scenario to define a minimum surge margin requirement and a cushion as a safety factor is left over. A performance benefit can be achieved if we assume that we can develop a combination of stall inhibitor (wiggly vanes, acoustic feedback) and detection/recovery (fast sensors with a fast-feedback loop to fuel flow and or compressor vane schedules or bleeds) systems which would allow design of a compressor operating point closer to its surge line.

A study using the T406 engine for the V-22 tiltrotor aircraft yields the following potential performance improvement assuming a 5% reduction in required surge margin, i.e., elimination of the cushion normally allowed for in doing a surge margin audit (see Figure 7). By reducing the surge margin 5% it is seen that the corresponding pressure delta yields a 0.7% decrease in SFC. If a compressor can be "taught" to live with 5% surge margin, or if the effective surge line can be moved, two or three times this effect can be achieved.

With the increased ability to manipulate the pressure characteristics within the compressor, additional analysis was performed to determine the benefit potential of redesign. It was estimated that if a 10% surge margin allowance could be won using compressor variable geometry, one complete stage of the compressor could be eliminated. This would yield a weight delta of 0.81%. Redesign, however, would require further detailed analysis. This does, however, demonstrate the SFC/weight trade-off.

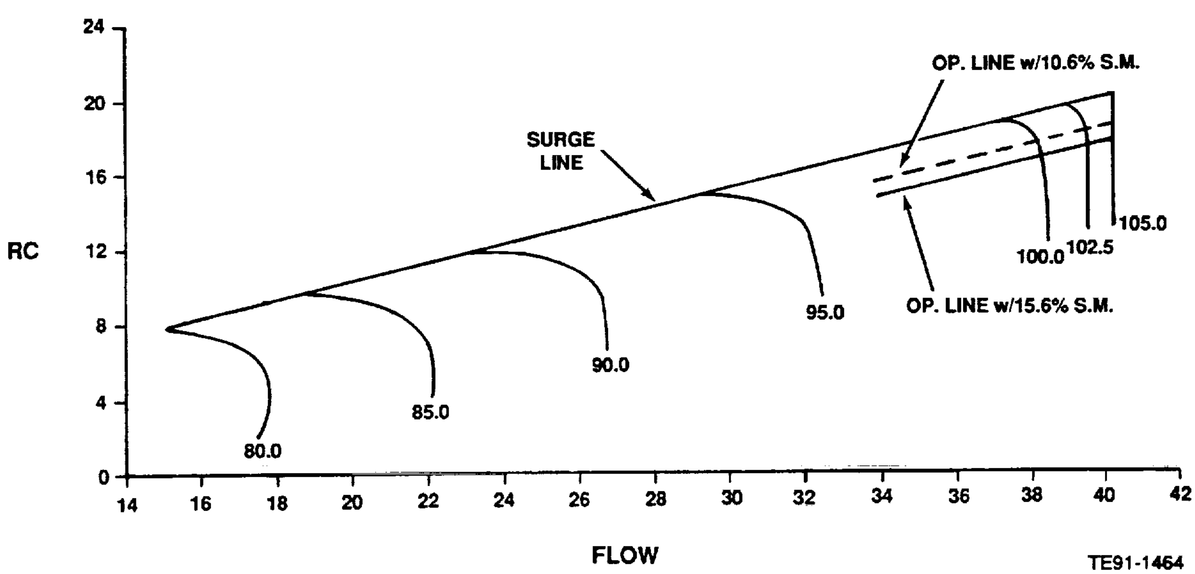


Figure 7. CVG benefits for reduced surge margin.

Currently, the T406 uses compressor variable geometry. Table IV shows the list of hardware used for the system with corresponding weights.

4.3 WIGGLING VANES AND SURGE CONTROL

Axial compressors are subject to two distinct aerodynamic instabilities, rotating stall and surge, which can severely limit compressor performance. Rotating stall is characterized by a wave travelling about the circumference of the machine, surge by a basically one-dimensional fluctuation in mass flow through the machine. Whether these phenomena are viewed as distinct (rotating stall is local to the blade rows and dependent only on the compressor, while surge involves the entire pumping system) or as related (both are natural modes of the compression system with surge corresponding to the zero order), they generally cannot be tolerated during compressor operation. Both rotating stall and surge reduce the pressure rise in the machine, cause rapid heating of the blades, and can induce severe mechanical distress.

The traditional approach to the problem of compressor flow field instabilities has been to incorporate various features in the aerodynamic design of the compressor to increase the stable operating range. Balanced stage loading and casing treatment are examples of design features that fall into this category. More recently, techniques have been developed that are based on moving the operating point close to the surge line when surge does not threaten, and then quickly increasing the margin when required, either in open or closed loop manner. The open loop techniques are based on observation, supported by many years of experience, that compressor stability is strongly influenced by inlet distortions and by pressure transients, such as is caused by aircraft angle of attack and yaw angle. Thus, significant gains have been realized by coupling the aircraft flight control and engine fuel control so that the engine operating point is continually adjusted to yield the minimum stall margin required at each instantaneous flight condition (see subsection 4.7).

Studies conducted at MIT regarding the onset of surge have revealed a small perturbation that apparently grows and ultimately results in the large scale surge that is damaging. The concept and subsequent

Table IV.
CVG components list.

	Weight--lb
Actuator (approximate wet weight)	4.1000
Actuator mounting hardware (approximate)	0.5000
Actuator ring and button assembly--IGV	2.0930
Arm and ball assembly--IGV	0.5040
Actuator ring and button assembly--stage 1	1.8320
Arm and ball assembly--stage 1	1.0400
Actuator ring and button assembly--stage 2	1.8300
Arm and ball assembly--stage 2	1.0800
Actuator ring and button assembly--stage 3	1.8080
Arm and ball assembly--stage 3	1.0800
Actuator ring and button assembly--stage 4	1.8080
Arm and ball assembly--stage 4	1.0800
Actuator ring and button assembly--stage 5	1.8080
Arm and ball assembly--stage 5	1.0800
Miscellaneous associated hardware	1.9040
Total weight	23.587

experiments performed at MIT work on the basis that active stabilization can be brought about by the passage of a convected field of vortices shed from upstream oscillating vanes. The vortices weakly disturb the downstream flow and prevent the development of a stall. This can be used to move the operating line up and provide improved gas turbine performance. The concept is depicted in simple block diagram form in Figure 8.

If, as the theory implies, rotating stall can be viewed as the mature form of the rotating disturbance, damping of the waves would prevent rotating stall from developing, thus moving the point of instability onset as shown in Figure 9. It was proposed that the compressor stability could be augmented by

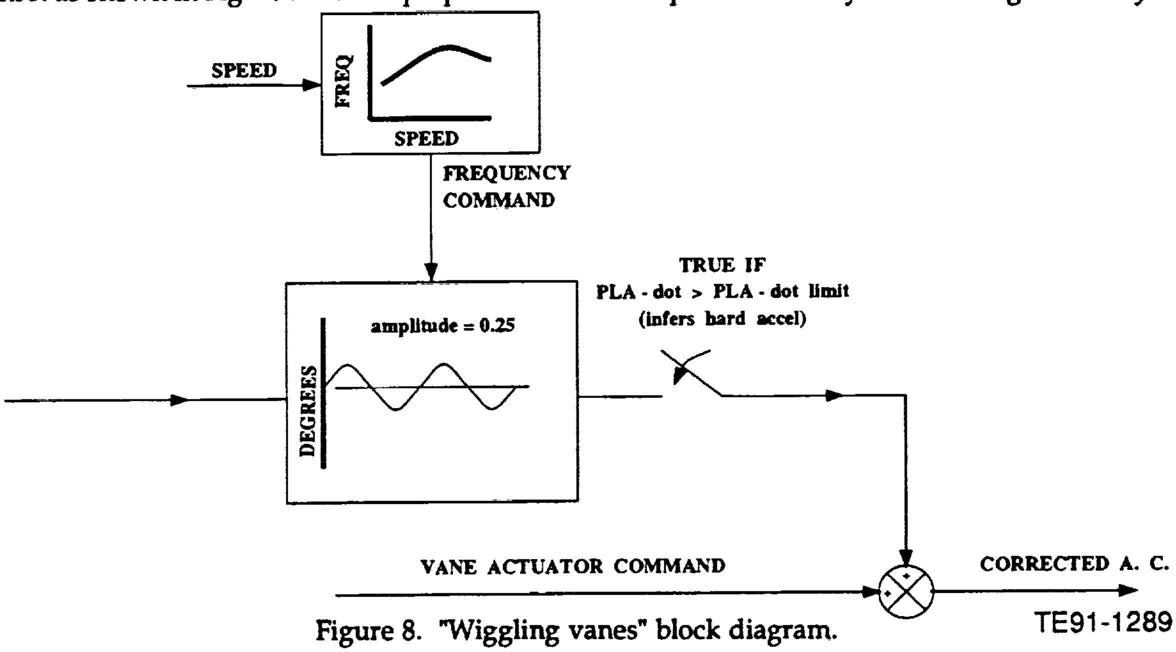


Figure 8. "Wiggling vanes" block diagram.

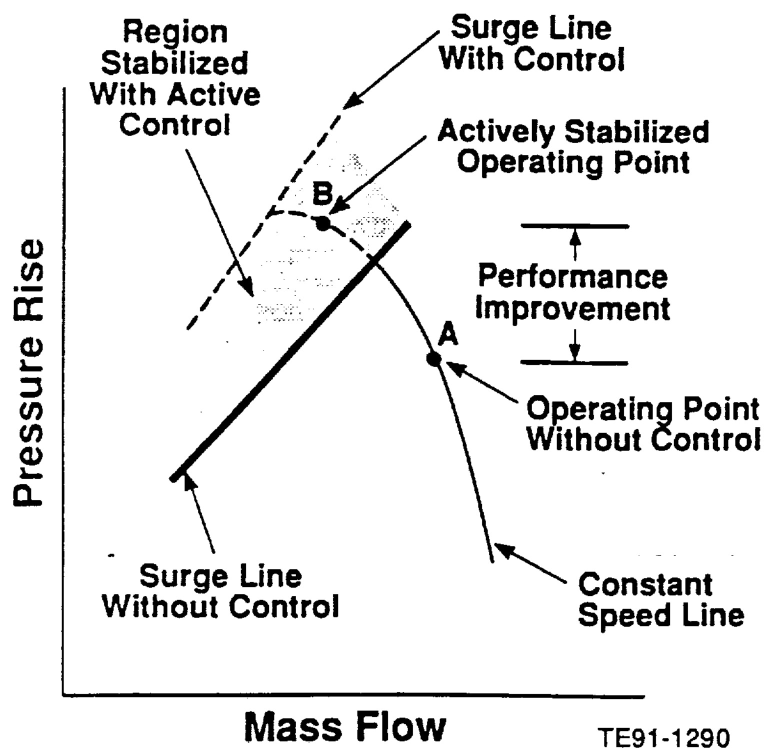


Figure 9. "Wiggling vanes" performance benefits.

creating a travelling disturbance with phase and amplitude based on real time measurement of the incipient instability waves. The basic concept is to measure the wave pattern in a compressor and generate a circumferentially propagating disturbance based on those measurements so as to damp the growth of the naturally occurring waves. Implementation of individual vanes in an upstream blade row are "wiggled" to create the travelling wave velocity disturbance (see Figure 10).

The current studies and experiments done by MIT have shown what type of benefit can be achieved with this concept. From this information approximations have been made for the T406 of the reference aircraft V-22. The T406 currently incorporates compressor variable geometry as shown in Figure 10. The addition of actuation hardware could be implemented at one stage of vanes to provide a ± 10 deg amplitude at 200-300 hertz frequency. This would result in SFC benefit, same as found in section 4.2. The hardware would result in a cost delta of +0.58% and a weight delta of +0.6%, based on a two actuator system (see Figure 11).

This concept requires a considerable amount of further research but shows a lot of promise. Studies on the current T406 compressor would be required to gather information for appropriate modeling. Also, the existing compressor variable geometry hardware would need to be assessed for implementation difficulties or modifications. The limitations of the overall system would have to be analyzed to determine what level of benefit could actually be obtained. The values herein are of a rough order of magnitude and rely solely on the studies done with MIT and the expected cost/weight analysis of implementation.

4.4 TURBINE VARIABLE GEOMETRY

Variable geometry can be used to enhance the performance of gas turbine engines. Turbine variable geometry can be useful in improving both steady-state and transient performance. In the transient mode, variable geometry can be used in place of an acceleration bleed valve in order to improve acceleration times while maintaining adequate surge margin. For the study at hand, turbine variable geometry was examined for benefits of SFC at cruise and potential horsepower increase at the one-engine-inoperative (OEI) engine sizing point (see Figure 12a-c). The commercial tiltrotor application precludes studying the positive impact of turbine variable geometry on accel time. In general, propeller pitch change mechanisms operate much slower than the engine, i.e., the engine can ramp up or down in power much faster than the propeller can absorb it. Thus, this application is not impacted by faster

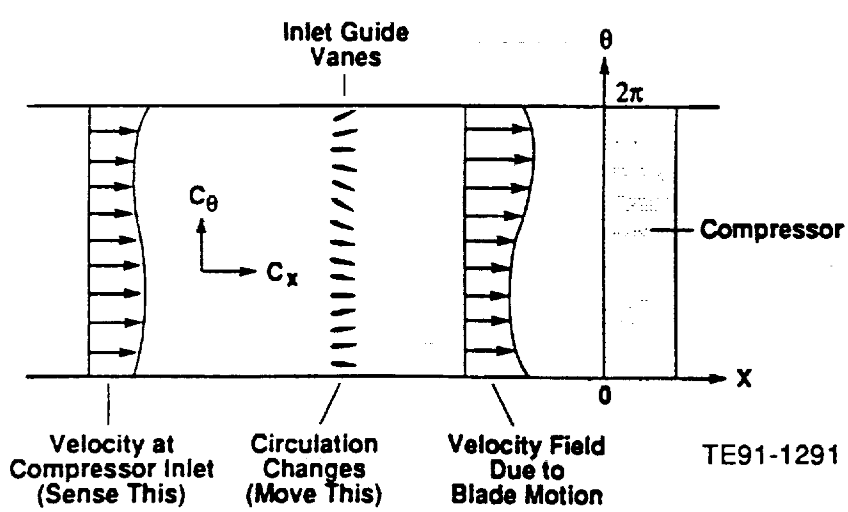


Figure 10. Circumferential wave disturbance.

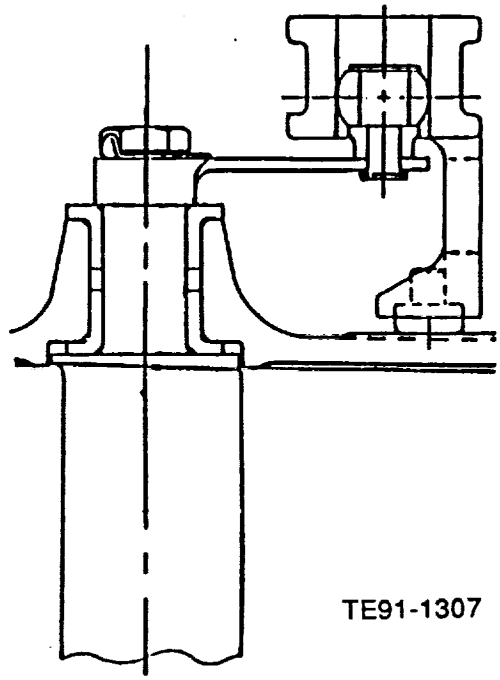


Figure 11. "Wiggling vanes" actuator location.

accel times as a combat helicopter mission would be. Data presented in the Phase I report (ref. 1) for the LH Comanche T800 engine is still applicable.

To determine the SFC benefit potential for cruise a simulation was performed for the T406 engine. In this implementation the assumption was made that the effect of varying the turbine vane angles would solely be a reduction in turbine flow capacity. The results of the simulation are given in plot form in Figures 13 and 14. The study shows the relationship between two pertinent parameters, namely horsepower and SFC. The turbine variable geometry was allowed to adjust flow ±10% in both the gas generator and the power turbine. By reducing gas generator flow by 10% and maintaining nominal flow in the power turbine it was found that an improvement to SFC of 1.3% was achieved. At these conditions a negligible loss in horsepower was experienced.

The other major benefit found in turbine variable geometry was in increased safety. When conditions arise that would require maximum output of the engine, SFC is no longer a concern. All SFC can be sacrificed to secure the safety of the commercial aircraft passengers. Any occasion for hard accel requirements or even the worse case scenario of one-engine-inoperative (OEI) demands the engine to provide horsepower to its full capacity.

For takeoff, using the data as portrayed in Figure 14, an increase in power turbine flow of +5% yields an increase of 275 hp while +10% flow yields near 400 hp. Again, the gas generator turbine flow was held at nominal.

To determine an impact on weight a list of essential hardware was compiled with individual component weights. The data were based on earlier experience Allison had with turbine variable geometry on the GMA 800 engine program. A scale factor was applied which yielded approximate hardware weights. The information is depicted in Table V. The total engine weight delta could then be found to be 3.3%. However, the option of redesign must be examined to explore the full benefit potential.

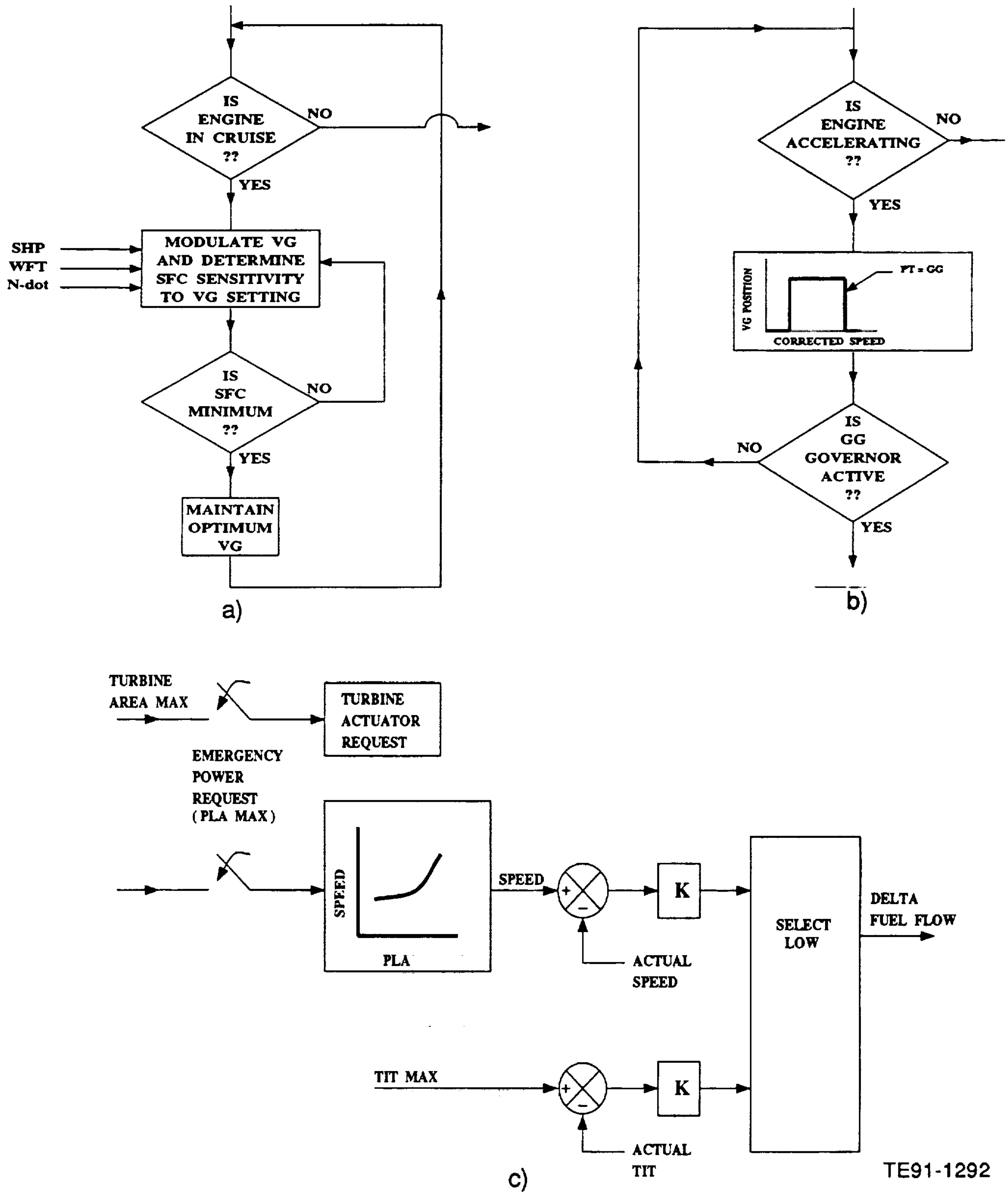


Figure 12. Turbine variable geometry block diagram.

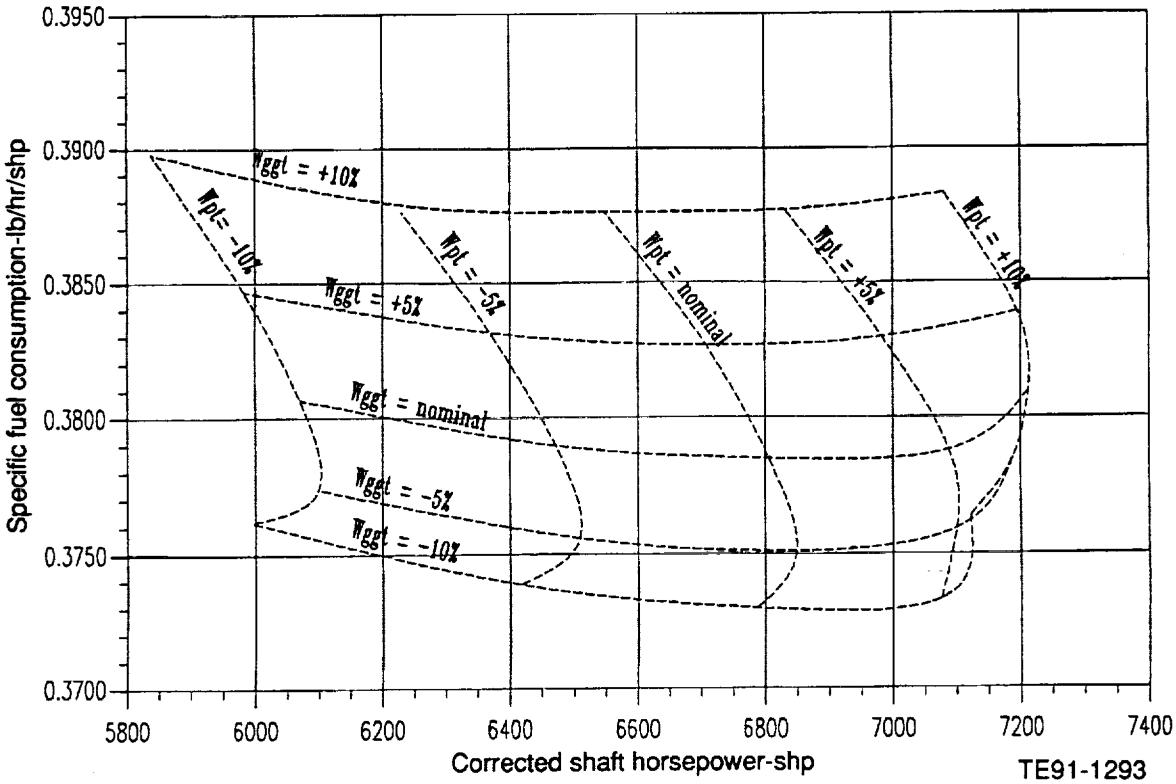


Figure 13. Turbine variable geometry potential at cruise.

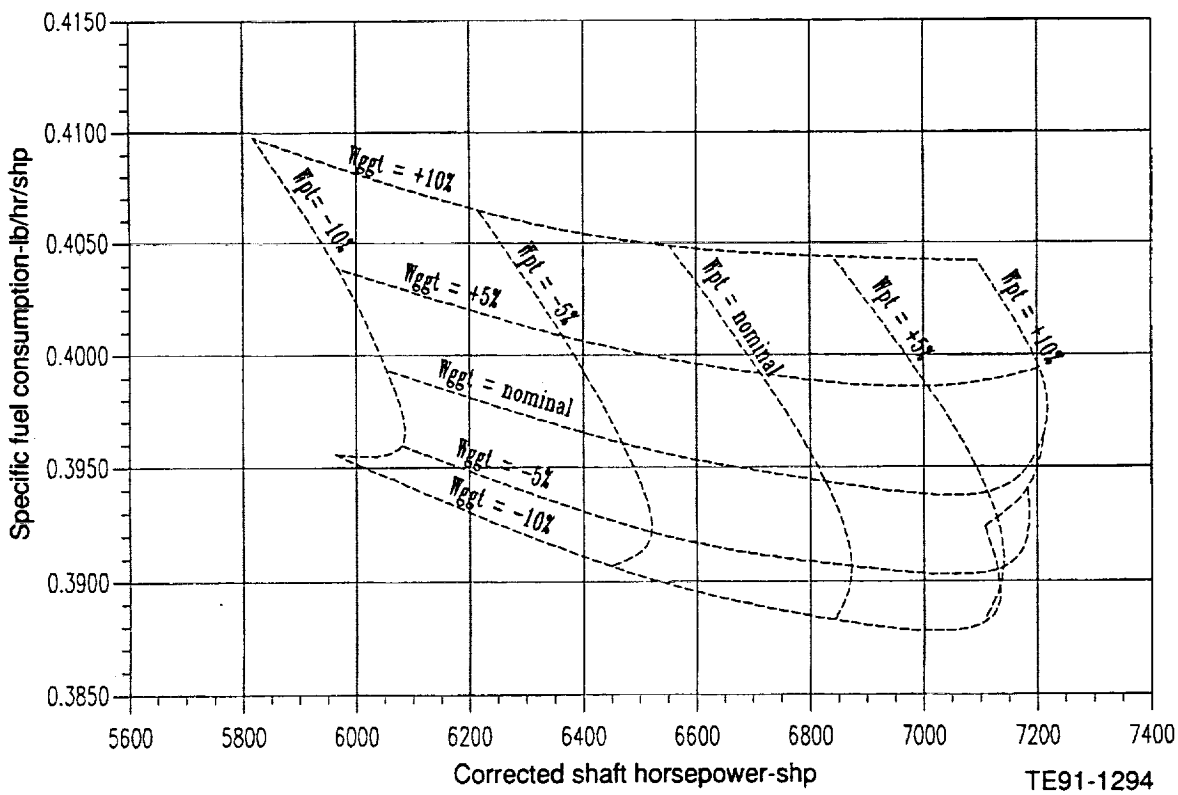


Figure 14. Turbine variable geometry potential at takeoff.

Table V.
Turbine variable geometry components list.

	GMA 800	T406
Vane quantity	30	42
Inner stem diameter	0.625	0.375
Outer stem diameter	0.5	0.25
Actuator ring mean radius	13.2	11.1
Compressor corrected airflow	65	37.7

	GMA 800 weight –lb	Scale factors					T406 weight –lb
		Vane quantity	Inner stem diameter	Outer stem diameter	Actuator ring diameter	Compressor corrected airflow	
Outer button	3.256	1.4	--	0.125	--	--	0.57
Inner button	2.646	1.4	0.216	--	--	--	0.80
Outer piston ring	0.344	1.4	--	0.125	--	--	0.06
Outer spindle	4.389	1.4	00	0.125	--	--	0.77
Inner spindle	3.293	1.4	0.216	--	--	--	1.00
Outer endwall	8.684	1.4	--	0.125	--	--	1.52
Inner endwall	8.322	1.4	0.216	--	--	--	2.52
Outer bearing	2.850	1.4	--	0.125	--	--	0.50
Inner bearing	2.850	1.4	0.216	--	--	--	0.86
Inner snap ring	0.144	1.4	0.216	--	--	--	0.04
Inner bearing nut	1.108	1.4	0.216	--	--	--	0.34
Outer bearing spacer	0.474	1.4	--	0.125	--	--	0.08
Inner bearing shim	0.029	1.4	0.216	--	--	--	0.01
Outer bearing seal ring	2.318	1.4	--	0.125	--	--	0.41
Inner bearing seal ring	0.708	1.4	0.216	--	--	--	0.21
Inner support structure	6.892	1.4	0.216	--	--	--	2.08
Strip seals	0.426	1.4	--	0.125	--	--	0.07
Subtotal	48.733						11.84
Actuation system							
Outer spindle hardware	4.500	1.4	--	0.125	--	--	0.79
Splined sleeve	0.130	1.4	--	0.125	--	--	0.02
Lever arm	7.200	1.4	--	--	--	0.58	5.85
Sync ring and hardware	10.460	--	--	--	0.841	--	8.80
Bearing lock nut	1.450	1.4	--	0.125	--	--	0.25
Insert spacer	2.400	1.4	--	0.125	--	--	0.42
Two actuators	37.440	--	--	--	--	0.58	21.72
Air motor	22.700	--	--	--	--	0.58	13.17
Flex air motor drives	2.000	--	--	--	--	0.58	1.16
Air motor brackets	1.000	--	--	--	--	0.58	0.58
Inlet and exhaust piping	2.000	--	--	--	--	0.58	1.16
Subtotal	91.280						53.91
Total	140.013						65.75

Assuming OEI conditions and size of the engine, a smaller diameter turbine could be designed, with variable geometry, to provide the required horsepower. For example, Figure 14 showed an increase of 400 hp from an increase of +10% in flow. This translates to a 5.8% increase of shaft horsepower. The T406 characteristics are such that a one-to-one (1:1) relationship exists between hp and weight, hence a 5.8% weight benefit is seen. This results in a net weight delta of -2.5%. For any redesign study, considerable further analysis is required.

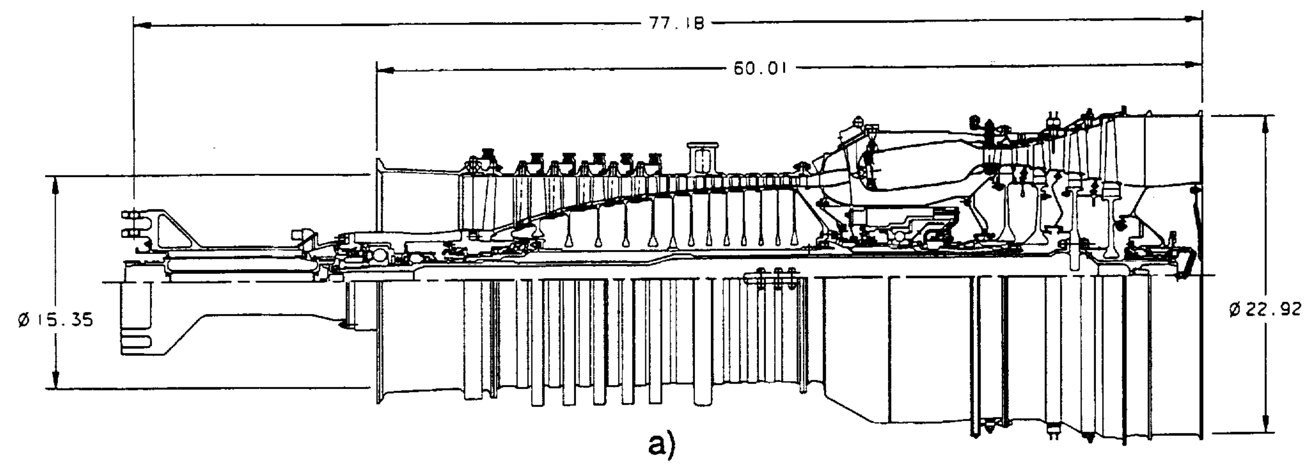
A cost factor was then processed by establishing a nonrecurring development cost and the cost of the hardware. The engine acquisition cost delta was found to be 7.3%. Some impact on maintenance would certainly be seen but the study is beyond the scope of this program. As is the case with most of the APCs further, more detailed studies are required to determine the full range of effects of adding turbine variable geometry. The hardware concept is shown in Figure 15.

4.5 PATTERN FACTOR CONTROL USING AN ACTIVE FUEL CONTROL SYSTEM

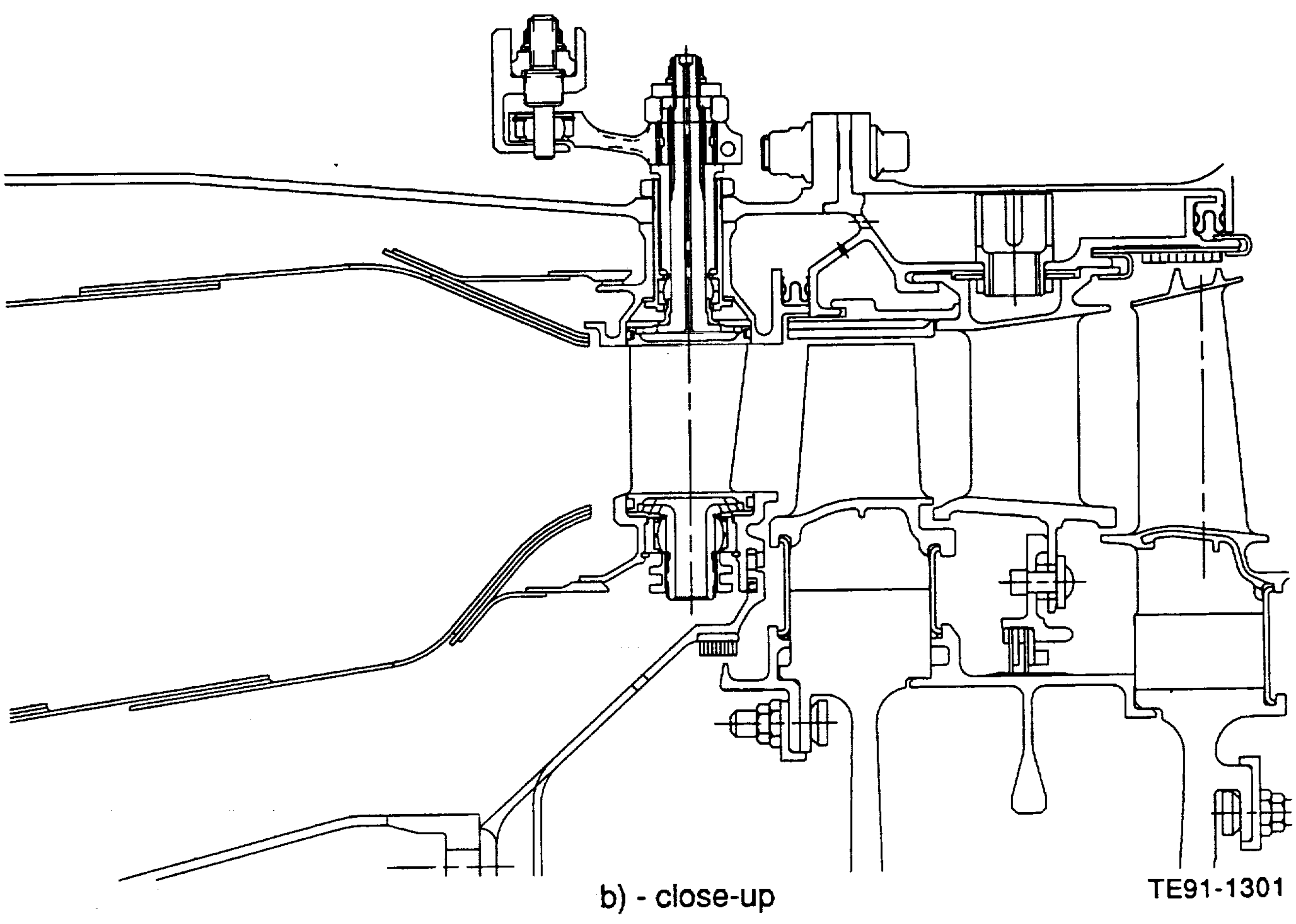
Advanced air-breathing engine applications will demand more efficient and longer lasting gas turbine engines. Higher engine efficiencies are obtained by selectively increasing the engine pressure ratio and increasing the burner outlet temperature. Allison presently has two ongoing programs dealing with the hot section design of an advanced T406 (straight annular) and T800 (reverse flow annular) combustors with operating conditions demanding burner outlet temperatures in the 3000°F range. The burner outlet temperature distribution in engines with BOTs above 3000°F becomes extremely critical in affecting turbine vane and blade component lifetime and therefore affecting overall engine maintainability. Therefore, parameters such as pattern factor and radial temperature profile become an even more critical as criteria in the design of the engine hot section.

Allison recognizes that the burner pattern factor (Tmax - Tav) divided by the temperature rise of the combustor (Tav - T3) is affected by several parameters including combustor primary zone mixing, dilution zone air distribution, and fuel nozzle performance. In annular combustors with several fuel nozzles, the fuel distribution around the combustor is a major contributor to the localized temperature variations which, in turn, produce changes in the pattern factor. The flow variation allowed in the T406 model fuel injectors is $\pm$5% at any operating condition. This variation alone can produce substantial temperature changes within the combustor. A 5% fuel flow rate increase in one nozzle can produce a 55°F increase in Tmax, thereby significantly affecting the turbine blades and vanes located downstream of the malfunctioning fuel injector. Fuel maldistribution is also the result of nozzle flow rate variations that could be caused by internal coking and general fuel nozzle degradation. In addition to the fuel nozzle flow variation, one has to contend with the airflow nonuniformities around the combustor liner due to many reasons, e.g., manufacturer ring variabilities. Given the operational requirements of the T406 engine, there is a need for a "smart" fuel system able to correct itself for fuel injector performance normal spec variation and temporal degradation. Allison is presently considering the use of an "active" fuel control system with a full feedback control.

An "active" fuel control system concept is shown in Figure 16. The fuel flow rate in each of the annular combustor's 16 fuel nozzles is measured and controlled by a "black box" controller, which drives a motorized fuel flow rate valve. The black box, in turn, is controlled by a commanding unit with sophisticated software which senses the output from the temperatures measured near the burner outlet plane. Much work is needed to determine the sensing technology required to implement this concept. Therefore, the fuel control system is designed to be a closed loop feedback system where the sensed aberrant temperature readings are fed to the control unit which then selects the proper combustor fuel manifold distribution necessary to eliminate that aberration. Therefore, there is a high certainty that a decrease or increase in temperature at the burner outlet plane at a certain location around the combustor correlates with the fuel nozzle at that same circumferential location. Small phase shifts, however, are expected due to the flow nature in typical annular combustors combined with the fact that some residual swirl is left in the flow after exiting the compressor exit guide vanes.



a)



b) - close-up

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Figure 15. Turbine variable geometry hardware.

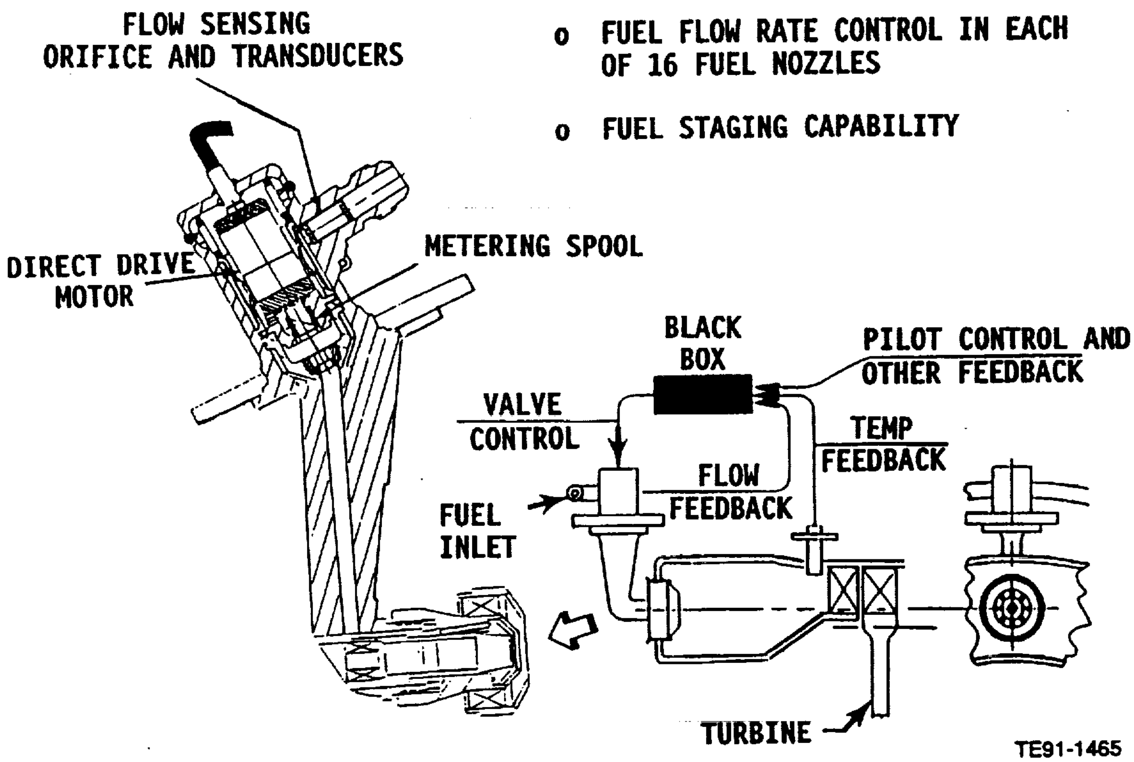

Figure 16. High stability combustor actively controlled fuel injector.

The fuel flow rate control box for each nozzle essentially contains a digital stepping motor with position feedback and a fuel flow rate valve. The digital stepping motor has both the required torque and accuracy which are essential to make the appropriate vernier fuel flow rate variations on the order of $\pm 1\%$. The position feedback in the stepping motor allows the commanding unit to sense the flow rate to provide a double feedback control loop along with the sensed burner outlet temperatures. The stepping motor will be chosen to operate in high temperature environments and will be capable of being totally submersed in the fuel for additional cooling purposes since the flow control "black box" will be located as close as possible to the fuel nozzle. Extra precautions will also be taken to select a stepping motor with the appropriate safeguards against fire hazards.

The master control unit incorporates indexing drivers (for all 16 stepping motors) and the logic hardware which supports the necessary software capable of processing the inputs from the temperature sensing devices and commanding the outputs to each individual nozzle flow rate control box. The concept demonstration will first be accomplished in a full scale annular combustion rig capable of simulating the appropriate inlet conditions of pressure, temperature, air, and fuel flow rates necessary to make the combustion system work as if it were installed in an engine. The combustor inlet and outlet conditions and combustion system performance parameters can be more accurately controlled and studied in a combustion rig compared to an engine test where extensive instrumentation is limited due to the space constraints. The temperature sensing devices in a combustor rig test can be provided by a rotating rake with radially located thermocouple probes across the annulus. The rotating probe should be capable of obtaining a full 360 deg temperature survey. Five temperature probes are mounted on the rotating thermocouple rakes at different radial locations to measure the temperature variations in the radial direction across the combustor outlet plane. For an engine demonstrator, however, special stationary (high temperature) long endurance thermocouples will be located in the burner outlet plane downstream of each of the 16 fuel injectors instead of a rotating temperature rake. Optical fiber optic temperature sensing devices will be installed in engine designs where the burner outlet temperature exceeds 2500°F since the conventional thermocouple component life is severely limited in high temperature environments.

The estimated pattern factor reduction using the active fuel control system can be more than 36% from 0.22 to 0.14. This change in pattern factor implies that the maximum temperature value at the burner outlet plane could be reduced by at least 100°F. This decrease in Tmax can potentially lead to a turbine component life increase of over 100% compared to the T406 turbine.

Therefore, the maintenance cycle can be significantly improved with the use of an "active" fuel control system. An accurate assessment of the benefits of the "active" fuel control system is presently difficult due to the lack of test data available. Allison is presently working on a test demonstration using a semiactive fuel control system where the test operator will provide the closed-loop feedback between the sensed temperatures at the burner outlet plane and the actual fuel control in each of the 16 nozzles in a T406 type combustor. This demonstration test, however, is only an initial step since further investigation is required to maximize the weight/performance trade-off. The present system is estimated to increase the weight of the engine by 2%, but due to material optimization, this estimate can be reduced to about 1% or less.

The present acquisition cost of the active fuel control system which includes a digital stepping motor, fuel valve, indexer driver for the stepping motor, power supply, temperature sensing device, software providing the active control between temperature and fuel flow rate, and associated electronic linkages between the center command has been estimated to be about $3000 for each fuel injector of which there are 16 in a T406 combustion liner. This cost amounts to 2.8% of the total engine acquisition cost. The production cost can be estimated to be significantly lower due to the quantity required per engine and the amount of engines manufactured.

In summary, this innovative fuel control system is able to correct the fuel delivery distribution, thereby decreasing the burner outlet pattern factor and decreasing the overall maximum temperature which significantly impacts the turbine component lifetime. The active fuel control system is also an effective design able to compensate for spec and temporal fuel injector flow rate changes thereby increasing the overhaul mean time between repair (MTBR) maintenance record of the present T406 baseline design.

4.6 ACTIVE CONTROL OF CHARGEABLE COOLING AIR

Cooling air requirements have a direct impact on engine performance. Typically, these levels are set by maximum temperature takeoff conditions and results in overcooling at other off-design conditions. This over-cooling is a significant performance loss. Having the capability of modulating this air to reduced levels at off-design conditions represents a potential performance payoff. Previously, the potential payoff for a modern tilt-rotor aircraft was estimated, but did not examine the details of the system. This work effort takes a next-step look at how this can be accomplished conceptually, and re-examines the benefits.

A T406-AD-400 engine with 6.7% chargeable cooling air was used as the baseline. Two cooling air feed circuits on the high pressure turbine were chosen for investigation because of the high potential payoff. A 20K, 0.5 Mn altitude cruise condition at 1870°F rotor inlet temperature was selected for evaluation. Figure 17 shows the details of these controllable circuits. The second stage vane, the first circuit analyzed, which was previously fed from the cavity between the inner and outer case, is now fed from a valve which extracts air from the outer combustor cavity. At the cruise condition, the gas path temperatures are lower than the allowable metal temperatures resulting in the ability to completely shut this air supply off. This results in a 0.7% savings in chargeable cooling air at this flight condition.

The second circuit examined is a much more complex system to evaluate. Cooling air exiting the preswirler supplies air to the first-stage blade and first- and second-stage wheel cavities. Heat transfer analysis of the rotor system at the altitude operating condition indicates that the blade requires no

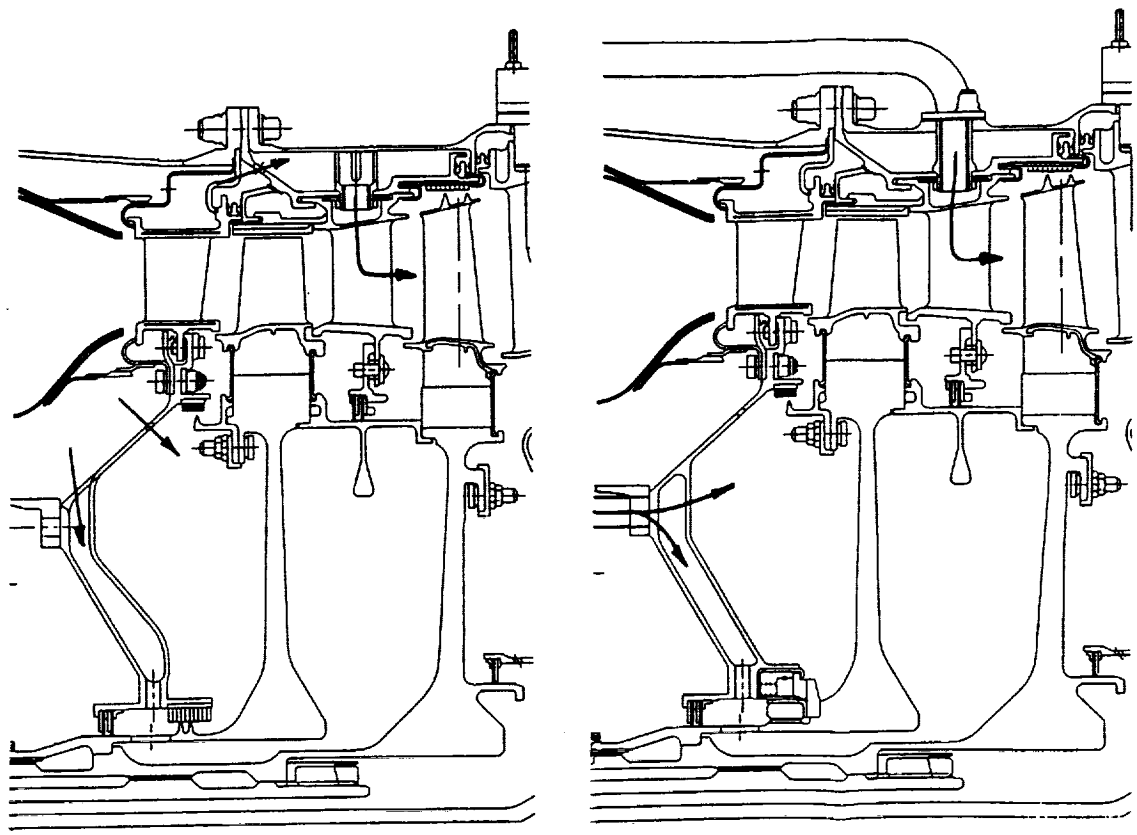

Figure 17. Active cooling air control.

cooling air and the wheel cavities can be reduced significantly. Analysis of the internal flow system indicates that the current T406 configuration would require an additional sealing change in addition to adding the valving system. The preswirler aft labyrinth seal would have to be replaced by an essentially zero leakage seal, such as a film-riding face seal. This would be required to prevent starvation of the first-stage wheel forward cavity. Figure 17 depicts the modified cooling air circuit, indicating that the preswirler flow can be reduced by 1.5%. Figure 18 shows the overall concept hardware implementation.

Examination of the baseline T406 engine suggests that 2.2% in cooling air can be modulated for an altitude cruise condition, resulting in a 1.3% decrease in engine SFC while maintaining life. While the ability to modulate the cooling air at this condition exists, there are additional implications that must be considered. Modification to the cooling circuit can alter blade tip clearances, interstage seal clearances, and blade/vane overlap gaps, all of which can impact performance and cooling air requirements. A detailed structural analysis would be required to assess the implications and trade-offs. Advanced engines in this class operating at 2600-3000°F would probably show an even higher SFC impact since base chargeable cooling flows are higher.

The system would be active only in the cruise condition where performance loss, due to design, is significant. Hence, performance is not affected at takeoff, as demonstrated by the simplified block diagram found in Figure 19.

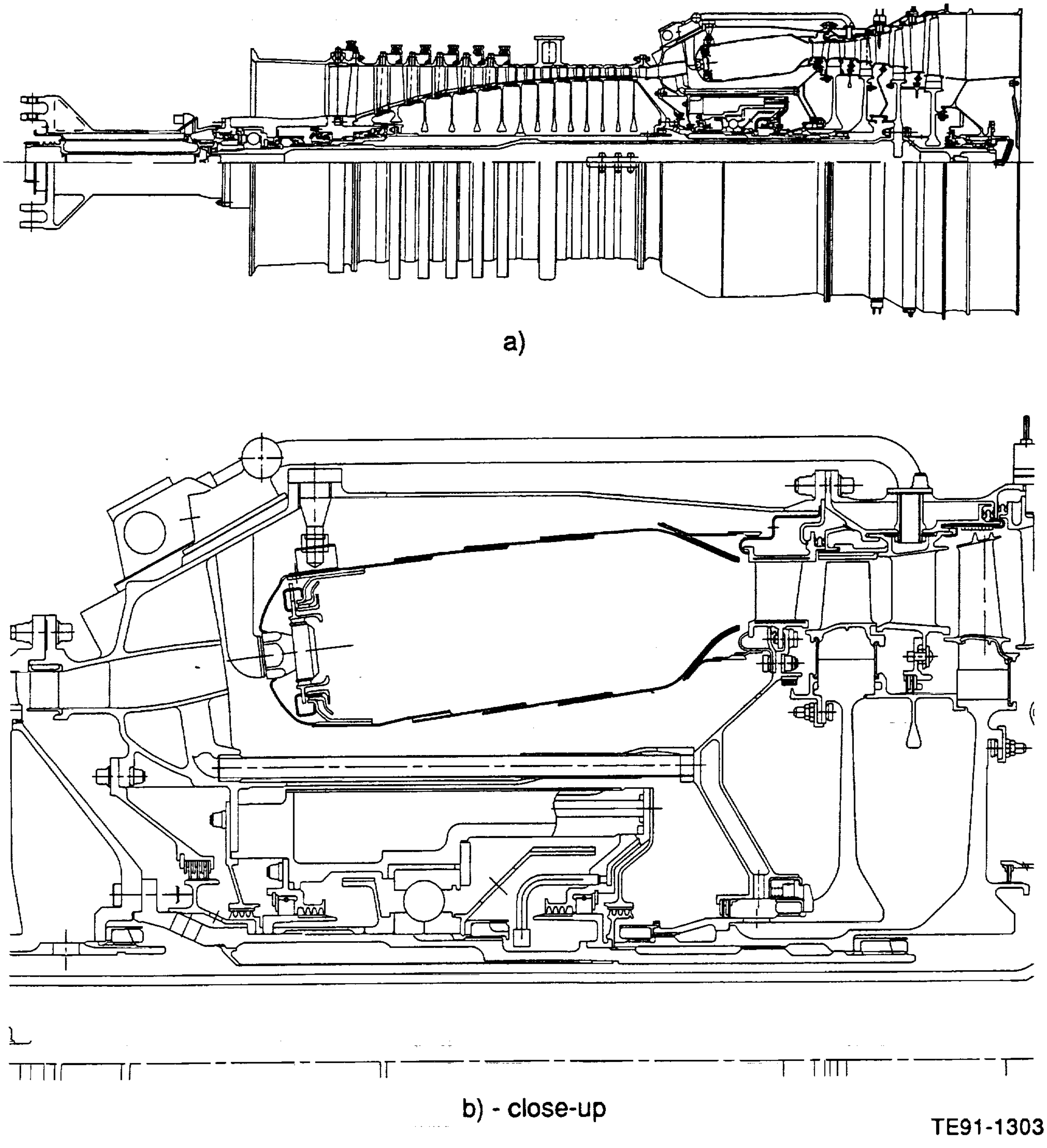

Figure 18. Active cooling air control hardware concept.

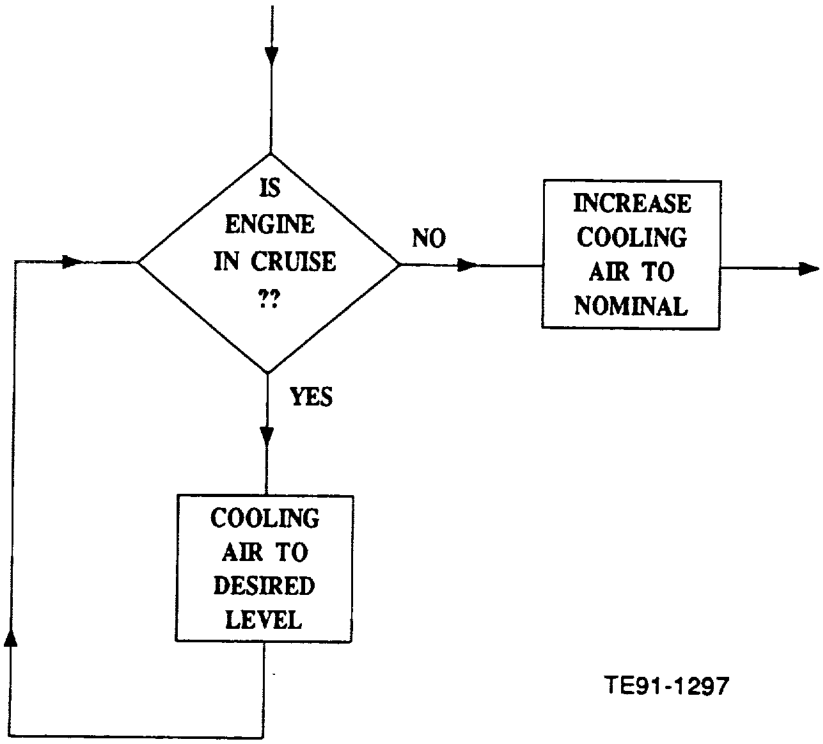

Figure 19. Active cooling control block diagram.

The implementation concept, yielding the performance benefits listed above, requires hardware for the cooling air tubes and for the seal at the preswirler. Some nonrecurring development and testing costs would be involved, but when considering the costs of the hardware per engine (primary) and the impact on maintenance costs (secondary), these can be considered negligible. The total cost impact for acquisition was calculated to be approximately 1.0%.

The hardware described will also have a weight impact. Table VI depicts the concept weight approximations. The total impact on engine weight is 0.8%.

Table VI.
Weight of active cooling concept hardware implementation.

	Unit weight--lb	Quantity	Total weight--lb
Control valve	1.20	4	4.80
Control valve hardware	0.75	4	3.00
Turbine vane cooling air tubes	0.24	4	0.97
Turbine vane outer hardware	0.35	14	4.90
Blade cooling air tubes	0.22	8	1.75
Film riding face seal	1.50	1	1.50
			16.92

4.7 PERFORMANCE SEEKING CONTROL

The application of performance seeking control (PSC) to the Civil Tiltrotor is approached in this study from two levels. The first is at the level of the propulsion system alone and the second includes the airframe in the optimization analysis. Before discussing these concepts a short description of the V-22 system is in order. The current engine/rotor control system for the V-22 tiltrotor is shown in Figure 20.

The Allison Full Authority Digital Electronic Controls (FADECs) and engines are shown as part of an overall thrust power management system (TPMS) which governs both the engine and rotor system to provide height/rate-of-climb control in the VTOL mode and airspeed control in the airplane mode (ref. 1). Throttle inputs are analogous to collective control in a helicopter and throttle control in an airplane. The TPMS is supplied by the airframer Bell-Boeing. In the TPMS system the inputs to the TPMS engine control are the pilot commands, shown as thrust control lever (TCL) and engine condition lever (ECL). Mast angle (engine nacelle angle) is controlled directly by the pilot using a separate lever and is set according to his feel for what works best. The TPMS provides for throttle (TCL) quickening to improve handling qualities, engine starting and throttle response shaping based on ECL command, and OEI compensation. The TPMS then produces a left and right power demand signal (PDS) to each FADEC system of the two T406 engines.

The TPMS rotor speed control provides conversion to collective pitch control of the propellers during transition from airplane to helicopter mode and it provides feed forward pitch control for improved airplane mode throttle response. Another feature of the TPMS is a torque command limiting system (TCLS) which prevents overstressing the V-22 transmission and provides for a more linear torque versus TCL position function.

The new propulsion control system addressed here involves the further integration of the TPMS and the engine FADECs into one integrated multivariable control system (representing Level 1) and the further integration still with the flight control system (Level 2). The Level 1 approach is shown in Figure 21 and represents the total propulsion system control (engines plus rotors) control as a MIMO system rather than the current multiple independent SISO systems currently employed on the V-22. The use of multivariable control is the natural progression that would be necessary to take advantage of the advanced control concepts being investigated in this program and to enhance the tiltrotor propulsion system in general.

The current T406 control, however, could still take advantage of an adaptive performance seeking control through trim inputs to its current fuel flow and compressor variable geometry commands. For the sake of clarity the rotor/propeller control signals currently generated by the TPMS are shown as a dashed line which themselves may be included in the aircraft PSC system. In this configuration the

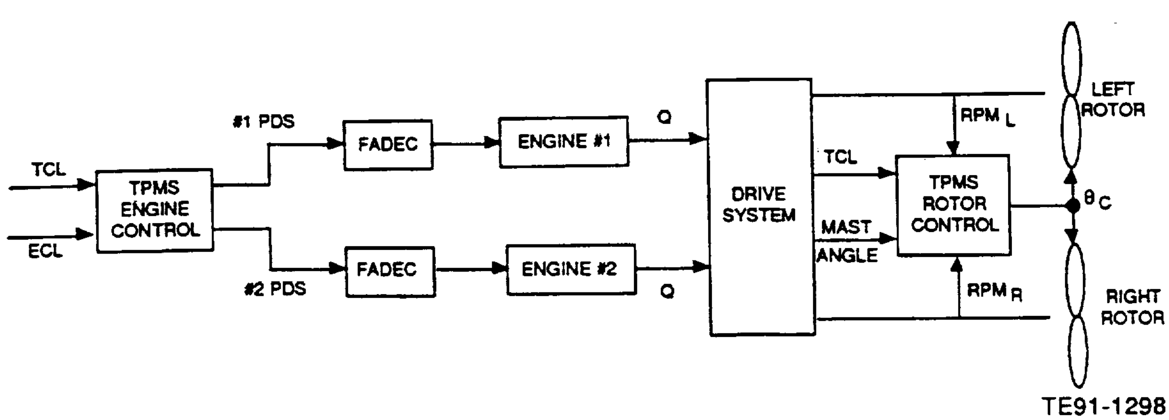

Figure 20. Simplified engine/rotor control block diagram.

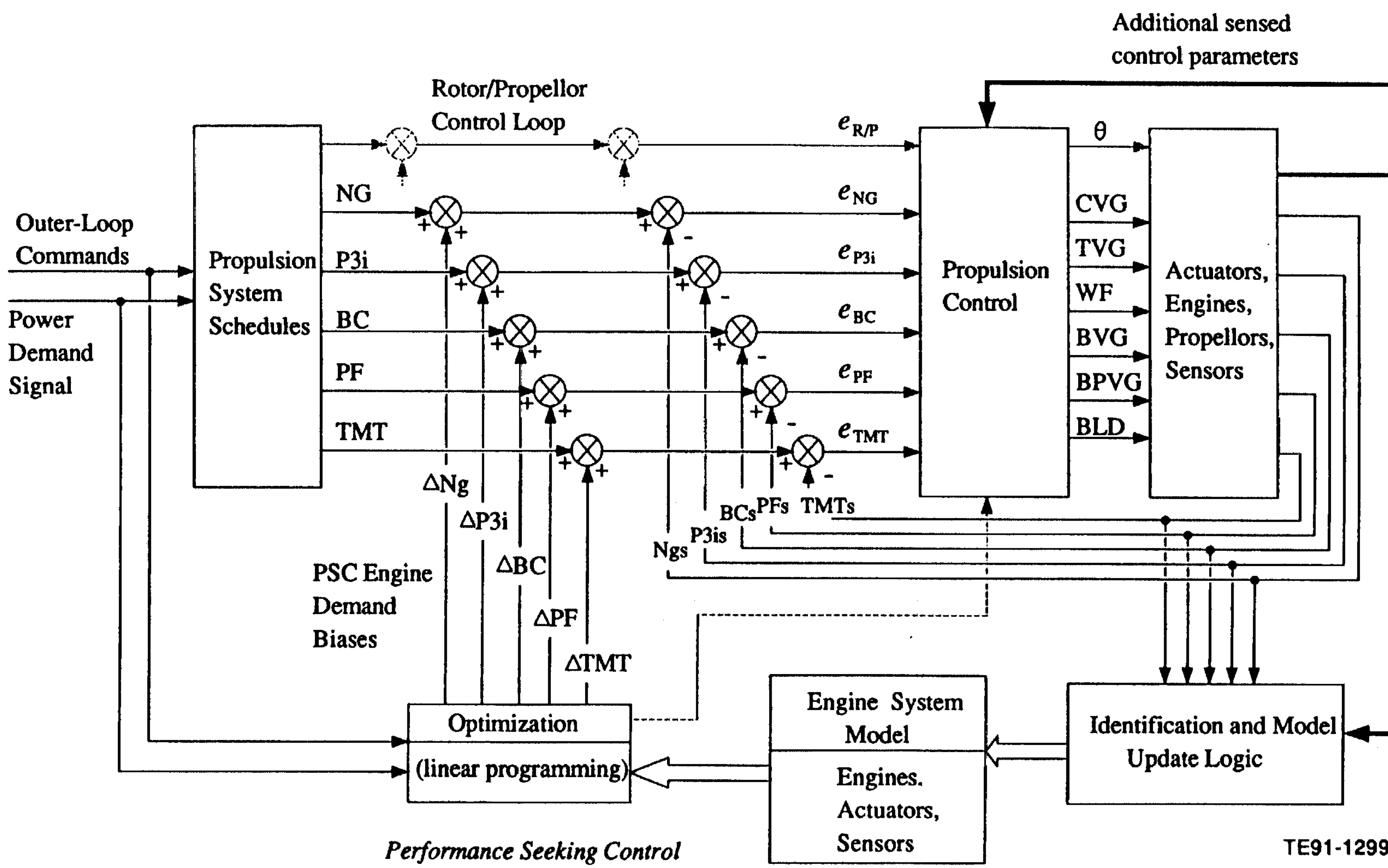

Figure 21. Propulsion system control loop with PSC (Level 1).

pilot TCL, ECL and any outer-loop commands are fed into the propulsion system schedules. The outer-loop commands would consist of mast angle (beta), flight condition (stick and pedal commands, cruise, take-off, landing, OEI), and air-data computer (angle of attack, side-slip angle) outputs. The propulsion system schedules then convert these commands to desired operating conditions in terms of the following:

- NG—gas generator speed
- $P3_i$—compressor pressure at the "i"th stage
- BC—burner condition (emissions)
- PF—pattern factor
- TMT—turbine metal temperature

and rotor/propeller operating conditions (not shown):

- NP—power turbine speed
- Q—rotor torque
- THETA—propeller pitch angle

These parameters cover the normal control loop (engine speed) and the variables of interest in this program with respect to advanced control modes (i.e., stall/surge control ($P3_i$); turbine variable geometry for increased power (NG); emissions (BC); pattern factor (PF), and active cooling control (TMT)). Maneuver predictions are provided from the flight condition data. Neglecting the PSC input biases for the moment, these command parameters are then compared with the actual engine operating conditions based on processed sensor information, and the errors are then fed into the engine MIMO control to perform actuation of the following:

- CVG—compressor variable geometry angle
- TVG—turbine variable geometry angle
- WF—fuel flow
- BVG— burner variable geometry position (combustor can)
- $BPVG_i$—burner pattern variable geometry ("i"th fuel nozzle flow)
- BLD—turbine cooling flow bleed

The block diagram also shows additional engine parameters being fed back into the control for protection logic which would include power turbine speed, engine torque and fuel flow limits. The form of the MIMO control is not important for this discussion but a concept used in the past by Allison is the "KQ-multivariable control" concept shown in Figure 22 in conjunction with a model-following regulator for feed forward control and improved performance and command following (ref. 2). This is an easily implementable control which is designed based on the desired response matrix. Allison has recently begun to investigate nonlinear control concepts such as neural nets fuzzy logic which may be of use for the Civil Tiltrotor.

The PSC system is shown implemented as an adaptive trim method essentially the same as that currently in the development and validation process on the NASA F-15 HIDEC aircraft (ref. 3) and as proposed for the High Speed Civil Transport (ref. 4). The actual engine performance is compared with an ideal mathematical model to update the model which is then used in the optimization logic (using a model rather than perturbing the actual aircraft and engine removes the error associated with sensor noise and response uncertainties). The optimization logic then seeks to optimize the parameter of choice whether it is specific fuel consumption, thrust, life or other parameter affecting direct operating cost (DOC). This technique should be capable of improving each of these parameters independently and possibly more than one at a time depending on how sophisticated the performance index and the optimization algorithm. Ultimately, the greatest payoff will be obtained by including both the

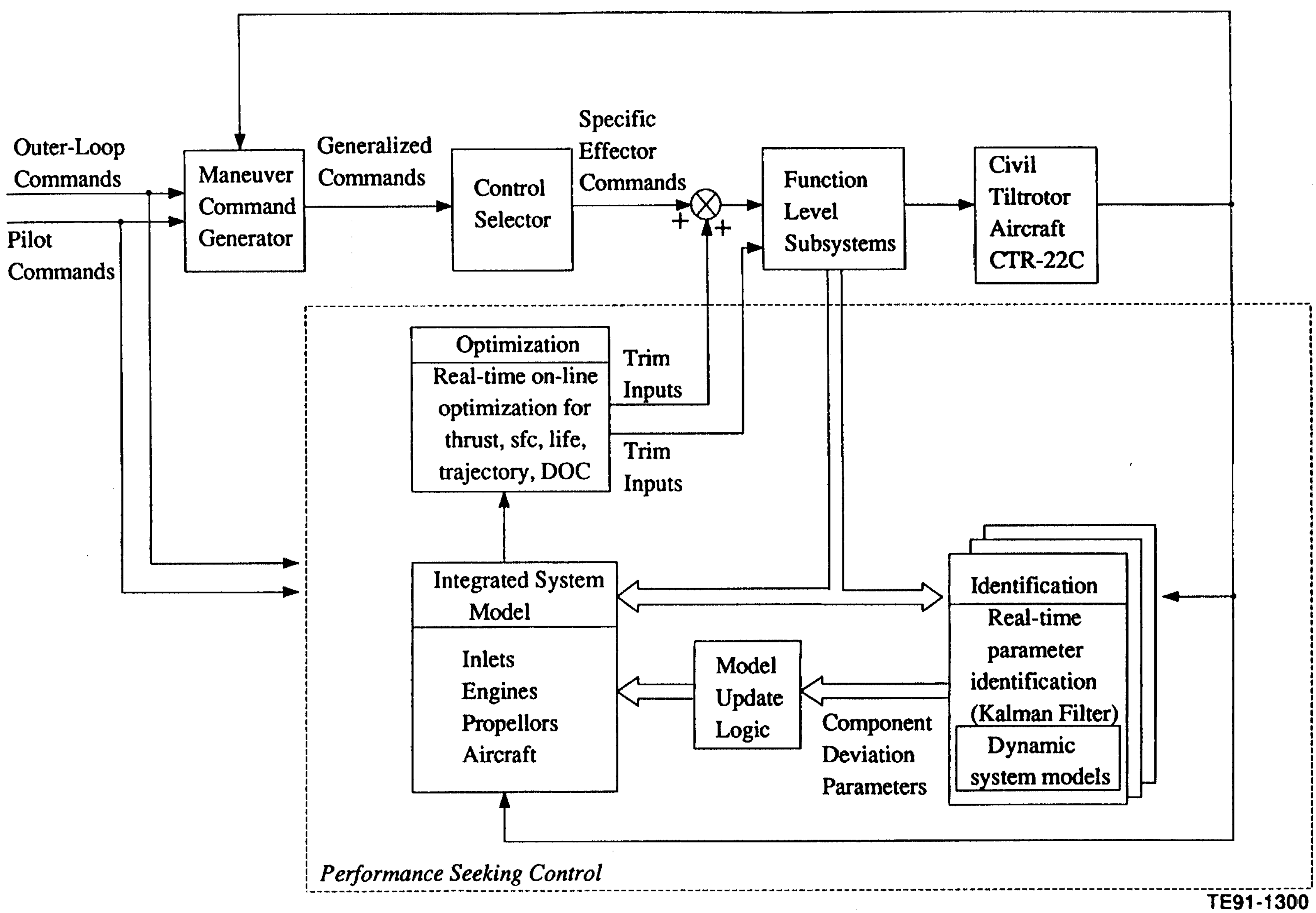

Figure 22. Total aircraft control loop with PSC (Level 2).

advanced propulsion controls concepts with the airframe in the PSC problem as shown in Figure 22. This is the second level of PSC which is discussed next.

In this treatment the Design Methods in Integrated Control Systems (DMICS) program (ref. 5) structure is shown with the PSC system providing trim inputs to the function level subsystem commands and each inner loop control. The PSC loop is closed around these subsystems and the airframe to perform optimization of not only the engine performance according to external inputs but also to drive the inputs to the engine by influencing the flight conditions and to improve aircraft system performance. The external inputs influencing engine performance are inlet conditions, propeller torque requirements, and throttle commands. These external inputs are affected by airspeed, angle of attack, mast angle, ambient temperature and pressure. The last two are essentially uncontrolled parameters whereas the first three are coupled to the flight control. That is to say that the airspeed, angle of attack and mast angle are interrelated with the airframe flight control surface deflections. This is where the PSC might gain additional performance enhancements through the optimization of parameters such as specific fuel consumption by "setting up" the aircraft in a low drag low inlet distortion flight condition. The optimization logic would determine the "cleanest" profile for the desired airspeed through the best balance of engine thrust angle, thrust magnitude and elevator angle while reducing inlet distortion for improved engine power.

4.7.1 Optimization Process

As stated, the performance seeking controller would employ an engine simulation which is continually updated to match the operating characteristics of the actual engine. The effects of each advanced engine control concept would be included in this model. The compact engine model (CEM) used in this process must necessarily be very accurate otherwise the PSC will provide poor performance and will not be able to adapt to aging engines or properly represent engine operation. The CEM would consist of a piecewise-linear steady state variable model (SSVM) and a portion devoted to modeling those nonlinear effects which are not accurately represented by the linear models. Kalman filtering would be used to estimate component deviations representing off-nominal performance (ref. 6). These component deviations would then be added into the model to force a match. For the T406 derivative it is expected that there would be low and high spool efficiency adders, and a compressor airflow adder. This technique was proven to result in accuracies within $\pm$2% for the HIDEC F-15 when compared to a nonlinear aero/thermodynamic engine model (ref. 7), used as the "truth model," and was considered sufficient for PSC purposes.

The PSC follow-on to the HIDEC program did not incorporate the flight control surfaces into the PSC system but focused on adjusting the inlet, engine variable geometry and nozzle according to predicted and actual angle-of-attack and sideslip angle. The system discussed for the Civil Tiltrotor would also include maneuver prediction but would benefit from including the flight control surfaces for maximum aircraft performance during cruise since the inlet and nozzle are fixed geometry components and the nacelle angle (mast angle) directly impacts drag and the thrust vector. However, the advanced engine control concepts, or "first level", may be incorporated without the airframe control loop to provide the enhancements outlined under each concept section.

The PSC also will contain models of the inlet and nozzle which in the case of the tiltrotor are fixed geometry components as mentioned earlier. Once modeled these components should not change significantly from build to build nor over time so these parts of the model will not require active updating.

To incorporate the airframe into the PSC (second level) a compact airframe model (CAM) and dynamics must be included with the CEM to optimize aircraft performance. This model would probably require less updating since the control surface and nacelle effects will not change noticeably over time. However, this would be useful for flight control failure detection and accommodation and essentially, if an FDIA system were incorporated in the flight controls, the model updates from such a system could be used for the PSC.

The compact models are used to determine the sensitivities of the outputs of interest (SFC, power, emissions, life) to control input changes. These are then used to form an overall propulsion system model through the definition of a matrix reflecting the control system sensitivities. The propulsion system matrix is a linear representation of the propulsion system about the specific operating point which is used to perform a series of linear programming optimizations using the Simplex method (ref. 8). The first pass through defines a local optimum within the constraints defined by the limits on maximum control input changes allowed by the linearization process and within the constraints of maximum allowable physical operating limits of the engine. Control input changes are then used to bring the engine to this new operating point from which a new propulsion system matrix about that point is formed. The linear programming optimization is then repeated to find a new local optimum. This process continues until the series of control input changes converge to a global optimum. These optimum control input biases are then summed with those of the standard control loop inputs.

Another method of searching for the optimum is through nonlinear programming techniques (ref. 9). However, the success of these nonlinear programs are highly dependent on the search method used. Often, as the "nonlinear surface" of the problem and its associated constraints change, as might happen with varying operating conditions and limits, the search method must be scaled or changed all together. The process could potentially be investigated for a variety of points throughout the operating envelope and revised search techniques for each point could be stored in memory. The pitfall associated with this is that there may be no way to assure reaching a global rather than local optimum for points that didn't happen to be selected for investigation. Also, constraints or boundaries pose special problems as do global optimums that reside in troughs or on peaks on the nonlinear performance surface being searched because the search may jump past the optimum point or take forever to get there. Often the point from which the search begins is crucial to the programs success. It is possible that artificial intelligence, neural networks or fuzzy logic may be of use in applying the nonlinear programming techniques in order to provide the on-line adaptability that is needed.

4.7.2 Advanced Propulsion Control Concepts Benefits

The benefits associated with including each of the advanced control concepts have already been summarized in the individual discussions. Each is essentially a method for improving the performance whether it be in the area of thrust, SFC, emissions or engine life. When incorporated into the PSC each of these subsystems will become an integrated part of the overall optimization process. Secondary control modes such as compressor "wiggling vanes" and turbine variable geometry will be superimposed over the primary airflow control modes used during steady-state and transients.

Neglecting the potential advanced control features, such as active cooling air control and variable geometry turbines, and focusing on control features already available to the T406, i.e., compressor variable geometry and fuel flow, the potential role of the PSC system and the associated benefits can be approximated. The primary advantages of the PSC system would, in this case, be through actively controlling surge margin based on flight condition, as discussed in Section 4.2 of this report. Tables exist for surge margin loss allowance that are keyed to such destabilizing effects as: service deterioration; inlet distortion; production variations, control system tolerances and errors; and service bleed off-take variation. In addition, net surge margin loss allowance associated with the compressor itself is included. These all add up to a base surge margin of 17.5%. In cruise mode the PSC could be used to trim the aircraft to a minimum inlet distortion condition and the engine essentially "tuned" through the optimization process to recover approximately half, or 8.75%, of the surge margin allowance. This represents a 1.2% improvement in specific fuel consumption.

Deterioration allowances built into the base surge margin value of 17.5% must be handled carefully. Starting the service life of the engine is possible with the control able to extract more power than normally available due to the derating of the engine through surge margin allowances. However, the operator has determined a series of design point power requirements for the engine. This is because the operator requires a certain base power output regardless of how close the engines are to overhaul. This is what the aircraft, the rotor/propellers, and the engine are designed for. The engine is not expected to drop below this power level between overhauls. By designing in a thrust optimization system that will automatically adapt to engine degradation over the course of the engine's life, the operator is faced with variable and possibly inconsistent aircraft performance levels that may be hard to track. Also, as one engine is derated due to deterioration, with the controller responding by adding surge margin, for instance, the other engine must be similarly derated regardless of its condition to provide balanced power for aircraft control. However, the commercial operator and pilot are asking for consistent performance expectations especially during takeoff and landing. Additional power might be useful in a one-engine-inoperative situation but will generally go unused. The prospect of having additional power on-demand appears to be more suitable for a military application in which this extra margin could be used in combat, special operations, or situations when it could provide the extra edge.

Nevertheless, cycle optimization at cruise with control of airflow and fuel alone may allow an approximate improvement of 3-5% in horsepower. This figure is based on the more significant level of results from the NASA programs associated with performance optimization of the F-15 test vehicle. In the case of the civil tiltrotor there is no controllable nozzle to fine tune engine performance, and the operating altitudes and speeds do not vary as greatly. Using an integrated rotor/propeller system and optimally scheduling the base engine control variables could provide the additional horsepower. This may also allow the operation of the engine at reduced turbine temperatures, thus improving life while providing the same rotor/propeller thrust.

Allison also investigated the use of the PSC to reduce turbine temperature margins designed into the base engine control. This margin allows the control to increase turbine temperature in response to loss of engine performance from such causes as turbine vane erosion. In this way the engine can provide consistent performance levels for a greater length of time. If this margin were reduced to gain as much performance as possible initially, then engine performance would begin to deteriorate sooner for lack of the ability to increase temperature further. As discussed earlier, the loss of turbine engine power over time is not considered a viable option in the commercial industry.

During the course of this program, it was decided that further analysis to determine the benefits and full potential of the PSC more accurately was required. For the level 2 concept a simple aircraft simulation and CAM are needed requiring airframer involvement.

The NASA/McDonnell Aircraft F-15 PSC program demonstrated significant thrust and SFC improvements. The F-15 program is now moving into a demonstration of the adaptability features of the PSC by intentionally degrading the engine performance for flight test. Discussions with NASA-Ames/Dryden and McAir have indicated that there should be tremendous potential for PSC incorporation into the Civil Tiltrotor. Further discussions with Boeing have uncovered a great interest in pursuing such a concept since most of the efforts to-date have been in the area of hardware improvements. PSC promises to enhance cruise, takeoff/landing, and OEI capabilities for both the military and civil applications of this aircraft. In addition, the potential exists for actual flight demonstration phases of various forms of the PSC concept whether or not the other advanced engine control modes are implemented. Beyond the thrust and SFC and life improvements possible there exists the enhanced maintenance possibilities provided by the adaptive engine models that are incorporated into the optimizer. Status information could be transferred to the on-board maintenance logging system to flag engine health problems for maintenance crews while the PSC will provide greater aircraft availability by accommodating off-nominal performance and improving flight reliability and safety.

The implementation of a PSC adds cost to the initial control algorithm/software development and so increases engine acquisition cost (EAC) by reason of the nonrecurring costs. This could translate into approximately four man-years plus two man-years for software development. However, when this is amortized over the course of the production program the added cost should be insignificant. There should actually be an added improvement in engine maintenance cost (EMC) and specific fuel consumption by reason of the detection schemes and control modes provided by the PSC. The final parameter impacting direct operating cost is engine weight which the PSC should have no effect on since there will be little or no electronics added and the data can be transferred to other flight/propulsion computers over a standard data bus. There will of course be the impact of the advanced control mode hardware covered in the other sections.

4.7.3 Additional Work

A more detailed analysis of the PSC concept needs to be performed. This could aid both the V-22 and the Civil Tiltrotor programs and therefore have a significant effect on the emerging VTOL technologies in the United States from both the military and commercial standpoint. Allison proposes a multi-faceted program involving the expertise of NASA Lewis, NASA Ames-Dryden, Boeing, and Allison to fully explore this concept.

5.0 DISCUSSION OF RESULTS

This report provides quantified measures of performance and operability improvement resulting from the application of advanced control technologies to an airbreathing engine as part of the ongoing APC program. The model aircraft of study was a 39-passenger civil tiltrotor based on the military V-22 Osprey, which utilizes two Allison T406 engines. A takeoff point and a maximum cruise point were selected from an expected civil mission profile to simplify this first-pass quantitative analysis. The engine performance and operability parameters examined were SFC, engine weight, engine acquisition cost, maintenance, emissions, and safety.

Members of the Boeing Helicopter Company, civil tiltrotor program were instrumental in defining the evaluation criteria. It was decided that the DOC would be an appropriate vehicle for "summing" the benefits versus the penalties. The equation for yielding the net result is:

$$\Delta DOC = 0.275 \times (\Delta SFC) + 0.004 \times (\Delta EW) + 0.250 \times (\Delta EAC)$$

where

ΔSFC = change in specific fuel consumption
ΔEW = change in engine weight
ΔEAC = change in engine acquisition cost

A summary of the results can be seen in Figure 23. From this summary chart, a "first-glance" evaluation may indicate that improvements were marginal. However, it is still maintained that each APC is a worthwhile venture and that further study is needed.

Due to the limited nature of the study, estimations were required to obtain the results. In many cases the estimates were conservative to maintain integrity. In addition, with hindsight, a heavier funded study could allow for a more analytical means of evaluation than currently undertaken. For example, determining impact on maintenance cost would be an expensive endeavor, yet many of the APCs studied would certainly have significant affect thereon. Hence, it is important to understand that the limits of this study must be bore in mind when reviewing the results as presented in Figure 23.

5.1 EMISSIONS

Currently, baseline emission requirements for a civil tiltrotor application are essentially nonexistent. However, the timeframe and geographical locations most likely to represent the expected implementation of such a system will inherently face strict federal regulations. Critical combustor design conditions are idle and maximum power conditions since CO and UHC tend to be high at idle while NOx are high at maximum power. Current fixed-combustor design yields acceptable emissions at maximum power yet much improvement is needed at the idle point. By controlling combustor fuel/air ratio, via variable geometry, reductions of CO by 53% and UHC by 69% were calculated at idle with no effect on the maximum power conditions.

Therefore it seems obvious that for little penalty in weight, future requirements regarding emissions will be more approachable with combustor variable geometry.

5.2 SFC

Turbine engine performance is severely limited by the requirements of surge margin. Allison continues to follow the successful studies and testing being conducted by Massachusetts Institute of Technology (MIT) in the area of surge inhibitor techniques. The concept of "wiggling" vanes to interrupt the development of a stall cell, believed to be the cause of surge, would allow operating the engine with a reduced surge margin yielding increased performance. To operate closer to surge would require some mechanization.

ADVANCED PROPULSION CONTROL CONCEPT	Δ DOC SENSITIVITIES					COMMENTS SAFETY, EMISSIONS, AND OTHER
	ΔSFC	ΔEW	ΔEAC	TOTAL*		
COMBUSTOR VARIABLE GEOMETRY	N.E.	+1.40	+1.90	+ 0.48		A decrease in CO emissions by 53% and a decrease in UHC by 69% at idle
COMPRESSOR VARIABLE GEOMETRY						
(a) OEI V/G settings	N. E.	U	U	U		(a) 0.5% increase in shp at OEI and 1.6% increase at max climb rating condition
(b) 5% less surge margin	- 0.70	U	U	- 0.19		
(c) 10% less surge margin w/ redesign	- 1.40	- 0.81	X	N. E.		(c) Redesign requires further detailed analysis. The T406 currently has CVG.
WIGGLING VANES SURGE CONTROL						
(a) 5% less surge margin	- 0.70	+ 0.60	+0.58	- 0.04		
(b) 10% less surge margin	0.00	- 0.20	+0.58	+ 0.14		
TURBINE VARIABLE GEOMETRY						
(a) GGT V/G	- 1.30	+6.60	+7.30	+ 1.49		
(b) PT V/G	N. E.	+6.60	+7.30	+ 1.83		+ 5.80% shp increase (400 shp) available for OEI (could trade SHP increase for reduced engine weight)
PATTERN FACTOR CONTROL	N. E.	+ 1.00	+ 2.80	+ 0.74		The effect of PFC on SFC is considered negligible Turbine component life is greatly impacted
ACTIVE COOLING CONTROL	- 1.30	+1.70	+1.00	- 0.10		
PERFORMANCE SEEKING CONTROL	-1.20	N. E.	N. E.	-0.33		Non-recurring development cost impact only

SFC - Specific Fuel Consumption
EW - Engine Weight
EAC - Engine Acquisition Cost
EMC - Engine Maintenance Cost (not evaluated under this study)

* See Table 3-I for weighting factors of DOC sensitivities
X - Beyond scope of this report
N.E. - Negligible Effect
U - Undetermined

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Figure 23. Summary of results.

So, for example, "wiggling" vanes in conjunction with compressor variable geometry would result in a benefit to SFC. An indirect method of using this APC pair is in resizing the compressor. Figure 23 shows that for 10% less surge margin an SFC benefit of -1.4% was achieved. Alternatively, for 10% less surge margin an entire stage of the compressor could be "designed-out" while still maintaining the baseline pressure characteristics.

Other items which affected SFC improvement, and more dramatically, were gas generator turbine variable geometry and active chargeable cooling air control. Incorporating gas generator turbine variable geometry, to allow varying flow by 10%, an improvement to SFC of 1.3% was achieved. Implementation of hardware allowing active cooling control also yielded a 1.3% improvement to SFC.

In military applications SFC would translate to increased range while the civil arena views the benefit in a monetary profit. With further study and eventual development costs and weights of needed hardware could be reduced from the conservative estimates presented herein.

5.3 OEI

Safety requirements are a vital aspect to any aircraft performance and more so in the civil sector. The worst case scenario of OEI is so important that the engine would be designed or "sized" by the criteria. Hence, any technology which increases horsepower can be extrapolated to either meet stricter safety requirements of the future or to allow reduced size yielding less weight for similar-to-baseline performance.

Concepts were examined for improved OEI capability, an important safety design criteria. At high compressor corrected speeds, 0.5% increase in horsepower was attainable while power turbine-turbine variable geometry yielded a 5.8% increase or 400 horsepower.

5.4 LIFE

In any turbine engine design criteria the life of the components must be considered. The cost of replacing failed or worn parts is high when the support personnel and facilities as well as the cost of down-time are considered. Burner outlet temperatures (BOT) become exceedingly important in determining the life of components in the turbine. Although an engine design utilizes a circumferential average BOT, hot-spots exist which adversely affect the components expected life. An actively controlled fuel nozzle system would allow for combustor circumferential pattern factor control. It was found that with 36% reduction in pattern factor the maximum burner outlet temperature could be reduced by at least 100°F (Allison holds that as much as 50% reduction is attainable-further study is required). This relates to an increase in turbine component life in excess of 100% which reduces maintenance cost.

5.5 APC MANAGEMENT

PSC was studied as not only an engine controller but as an outer loop for combining airframe and engine in the optimization analysis. Although beyond the scope of this report to quantify, PSC is expected to improve any other APC performance benefit as well as optimize the coordination of any combination of implemented APCs. Therefore it is recommended that although PSC could be studied independently that any further study of APC combinations should include PSC as a performance enhancing and managing tool.

5.6 SUMMARY

This is not intended to be a final ranking of the APCs but simply one method of recording the results. It is recommended that a downselect process be performed on the basis of this report and that further, more detailed, analysis be conducted by way of computer simulation and if appropriate, eventual engine implementation and testing.

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13. ABSTRACT *(Maximum 200 words)*

The application of advanced control concepts to airbreathing engines may yield significant improvements in aircraft/engine performance and operability. Screening studies of advanced control concepts for airbreathing engines have been conducted by three major domestic aircraft engine manufacturers to determine the potential impact of concepts on turbine engine performance and operability. The purpose of the studies was to identify concepts which offered high potential yet may incur high research and development risk. A target suite of proposed advanced control concepts was formulated and evaluated in a two-phase study to quantify each concept's impact on desired engine characteristics. To aid in the evaluation specific aircraft/engine combinations were considered: a Military High Performance Fighter mission, a High Speed Civil Transport mission, and a Civil Tiltrotor mission. Each of the advanced control concepts considered in the study are defined and described. The concept potential impact on engine performance was determined. Relevant figures of merit on which to evaluate the concepts are determined. Finally, the concepts are ranked with respect to the target aircraft/engine missions. A final report describing the screening studies has been prepared by each engine manufacturer. Volume 3 of these reports describes the studies performed by the Allison Gas Turbine Division.

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