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ROTORCRAFT CONTINGENCY POWER STUDY

Robert Hirschkron
John F. Haynes
David N. Goldstein
Richard H. Davis

GENERAL ELECTRIC

Aircraft Engine Business Group
Lynn, Massachusetts

prepared for

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INTRODUCTION

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SUMMARY

INTRODUCTION

The One Engine Inoperative (OEI) condition is the power requirement sizing for engines used in Army rotorcraft. Contingency Power ratings were created to supply this temporary need for more power under special circumstances. The most interest is in providing as much Contingency Power as possible for a helicopter turboshaft engine to permit the use of relatively smaller, lighter, and less costly engines. This study explores the ways and means of providing Contingency Power, and its ultimate payoff in two rotorcraft.

This study was first suggested in connection with turbine cooling system water injection development work done for NASA as part of the T700 STEP program (NAS 3-21579). It was designed by NASA to provide balanced, quantitative answers to several issues:

1. Define design changes necessary for contingency power ratings.

2. Determine economic payoff of rotorcraft with engines that have contingency power ratings.

3. Compare the merits of various novel schemes for contingency power ratings on the basis of economic payoff.

The work statement specified four novel concepts for evaluation: cooling air flow modulation, compressor water injection, turbine cooling air water injection, and a propellant-powered auxiliary unit. An engine designed for contingency power by conventional means, designated as "throttle push", was added to the list by General Electric.

The framework of the study consisted of a civil and a military rotorcraft each powered by baseline engines with nominal contingency power capability.

Sikorsky Aircraft Division of United Technology Corporation was subcontractor to General Electric. They selected the baseline rotorcraft missions for maximum market potential in the 1990's. The rotorcraft were specified to be of conventional design, i.e., not high speed types like ABC or X-Wing. The baseline engines were likewise designed on the basis of technology consistent with introduction in the 1990's.

The engines with novel concepts and higher levels of contingency power were all designed to meet the same design life criteria. Design penalties versus the baseline engine were then established and compared to the contingency power related rotorcraft benefits. The net benefit for each system was then compared on the basis of an economic model and evaluation criteria established by General Electric and Sikorsky Aircraft and approved by NASA.

The order of this report follows the work statement.

Task 1 - Is a description of the baseline rotorcraft missions, design criteria, design parameters, economic assumptions and models, trade factors, and evaluation criteria.

Task II - Consists of the baseline propulsion system design approaches and characteristics such as performance, weight, cost, and maintenance.

Task III - Consists of a qualitative description of the novel concepts including the controls system and design changes from the baseline engines. Task III also covers the design limits which were established.

Task IV - Proceeds on to the quantitative design changes for each of the novel concepts studied. This includes the component and material substitution as required to meet life objectives.

Task V - All the factors above are combined in Task V for a benefit assessment using aircraft trade factors.

Task VI - Covers the study recommendations with respect to desirable R&T effort found to be needed to overcome barrier problems.

SUMMARY

The results of the study indicate a significant potential advantage for rotorcraft designed with higher contingency powered engines than the baseline engine which has contingency power ratio of 1.15.

The ranking of the systems in a civil and military rotorcraft are indicated in Tables 1 and 2 at two selected contingency power levels.

TABLE 1. CIVIL ROTORCRAFT

CRP/TOP*	1.30		1.50		
System	DOC** (%)	Ranking	DOC** (%)	Ranking	
Throttle Push	1.9	2	2.7	3	Competitive Systems
Cooling Flow Modulation (Rotor only)	1.7	3	2.9	2	
Cooling Flow Modulation (Rotor and Shroud)	2.0	1	3.1	1	
Water Injection into Turbine Cooling System	1.2	4	2.7	4	
Water Injection into Compressor and Turbine Cooling System	-	-	2.3	5	

* Contingency Rated Power (CRP) to Takeoff Power (TOP) ratio.

** 1% Direct Operating Cost (DOC) = $25,000/year/aircraft or $200 million for a fleet of 400 aircraft over 20 years.

TABLE 2. MILITARY ROTORCRAFT					
CRP/IRP*	1.30		1.35		
System	LCC** (%)	Rank	LCC** (%)	Rank	
Throttle Push	2.2	2	2.5	1	Competitive Systems
Cooling Flow Modulation (Rotor only)	2.2	3	2.4	3	
Cooling Flow Modulation (Rotor and Shroud)	2.3	1	2.4	2	
Water Injection into Turbine Cooling System	2.0	4	2.3	4	
Water Injection into Compressor and Turbine Cooling System	-	-	2.1	5	

* Contingency Rated Power (CRP) to Intermediate Rated Power (IRP) ratio.

** 1% Life Cycle Cost (LCC) = $100 million for a fleet of 400 aircraft over 20 years.

Design penalties were primarily due to overcoming temperature limits and airflow limits. The design changes to overcome airflow limits consisted of rematching the IRP and TOP compressor operating condition to a lower speed. Design changes to overcome temperature limits included cooling flow increases and material substitutions.

Throttle push, cooling flow modulation, and water injection into turbine cooling system were the design approaches resulting in the least engine penalty and/or maximum net system benefit for provision of contingency power capability in an advanced turboshaft engine. These systems are all close enough to one another to be competitive in a practical engineering evaluation.

R&T programs to eliminate barriers to incorporation of contingency power ratings include material research for better blade coating and shroud bonds as well as turbine cooling analysis and test of extended range cooling flow modulation systems.

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TASK I

SELECTION OF REPRESENTATIVE VEHICLES, DESIGN CRITERIA, MISSIONS, AND EVALUATION CRITERIA

TASK I - SELECTION OF REPRESENTATIVE VEHICLES, DESIGN CRITERIA, MISSIONS, AND EVALUATION CRITERIA

BASELINE CIVIL MISSION

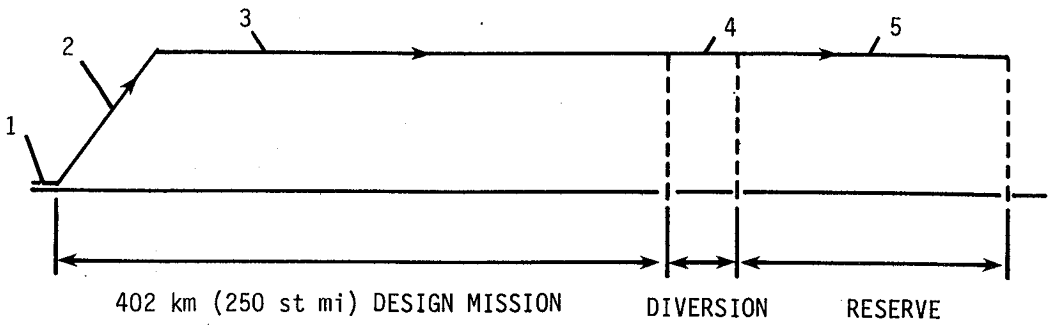
The civil rotorcraft used in this study is a single rotor helicopter with tail rotor, designed for future commercial airline shorthaul operation between city center heliports. It is sized to carry up to 30 passengers over 402 kilometers (250 statute miles) at a cruise speed of 296 km/hr (160 kt). Figure 1 describes the design mission in detail.

Figure 2 describes the typical mission profile used (as opposed to the more extreme design mission) to determine the fuel burned and block time when calculating the operating economics. The significant points are that the vehicle was flown at 65% load factor and that the fuel burned was calculated as the average for two successive 16/km (100 miles) statute lengths without refueling while cruising at the design cruise speed of 296 km/hr (160 kt).

Civil Rotorcraft Design Criteria

The design criteria are summarized in Table 3. The payload of 2,720 kg (6,000 lb) corresponds to 30 passengers at 90 kg (200 lb) each. The mission with this payload is as described in Figure 1. The engine is sized by the most demanding of several criteria. Figure 3 illustrates how these criteria relate to one another. The requirement to HIGE (hover in ground effect) with OEI (one engine inoperative) at the design gross weight at 305 m (1,000 ft) ISA + 15°C (27°F) using the CRP rating, sizes the engine until a CRP/TOP value is reached where another criterion predominates. HIGE with OEI was used to represent vertical CAT 'A' takeoff and landing capability from/to a small heliport. It is seen that it is by far the most demanding when the CRP/TOP ratings are in the present relationship of about 1.15. If a CRP/TOP ratio of 1.50 is provided then the CAT 'A' requirement for 46 m/min (150 ft/min) ROC (rate of climb) at OEI enroute power begins to size the engine. This presumes that the 30-minute OEI rating is set equal to the AEO (all engines operating) takeoff rating. If this criterion should be relaxed by increasing the 30-minute OEI enroute rating, then the ability to HOGE (hover out of ground effect) AEO becomes the next controlling requirement. The power loading required to cruise at 296 km/h (160 kt) at Maximum Cruise power at an altitude of 610 m (2,000 ft) above the takeoff altitude does not influence the engine sizing until very high CRP/TOP values are provided.

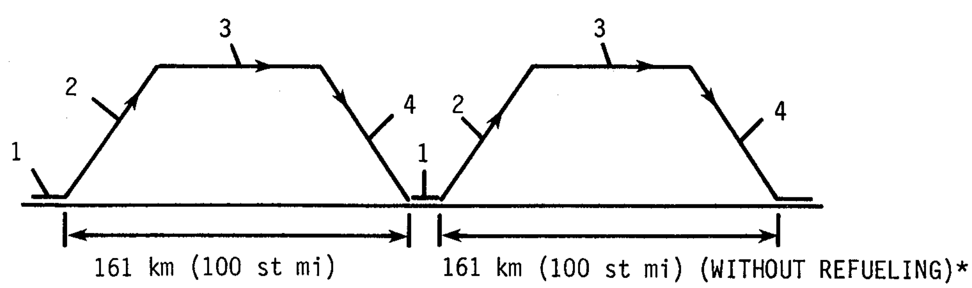
DESIGN PAYLOAD 2720 kg (6000 lb)



1. Warm-Up, Taxi, Liftoff: Equivalent 2.5 minutes engine operation at Max Cruise Power, 305 m (1000 ft) ISA + 15°C (27°F)
2. Climb, V = 148 km/h (92.0 mi/hr) from 305 m (1000 ft) to 915 m (3000 ft), ROC = 182 m/min (600 ft/min) Standard Temperature; Distance Credit 8.2 km (5.1 mi)
3. Level Cruise, V = 296 km/h (160 kt), 915 m (3000 ft) 9°C (48.3°F); Distance 394 km (244.9 mi), miles to destination
4. Alternate Airport Diversion 40 km (25 mi), at 915 m (3000 ft), 9°C (48.3°F), V = 296 km/h (160 kt)
5. Reserve 30 minutes, V = 296 km/h (160 kt), 915 m (3000 ft) 9°C (48.3°F),

Figure 1. Civil Airliner Design Mission Definition.

PAYLOAD 1770 kg (3900 lb) (65% LOAD FACTOR)



1. Typical Mission Warm-Up, Taxi, Liftoff, Maneuvers: Equivalent 2.0 min. engine operation at Max. Cruise Power, 305 m (1000 ft) ISA.
2. Typical Mission Climb to 915 m (3000 ft), at 182 m/min (600 ft/min) ROC, V = 148 km/h (80 kt) Average, Standard Temperature, Distance Credit 8.2 km (5.1 mi)
3. Typical Mission Level Cruise, V = 296 km/h (160 kt), 915 m (3000 ft), 9°C (48.3°F); Distance 145 km (89.8 mi)
4. Typical Mission Descent and Land at 182 m/min (600 ft/min) ROC, V = 148 km/h (80 kt) average, Distance Credit 8.2 km (5.1 mi)

*Repeated Missions for Fuel Burned Calculation.

Figure 2. Civil Airliner - Typical Off-Design Mission for Direct Operating Cost.

TABLE 3. CIVIL AIRLINER - DESIGN CRITERIA	
Aircraft	30-Passenger Commuter Airliner
Aircraft Design	FAR Part 29, Airworthiness Standards, Transport Category Rotorcraft
Crew	2 Pilots and 1 Attendant
Design Range	402 km (250 statute miles)
Payload	2,720 kg (6,000 lb)
Takeoff	305 km (1,000 ft), ISA + 15°C (27°F), TOGW
Design Hover	HOGE at TOP, Dual Engines, 305 m (1,000 ft), ISA + 15°C (27°F), TOGW
OEI Hover	HIGE, CRP on Remaining Engine, 305 m (1,000 ft), ISA + 15°C (27°F), TOGW
OEI Enroute	45.7 m/min (150 ft/min) minimum ROC at 30-minute rating
Stay-Up-Ability	At Speed for Best Rate of Climb (Approx 80 kt), 610 m (2,000 ft), ISA + 15°C (27°F), TOGW
Design Cruise	V = 296 km/min (160 kt) at MC, Dual Engines, 915 m (3,000 ft) ISA
CRP/TOP	1.15 at 305 m (1,000 ft), ISA + 15°C (27°F)
Reserve	40 km (25 SMI) Diversion Plus 30-minute Cruise at 296 km/h (160 kt)

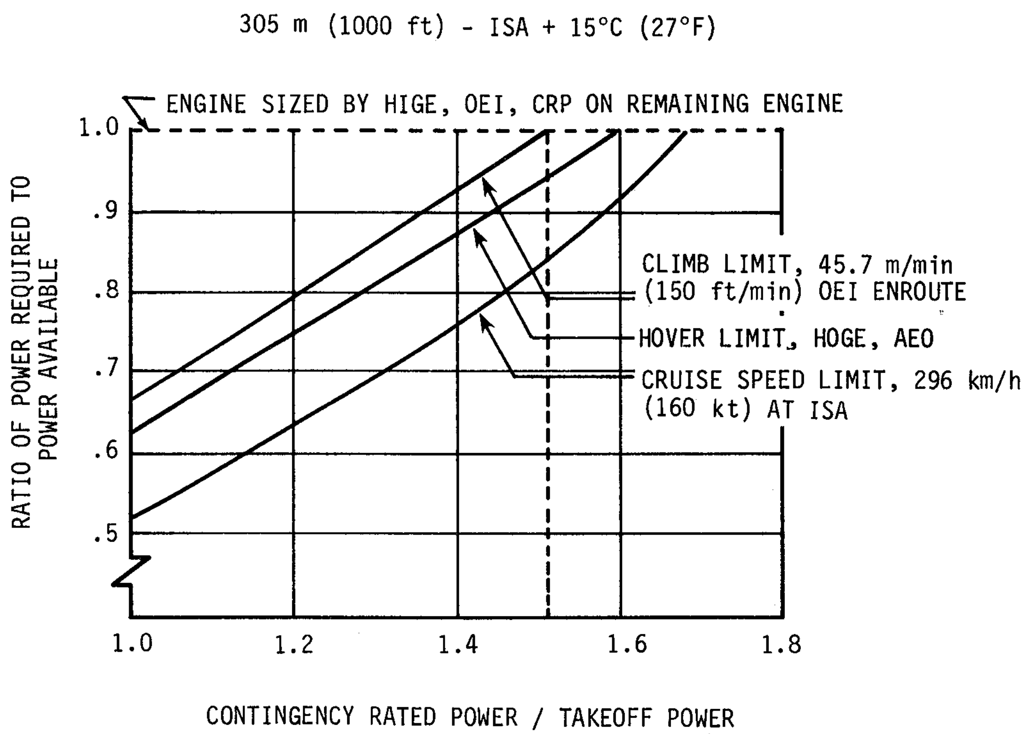


Figure 3. Rotorcraft Powerplant Sizing Trends - Civil Commuter.

BASELINE CIVIL MISSION - Continued

Baseline Civil Rotorcraft

The civil rotorcraft design that results from the design mission and sizing criteria is described in Table 4. This is the baseline vehicle designed around the baseline engines with a CRP/TOP ratio of 1.15 at the design condition of 305 m (1,000 ft) ISA + 15°C (27°F). (This ratio does not hold for SLS ISA uninstalled.) The exact magnitude associated with this baseline design is not as important as the fact that all the contingency concepts evaluated with different CRP/TOP ratios are consistent with it. All differences in engine weight, SFC, cost, maintainability, etc. are a result of achieving the different CRP/TOP ratio and not due to arbitrary changes in cycle or technology level.

TABLE 4. CIVIL COMMUTER AIRLINER BASELINE AIRCRAFT ATTRIBUTES

Gross Weight, kg (lb)	12,640 (27,860)
Payload, kg (lb)	2,720 (6,000)
Number of Engines	2
SLS Standard Day Engine kW (shp), Uninstalled	
Contingency Rated Power (CRP)	2,520 (3,380)
Takeoff Power (TOP)	2,300 (3,085)
Maximum Continuous (MC)	2,065 (2,770)
Engine Weight, kg (lb)/Engine	240 (530)
Fixed Operating Equipment Weight, kg (lb)	275 (605)
Fuel Weight, kg (lb)	1,215 (2,680)
Empty Weight, kg (lb)	8,425 (18,575)

Civil Economic Assumptions

The economic analysis was limited to the calculation of DOC and the impact on DOC of designing for different CRP/TOP ratios. As calculated the DOC was comprised of the following:

1. Flight Operations:

   a. Crew Costs.
   b. Fuel and Lube.
   c. Insurance.

BASELINE CIVIL MISSION - Continued

2. Maintenance:

   a. Labor on the airframe (less engine) including burden.
   b. Parts for the airframe.
   c. Overhaul allowance for the airframe.
   d. Engine parts (Total $/EFH).
   e. Engine Labor (Total $/EFH) including burden.

3. Depreciation:

   Total airframe plus engine including spares.

Table 5 lists the DOC assumptions.

TABLE 5. CIVIL COMMUTER AIRLINER DOC MODEL ASSUMPTIONS

1.	1983 Dollars
2.	Production 400 Units
3.	Development Cost Amortization into Vehicle Price
4.	Airframe Maintenance Burden, 1.5 x Direct Labor
5.	Engine Burden 2 x Direct Labor
6.	Insurance is 4% of Airliner Price
7.	Aircraft Spares 15%
8.	Engine Spares 30%
9.	Straight-Line Depreciation, 10 Years to 25% Residual
10.	Fuel $0.264/l ($1.00/gal)
11.	Maintenance Labor $15/hour
12.	Utilization 2,000 hours/year
13.	Crew Costs -- $35,000/year/pilot for Two Pilots (80 hours/month)
14.	Off-Design Mission, 65% Load Factor

BASELINE CIVIL MISSION - Continued

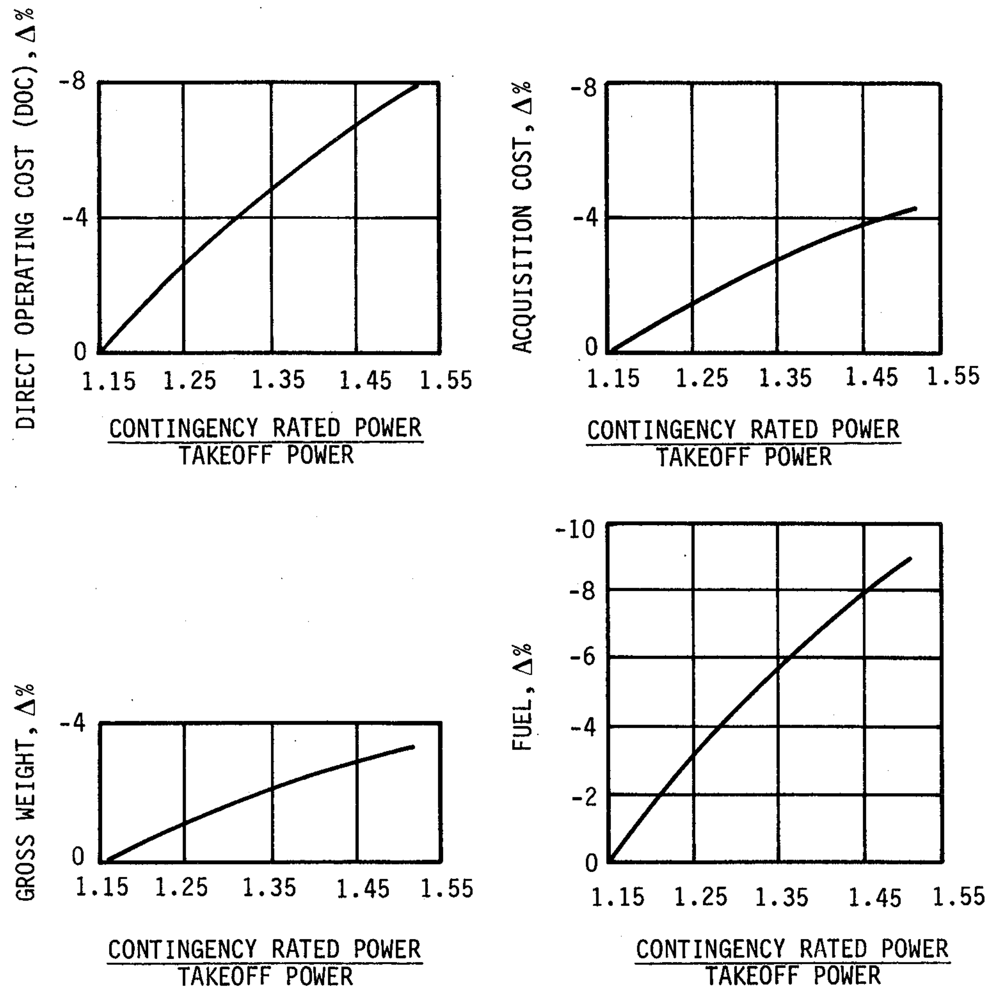
Trade Factors for Civil Application

Figure 4 provides the CRP/TOP trade factors and Table 6 the other trade factors used to judge the various alternative ways of providing high CRP/TOP ratios. These come from detailed studies where SA (Sikorsky Aircraft) resized the vehicle for independent changes in CRP/TOP ratio, SFC, and engine weight, one at a time and then recalculated the acquisition cost and DOC for each of these changes and for changes in engine price and maintenance cost.

TABLE 6. CIVIL MISSION TRADE FACTORS CONSTANT RANGE-PAYLOAD RUBBER ENGINE/RUBBER AIRCRAFT

	Delta Parameter	Gross Weight (%)	Fuel (%)	Engine Scale Factor (%)	Acquisition Cost (%)	DOC (%)
SFC	+1%	+0.22	+1.33	+.2	+0.16	+0.41
Engine System Weight	+1%	+0.12	+0.09	+.11	+0.13	+0.25
Engine System Cost	+10%	-	-	-	+1.2	+0.60
Engine System Maintenance Cost (Parts Only)	+10%	-	-	-	-	+0.48
Maintenance Cost (Parts & Labor)	+10%	-	-	-	-	+0.75

The method used to judge the various design alternatives for providing high CRP/TOP ratios consisted of comparing the alternative engine to the baseline, and summing the effects on DOC due to CRP/TOP ratio, SFC, etc. using the trade factors. This total sum yielded the DOC benefit due to CRP/TOP increases.



NOTE: A 1% change in DOC means ≈ \$25,000/yr/ac; means \$200 million total for a fleet of 400 aircraft operating for 20 yrs.

Figure 4. Civil Mission Trade Factors - Constant Range-Payload, (Rubber Engine/Rubber Aircraft).

BASELINE MILITARY MISSION

The military rotorcraft used in this study is a single rotor helicopter with tail rotor, designed for the USMC amphibian assault role. It is sized to carry 24 assault equipped troops a distance of 370 km (200 nmi) and then return empty, and it has a rear loading fuselage for carrying heavy equipment. Tactical surprise and timely support of emplaced combat units call for a relatively high cruise speed of 333 km/h (180 kt).

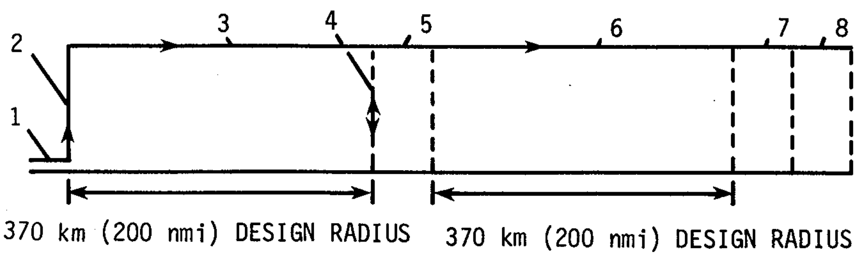
Figure 5 describes the design mission. It is based on the HXM Land Troop Assault Mission as recently defined for the JVX.

Table 7 is a tabulation of the typical mission distribution used to determine the fuel burned when calculating the LCC (life cycle cost). Sikorsky Aircraft has studied this application in detail in the past and therefore it was possible to use this rather elaborate mission distribution rather than a single representative off-design or peacetime mission.

TABLE 7. MILITARY ROTORCRAFT - OFF-DESIGN COMPOSITE MISSION FOR LCC MODEL

Mission	% Time in Composite
A. Terrain Following	5.2
B. Weapons Firing	1.8
C. Light Helicopter Assault Operations	5.0
D. Instrument Flight Rating (IFR) Training	6.6
E. External Cargo Training	6.2
F. Pilot Proficiency	8.0
G. Troop Transport	7.9
H. External Cargo Operations	37.6
I. Internal Cargo Operations	14.3
J. Maintenance	5.0
K. Ferry	2.4
	100.0

DESIGN PAYLOAD 2615 kg (5760 lb)



1. Warm-Up at 915 m (3000 ft), 33°C (91.5°F) for 2.0 minutes Engine Operation at Maximum Continuous Power (MCP) at Takeoff Gross Weight (TOGW).
2. Hover and Takeoff at 915 m (3000 ft), 33°C (91.5°F) for 1.0 minute.
3. Level Cruise at V = 333 km/h (180 kt), 915 m (3000 ft), 33°C (91.5°F), Distance 370 km (200 nmi).
4. Hover with Payload 2 minutes, Land and Discharge Payload. Takeoff and Hover without Payload 1 minute.
5. Maneuver Fuel Allotted; Equivalent 10 minutes Engine Operation at IRP.
6. Level Cruise at V = 333 km/h (180 kt), 915 m (3000 ft), 33°C (91.5°F), Distance 370 km (200 nmi) Back to Origin without Payload.
7. Hover without Payload 1 minute and Land.
8. Reserve Fuel for 30 minutes at V Best Endurance.

Figure 5. Military Utility/Transport Design Mission Definition.

BASELINE MILITARY MISSION - Continued

Military Rotorcraft Design Criteria

The design criteria are summarized in Table 8. The payload of 2,615 kg (5,760 lb) assumes 24 troops at 109 kg (240 lb) each. The mission with this payload is as described in Figure 5. The engine is sized by the most demanding of several criteria. Figure 6 illustrates how these criteria relate to one another. The requirement to HIGE with OEI at the design gross weight at 915 m (3,000 ft), 33°C (91.5°F) using the CRP rating sizes the engine until a CRP/IRP ratio is reached where another requirement takes over.

TABLE 8. MILITARY UTILITY/TRANSPORT - DESIGN CRITERIA

Aircraft	24 Troop Military Assault Transport
Aircraft Design	Latest HXM Marines Land Assault Mission
Crew	2 Pilots plus 2 Gunners
Design Range	370 km (200 nmi) Outbound with 24 Troops and Gear
Payload	24 Troops at 109 kg (240 lb), 2,615 kg (5,760 lb)
Takeoff	915 m (3,000 ft), 33°C (91.5°F) at ≤IRP at TOGW
Design Hover	HOGE at ≤95% IRP, Dual Engine, 915 m (3,000 ft) 33°C (91.5°F)
OEI Hover	HIGE, CRP on Remaining Engine, 915 m (3,000 ft), 33°C (91.5°F), TOGW
OEI Enroute	30.5 m/min (100 ft/min) Minimum ROC at ≤IRP on remaining Engine at speed for BROC (approx 148 km/h (80 kt), 915 m (3,000 ft), 33°C (91.5°F), TOGW
Design Cruise	V = 333 km/h (180 kt) at ≤MCP, Dual Engine, 915 m (3,000 ft), 33°C (91.5°F)
CRP/IRP	1.15
Fuel Consumption	SFC = 1.05 Engine SFC
Reserve	30 Minutes at Best Endurance 915 m (3,000 ft), 33°C (91.5°F)

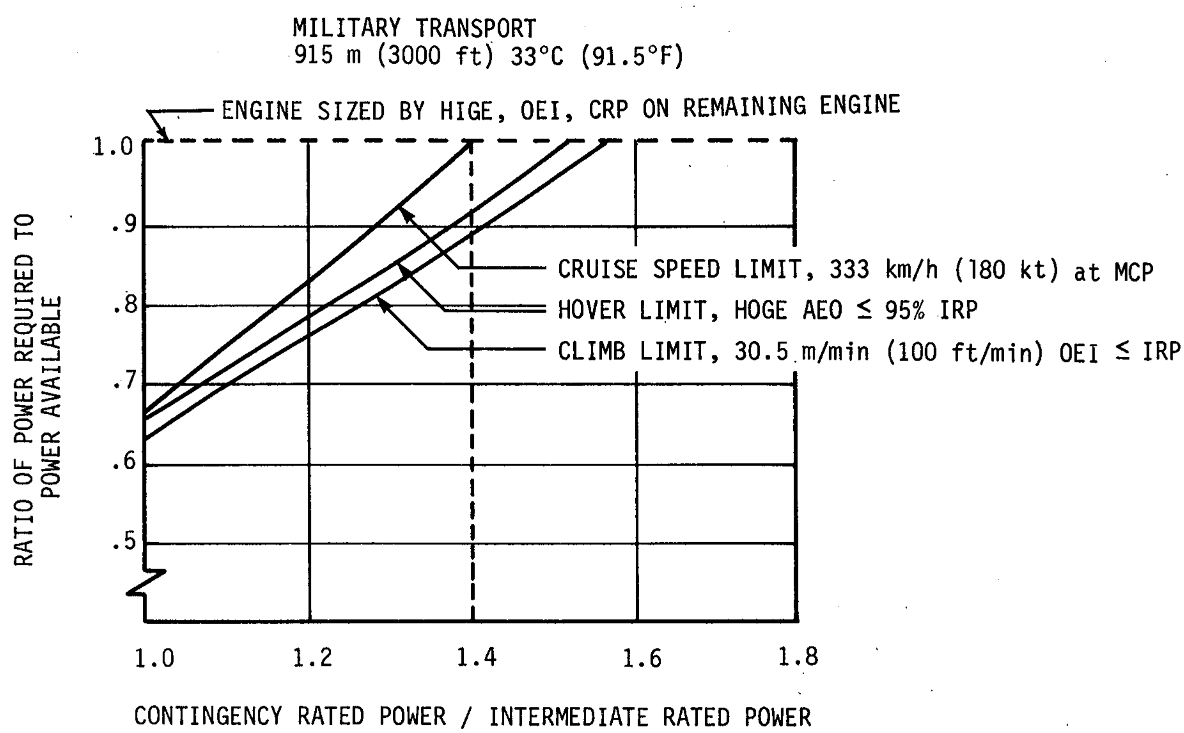


Figure 6. Rotorcraft Powerplant Sizing Trends.

BASELINE MILITARY MISSION - Continued

HIGE with OEI was selected by Sikorsky Aircraft as a requirement which results in the excess power margin desired by the Military to assure satisfactory OEI emergency land back performance. It is seen that it is the most demanding until a CRP/IRP ratio of 1.4 is provided. Above this point the power required to cruise at 333 km/hr (180 kt) sizes the engine. This is different than for the civil application where cruise speed was the least demanding of the engine sizing criteria. If design choices were made which removed or delayed cruise speed as an engine sizing consideration then AEO hover would become critical above a CRP/IRP of approximately 1.5 followed by the OEI enroute climb requirement.

Baseline Military Rotorcraft

The military rotorcraft design that results consistant with the design mission and sizing criteria is described in Table 9. This is the baseline vehicle designed around the baseline engines with a CRP/IRP ratio of 1.15 (installed) at the design condition of 915 m (3,000 ft), 33°C (91.5°F). (As with the civil application it is seen that this ratio does not hold for SLS ISA uninstalled.) All the alternative engine designs with their different approaches to achieving higher CRP/IRP ratios were used to power alternate vehicles which satisfied the same design mission and design criteria. They were then judged against this baseline design.

TABLE 9. MILITARY UTILITY TRANSPORT BASELINE AIRCRAFT ATTRIBUTES

Gross Weight, kg (lb)	16,490 (36,360)
Payload, kg (lb)	2,615 (5,760)
Number of Engines	2
SLS Standard Engine kW (shp), Uninstalled	
Contingency Rated Power (CRP)	4,090 (5,485)
Intermediate Rated Power (IRP)	3,755 (5,035)
Maximum Continuous (MC)	3,405 (4,565)
Engine Weight, kg (lb)/Engine	340 (745)
Fixed Operating Equipment Weight, kg (lb)	805 (1,775)
Fuel Weight, kg (lb)	2,750 (6,065)
Empty Weight, kg (lb)	10,325 (22,760)

BASELINE MILITARY MISSION - Continued

Military Economic Assumptions

The military designs were judged on the basis of their total LCC. Table 10 lists the basic assumptions. The unit costs are based on a production run of 400 vehicles. The Sikorsky Aircraft computerized HDM (Helicopter Design Model) calculates the LCC as a subroutine. This is a top-level LCC model using parametric cost equations which provide costs as a function of component weights, installed power, major subsystem mean time between removal and mission fuel. It includes all aspects of expenditure accountable to the program including development, production, operating, support, prime contractor and government expenses. Table 11 provides a complete listing of all the elements of the LCC model.

TABLE 10. MILITARY TRANSPORT - LCC MODEL ASSUMPTIONS
1. 1983 Dollars
2. Production 400 Units
3. Force Structure - HXM LCC Model
4. Fuel \$0.264/l (\$1.00/gal), 2% Spillage
5. Utilization 360 hours/year Nominal Value
6. 20-Year Life Cycle

Trade Factors for Military Application

The design sensitivities provided by Sikorksy Aircraft for rubber engine/rubber aircraft assumptions were used to generate the trade factors shown in Figure 7 and Table 12. These are the result of detailed studies wherein the vehicles were resized for independent changes in CRP/IRP ratio, SFC and engine weight and the total LCC calculated for each change as well as for changes in engine cost and engine maintenance cost.

The trade factors were used to judge the various alternative ways of providing high CRP/IRP ratios by summing all the effects on the LCC to arrive at a net benefit for each design approach.

TABLE 11. LIFE CYCLE COST - MILITARY MODEL

Development Cost (RDTE)	Acquisition Cost	Operating Cost Over 20 Years
		UNIT OPERATING COST (360 FLIGHT
NON-RECURRING COSTS	UNIT ACQUISITION COST	HOURS/YEAR)
Airframe RDTE	Non-Recurring Cost	Deployed Unit Operations
Engine RDTE	Airframe Tooling	Personnel
Avionics RDTE	Engine Tooling	Officers
Mission Equipment RDTE		Enlisted Men
Ground Test Vehicle	Recurring Cost	Operating Consumables
Static Test Article	Airframe	POL
GSE RDTE	Engines	O&I Consumables
	Avionics	
RECURRING COST (3 PROTOTYPES)	Mission Equipment	Depot Rework
		Airframe (Scheduled)
Airframe Cost/Aircraft	Flyaway Cost	Engine (Scheduled)
Engine Cost/Aircraft		Component
Avionics Cost/Aircraft	SUPPORT COST	Airframe
Mission Equipment/Aircraft		Dynamic System
Recurring Cost/Aircraft	Spares	Engine
	Airframe	Avionics
SUPPORT COST	Engine	Second Destination Transportation
	Avionics	Sustaining Investment
Customer Program Cost	GSE Cost	Replenishment Spares
Training and Data Cost	Initial Training	Airframe
GSE Cost	Training and Data	Dynamic System
Initial Spares	Customer Programming Cost	Engine
Airframe		Avionics
Engines	FIRST DESTINATION TRANSPORTATION	Engr Technical Supt
Avionics		Modifications
		Publication Updates
		Training Ordinance
		INDIRECT COSTS

BASELINE MILITARY MISSION - Continued

TABLE 12. MISSION TRADE FACTORS CONSTANT RANGE-PAYLOAD (RUBBER ENGINE/RUBBER AIRCRAFT)

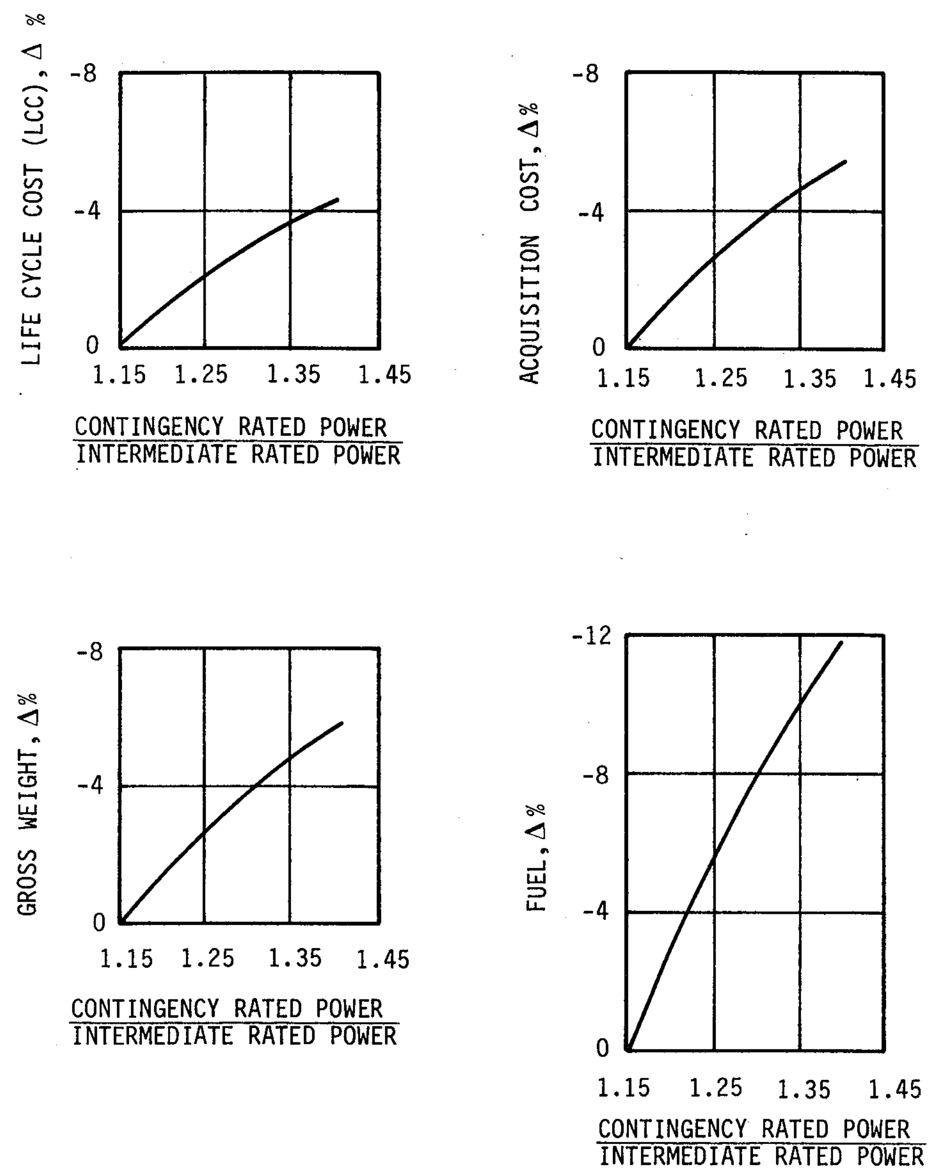
	MILITARY					
	Delta Parameter (%)	Gross Weight (%)	Fuel (%)	Scale Factor (%)	Acquisition Cost (%)	LCC (%)
SFC	+1%	+0.54	+1.53	+.87	+0.40	+0.39
Engine System Weight	+1%	+0.19	+0.20	+.30	+0.17	+0.13
Engine System Cost	+10%	-	-	-	+1.38	+0.57
Engine System Maintenance Cost	+10%	-	-	-	-	0.11

TASK I SUMMARY

- Each alternative method of providing different levels of Contingency Power was judged in terms of its impact on vehicle size, cost, fuel burned and total economics using the trade factors.
- All penalties (or improvements) that exist as a result of providing Contingency Power were judged for their impact.
- The net impact, or benefit, was found for each method of providing different levels of Contingency Power.

Evaluation Criteria

The primary and secondary criteria used to judge the novel concepts are listed in Table 13. Including the secondary factors did not modify the results of the evaluation based solely on DOC and LCC.



NOTE: A 1% change in LCC means ≈ $100 million total for a fleet of 400 aircraft operating for 20 years.

Figure 7. Military Mission Trade Factors - Constant Range-Payload, (Rubber Engine/Rubber Aircraft).

TABLE 13. EVALUATION CRITERIA

	Civil	Military
PRIMARY	DOC For Off-Design Missions	LCC For Off-Design Missions
SECONDARY	Fuel Burned	Fuel Burned
	Propulsion System Size	Propulsion System Size
	Gross Weight	Gross Weight
	Empty Weight	Empty Weight
	Acquisition Cost	Acquisition Cost
	Reliability	Reliability
	Logistics and Special Maintenance	Logistics and Special Maintenance

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TASK II

BASELINE PROPULSION SYSTEM DEFINITION

TASK II - BASELINE PROPULSION SYSTEM DEFINITION

CIVIL APPLICATION

Baseline Engine

The same baseline turboshaft engine is used for both the civil application and the military application, scaled and rated as described below. The compressor is a single rotor axial-centrifugal design in the 20:1 pressure ratio class. The engine has an annular combustor, two stage cooled high-pressure turbine, three stage low-pressure turbine and integral inlet particle separator. The technology level is consistent with entry into service in the late 1980's. A cross section is shown in Figure 8.

Sizing Procedure and Performance

The civil engine was matched in an identical manner as the military engine (see Military Application Sizing Procedure and Performance section, pg 31) but the turbine rating temperature was set lower by 56°C (100°F) at 1315°C (2400°F) which reflects the need for greater mission life. The critical power sizing condition for the engine is determined by hover in ground effect (HIGE) with one engine inoperative (OEI) at 305 m (1,000 ft) altitude, 28°C (82.4°F) ambient temperature [ISA + 15°C (27°F)].

The baseline engine included conventional Contingency Rated Power (CRP) of +15% over Takeoff Power (TOP) at this design condition. This resulted in 2,005 kW (2,690 hp) at TOP. Table 14 summarizes these data and Figure 9 shows the TOP point at the design condition on the compressor map in relation to the compressor aero design point. The thermodynamic cycle of this baseline engine was not compromised in an effort to provide +15% increase in power at CRP; that is, compressor physical speed or turbine inlet temperature were not arbitrarily reduced at non-CRP conditions. The turbine cooling air was adjusted to be consistent with engine life requirements and the mission which also includes some use of Contingency Power. Table 14 shows an increase of 25°C (45°F) in compressor discharge temperature (T_3) and 78°C (140°F) in turbine rotor inlet temperature (T_{41}) between TOP and CRP. Additionally, the rotor speed (NH) increased +1.5%. All of these effects are accounted for in the engine design.

Life Analysis

Life usage for the components studied was estimated for both a certification test and a composite mission. The test conditions were based on FAA requirements with 25 cycles each of 6 hours duration. Contingency Power is reached twice during each cycle to give a total test time at Contingency Power of 125 minutes. The power levels for the test cycle for the baseline engine are shown in Figure 10.

The mission consists of a combination of commuter and training segments. The total mission life taken was 20,000 hours, with 500 hours being allocated to training flights. The separate revenue and training mission are shown for the baseline engine in Figure 11. Only one 2-1/2 minute Contingency Power operation was considered for the total revenue part of the mission, while it was assumed that Contingency power was reached for 30 seconds once in each of 1,050 training flights, giving a total time at Contingency Power of approximately 9 hours for the composite mission. Sikorsky Aircraft supplied the estimates for these missions based on actual in-service experience with civil operators.

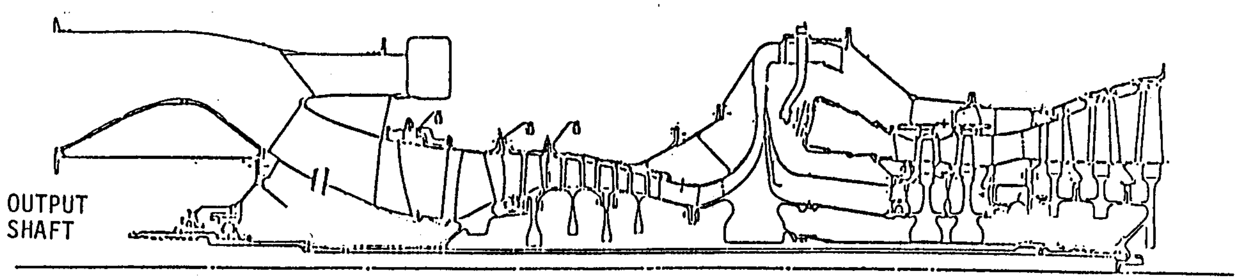

Figure 8. Rotorcraft Contingency Power Study - Baseline Engine.

TABLE 14. BASELINE ENGINE CYCLE - CIVIL APPLICATION

Alt/Mach/Temperature	315m/0/28°C (1K/0/82.4°F)	----
Rating	TOP	CRP
Contingency Rated Power to Takeoff Power Ratio (CRP/TOP)	----	1.15
Shaft Horsepower (SHP), kW (hp)	2,005 (2,690)	2,310 (3,095)
100% Airflow (W_{2R}), kg/s, (lbm/sec)	6.76 (14.9)	----
Compressor Discharge Pressure Ratio (P_3/P_2) design	20:1 class	----
Turbine Inlet Temperature (T_{41}), °C(°F)	1,315 (2,400)	1,395 (2,540)
Compressor Discharge Temperature (T_3), °C(°F)	770 (1,420)	795 (1,465)
Rotor Speed (NH), %	101.7	103.2

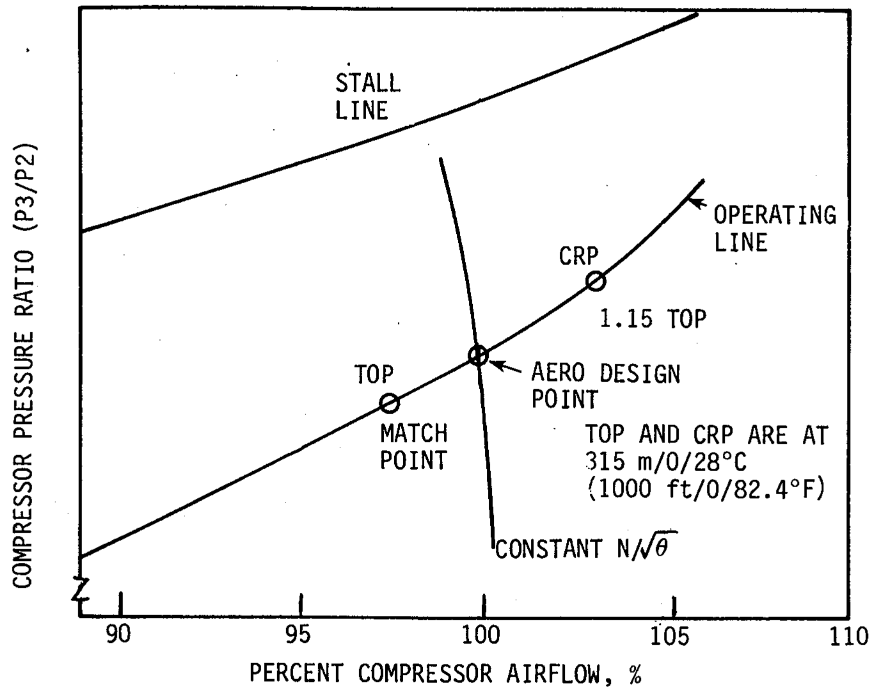

Figure 9. Baseline Engine - Civil Application.

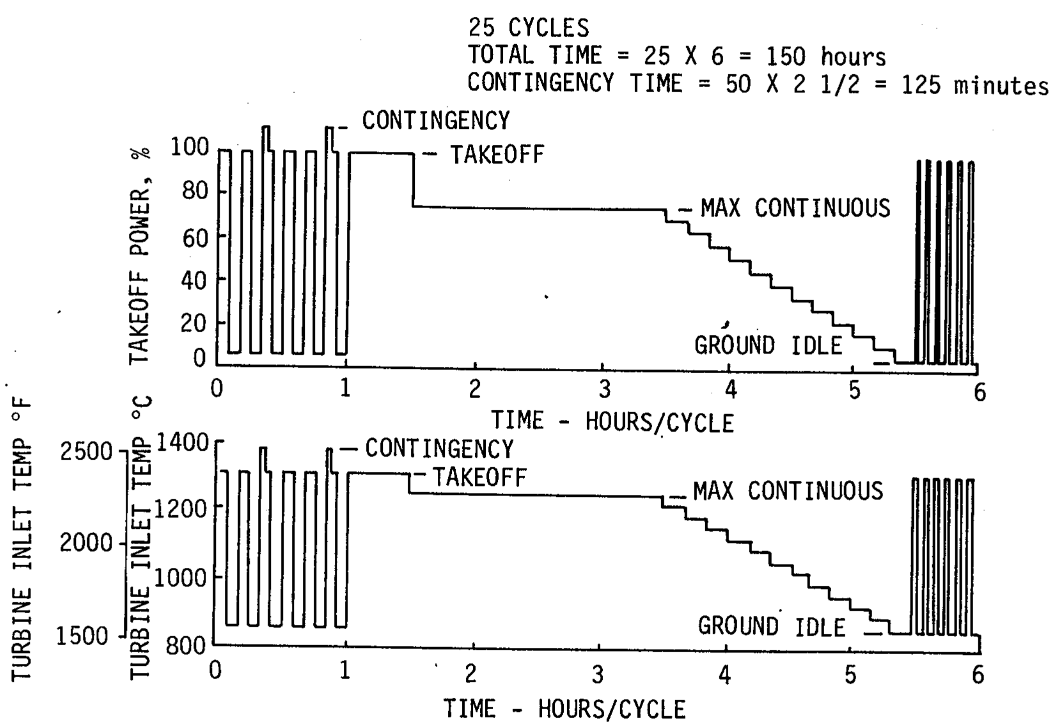

Figure 10. Civil Certification Test (FAA).

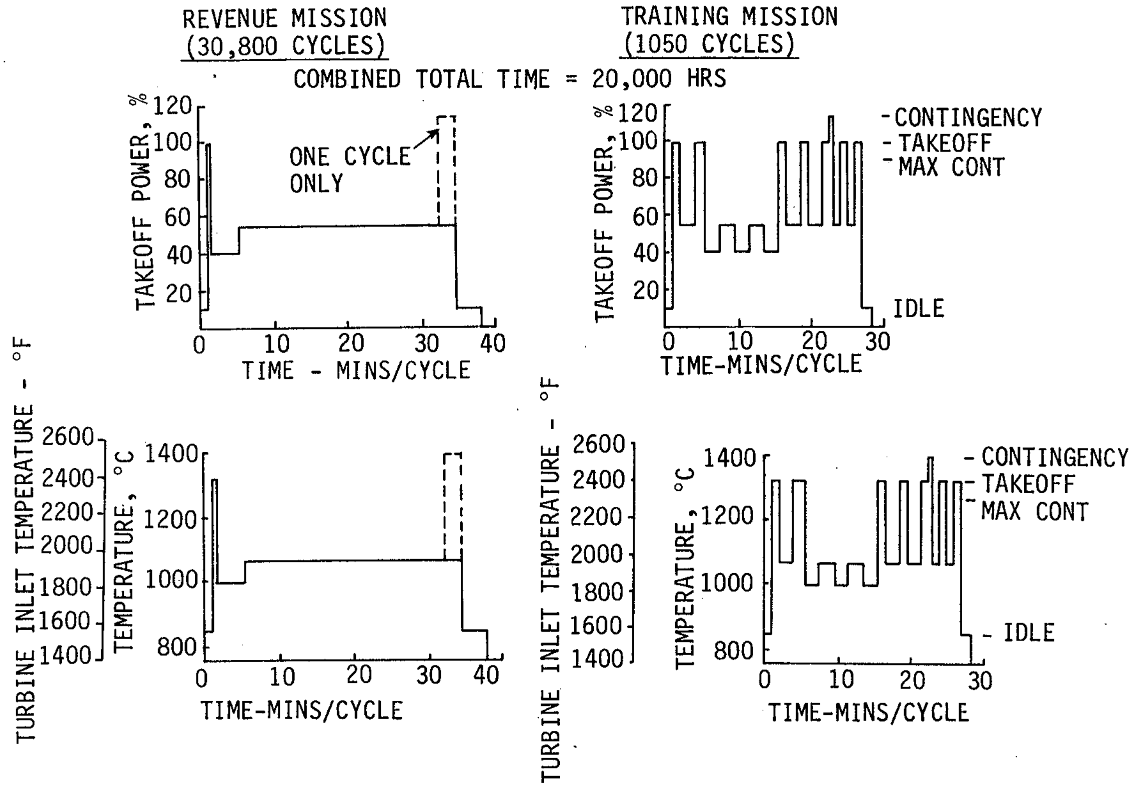

Figure 11. Civil Duty Cycle.

CIVIL APPLICATION - Continued

The distributions of power usage for the baseline engine used in the life analysis for the endurance test and mission are shown in Table 15.

TABLE 15. POWER USAGE FOR CIVIL ENDURANCE TEST AND MISSION

Endurance Test - 150 hours		Mission - 20,000 hours	
Power	% Usage	Power	% Usage
Contingency Rated Power (CRP)	1.39	CRP	0.045
Takeoff Power (TOP)	16.11	TOP	1.101
Max Continuous (MC)	33.33	60% MC	31.909
83% Takeoff Power (TOP)	2.78	60% MC	66.945
76% Takeoff Power (TOP)	2.78		
69% Takeoff Power (TOP)	2.78		
65% Takeoff Power (TOP)	40.83		

For the engine components considered, creep rupture life was important in the cases of the high-pressure turbine first and second stage rotor airfoils and the second stage disk root fixing posts, and also the low-pressure turbine first stage rotor airfoil.

CIVIL APPLICATION - Continued

Life usage curves were obtained from component material properties and the stress levels at the locations considered. Calculated metal temperatures determined percentages of life used from these curves. The maximum life usage is at the trailing edge of the 70% span of the first stage high-pressure turbine rotor airfoil. At this point, 100% of the design life is used in the mission, while only 16.3% is used in the test. A breakdown of life usage is shown in Table 16.

TABLE 16. LIFE USAGE SUMMARY - BASELINE CIVIL ENGINE (High-Pressure Turbine Stage 1 Blade)

Condition	Test	Mission
Contingency Rated Power (CRP)	3.87	16.90
Takeoff Power (TOP)	8.23	76.20
Maximum Continuous (MC)	4.24	----
Part Power 1	----	3.37
Part Power 2	----	3.53
Total Life Used (%)	16.34	100.0
Total Hours	150	20,000

Weight, Price, and Maintenance

The weight breakdown for the civil engine is shown in Table 17. A nominal price of $581,000 was established for use in this study.

TABLE 17. WEIGHT BREAKDOWN - CIVIL ENGINE

Component	Weight kg	(lb)
Compressor	45.5	(100.3)
Combustor	10.6	(23.4)
High Pressure Turbine	25.1	(55.3)
Low Pressure Turbine	39.2	(86.5)
Frames, Sumps and Drives, Shafts	44.1	(97.0)
Controls and Accessories, Accessory Gearbox	62.5	(137.5)
Total	227.0	(500.0)

The maintenance costs were defined as follows:

Maintenance parts cost = (.054 x price)/1000 = 31.38 $/EFH
Maintenance labor cost = 15.00 $/HR + 200% burden = 45.00 $/HR
Total maintenance cost = 76.38 $/EFH.

Scaling Data

Weight and price scaling curves for the baseline civil engine are shown in Figures 12 and 13 respectively. The maintenance parts cost scaling curve is shown in Figure 14.

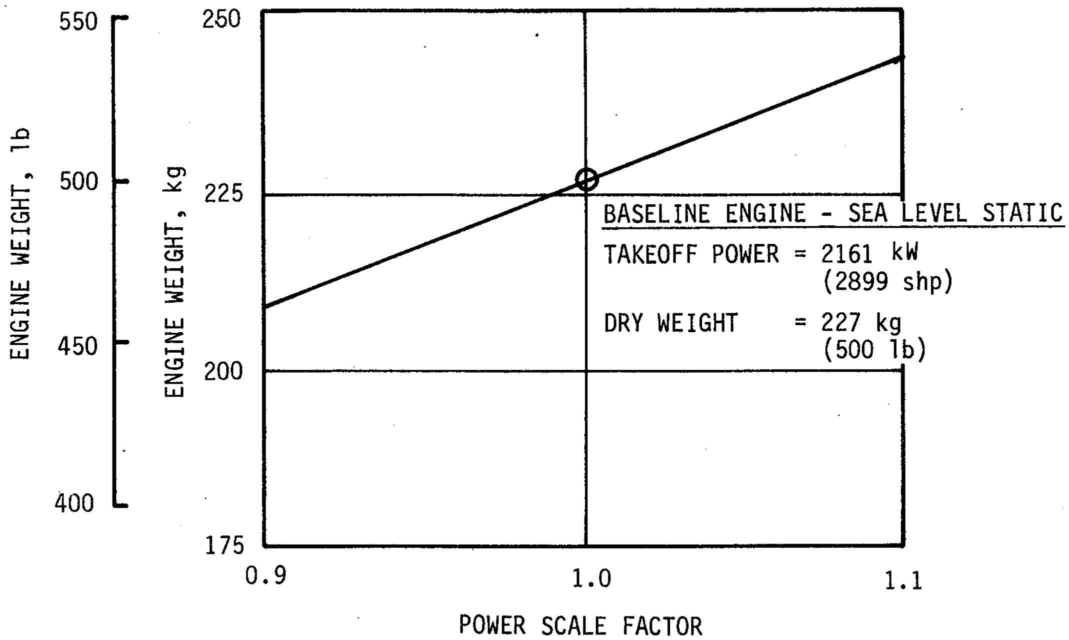

Figure 12. Weight Scaling Curves - Civil Engine.

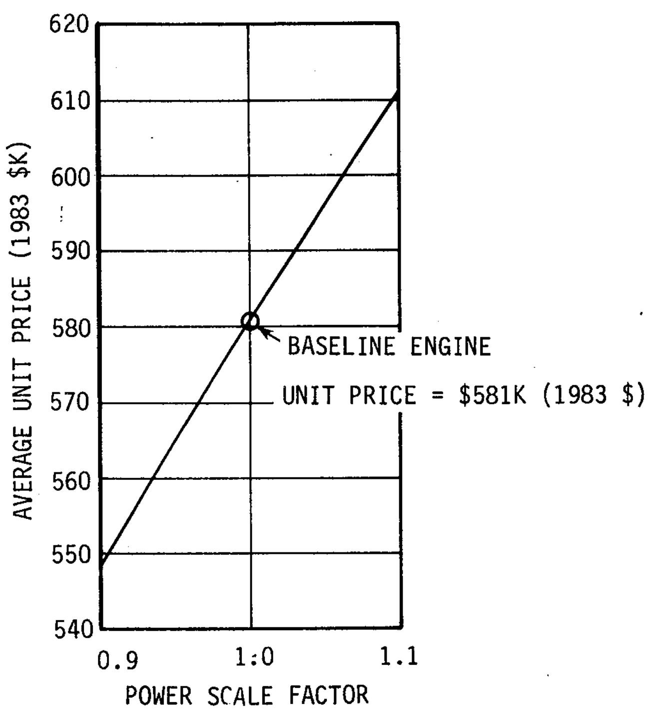

Figure 13. Civil Engine - Production Engine Average Unit Price.

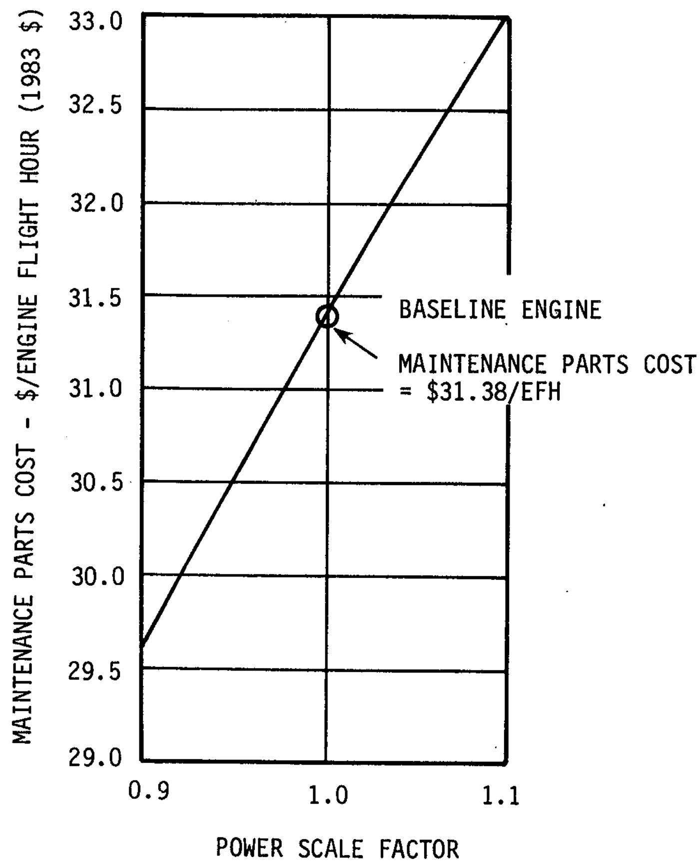

Figure 14. Civil Engine Maintenance Parts Cost.

MILITARY APPLICATION

Baseline Engine

The baseline turboshaft engine for the military application utilizes the same configuration as the engine for the civil application. The late 1980's technology level is the same but the life requirements are reduced to 7200 hours over 20 years. This reduced life requirement permits operation at 1,371°C (2,500°F) at IRP versus 1,315°C (2,400°F) at TOP for the civil engine. The engine cross section is shown in Figure 8.

Sizing Procedure and Performance

The requirements for the military rotorcraft design (wartime) mission plus eleven detailed peacetime missions provided the requirements necessary to optimize the engine cycle. This was accomplished in the Advanced Technology Engine Study[1]. The critical power sizing condition for the engine is determined by hover in ground effect (HIGE) with one engine inoperative at 915 m (3,000 ft) altitude, 33°C (91.5°F) ambient temperature (hot day). The baseline engine included conventional Contingency Rated Power of +15% over Intermediate Rated Power (IRP) at this design condition. This resulted in 2,940 kW (3,940 hp) at IRP. Table 18 summarizes these data and Figure 15 shows the IRP point at the design condition on the compressor map in relation to the compressor aero design point.

TABLE 18. BASELINE ENGINE CYCLE MILITARY APPLICATION
915 m/0/33°C (3,000 ft/0/91.5°F)

Rating	IRP	CRP
Contingency Rated Power to Intermediate Rated Power Ratio (CRP/IRP)	---	1.15
Shaft Horsepower (SHP), kW (hp)	2,940 (3,940)	3,380 (4,530)
100% Airflow (W_{2R}), kg/s (lbm/s)	10.2 (22.4)	---
Compressor Discharge Pressure Rates (P_3/P_2) design	20:1 class	---
Turbine Inlet Temperature (T_{41}), °C(°F)	1,370 (2,500)	1,445 (2,635)
Compressor Discharge Temperature (T_3), °C (°F)	775 (1,430)	800 (1,475)
Rotor Speed (NH), %	102.2	103.3

1. Brahm, D.A., Sewell, J.R., and Willis, W.S., ADVANCE TECHNOLOGY ENGINE STUDY, Technical Information Series report R82AEG353, General Electric Co., Aircraft Engine Business Group, NASA Contract No. N00019-80-C-02227, Final Report, July 1982.

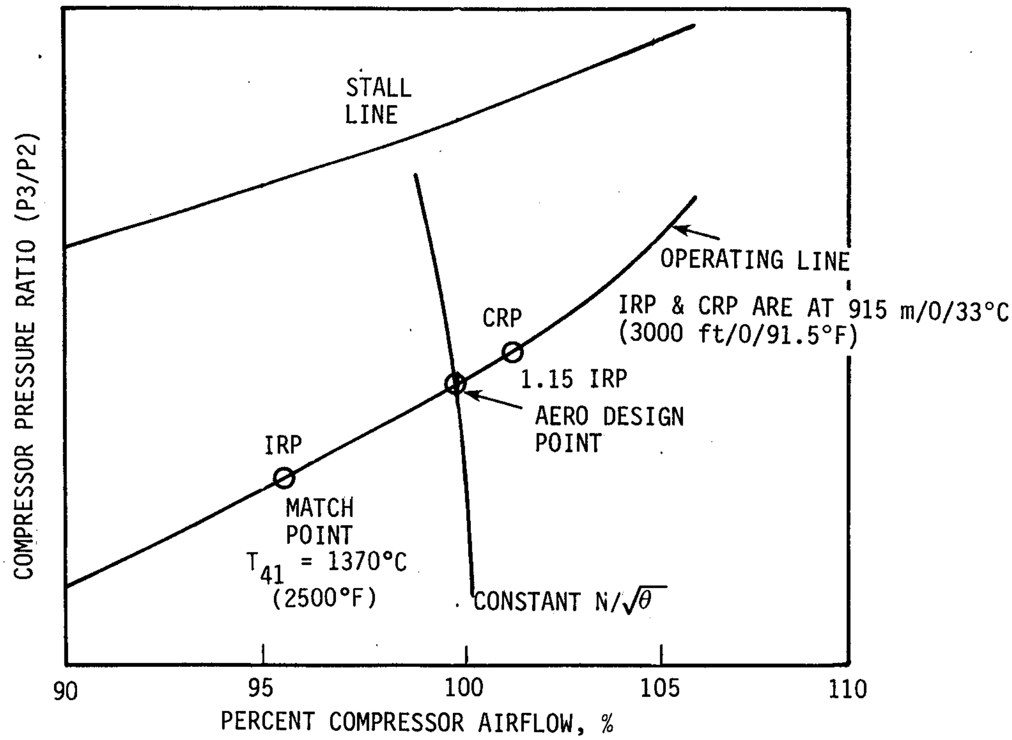

Figure 15. Baseline Engine - Military Application.

TASK II - BASELINE PROPULSION SYSTEM DEFINITION - Continued

MILITARY APPLICATION - Continued

Sizing Procedure and Performance - Continued

The cycle was selected for the missions without regard to CRP. However, turbine cooling air was adjusted to provide consistency with engine life requirements and the mission which includes some use of Contingency power. Table 18 shows an increase of 23°C (42°F) in compressor discharge temperature (T_3) and 75°C (135°F) in turbine rotor inlet temperature (T_{41}) between IRP and CRP. Additionally, the rotor speed (NH) increased +1.1%. All of these effects are accounted for in the engine design.

Although the baseline engines provide a 15% increase in power at the design condition, this power increase diminishes as compressor inlet temperature decreases. Figure 16 shows this effect and that the absolute level of power for both IRP and CRP increase with decreasing temperature but the rate of increase is slower at CRP. This trend is also true for the engine in the civil application. This effect is due to migration of the IRP point on the compressor map to higher corrected speed, as compressor inlet temperature decreases (see Figure 15).

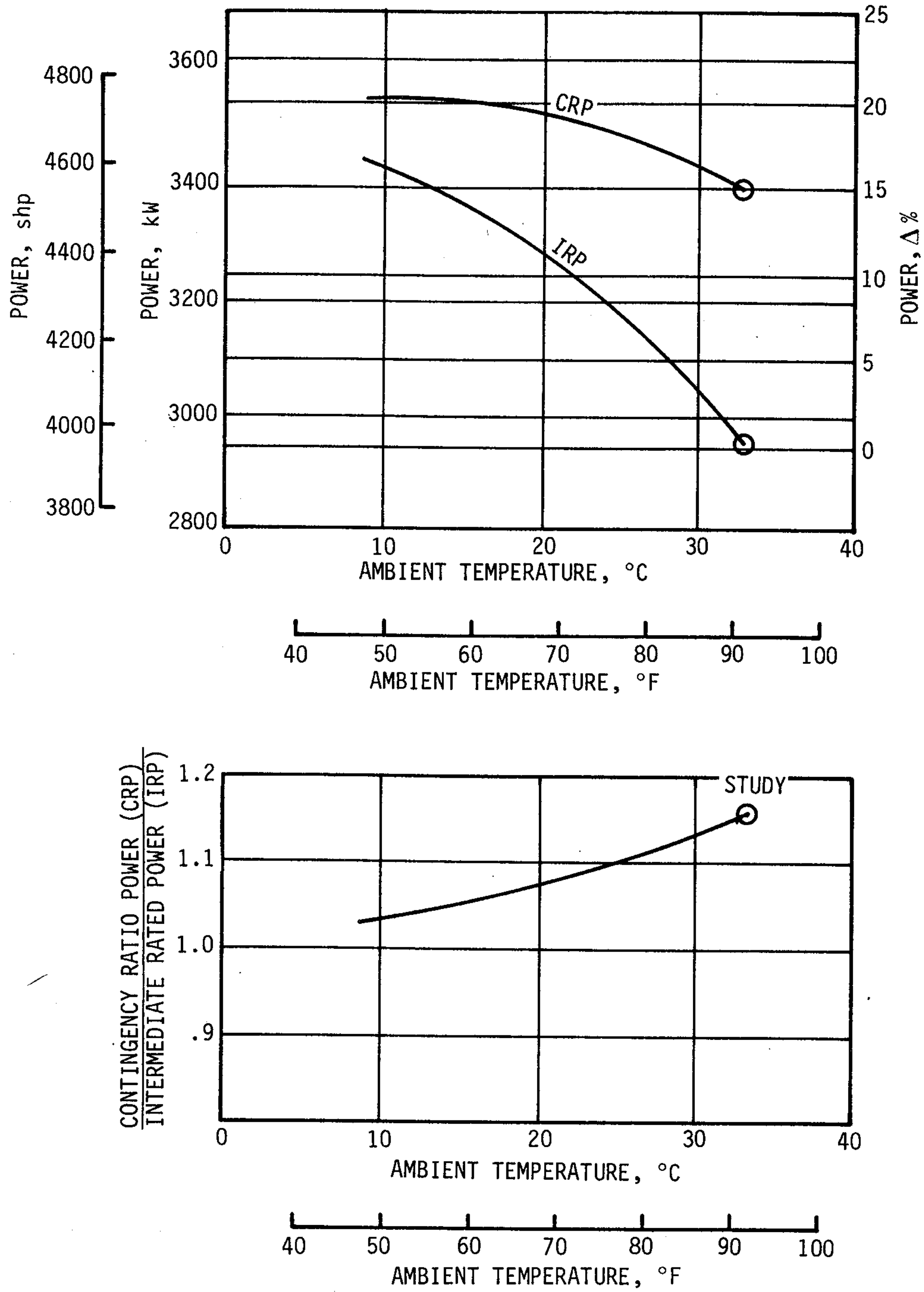

Figure 16. CRP/IRP Ambient Temperature Trends - Baseline Military Engine.

MILITARY APPLICATION - Continued

Life Analysis

Life usage for the components studied was estimated for both a qualification test and a composite mission. The test conditions were based on the T700-400 (LAMPS) engine test requirements, which were thought to be realistic for this application in the absence of any stipulated test. The 300 hour test consists of fifty cycles during four of which contingency power is reached, giving a total time at contingency of 10 minutes. The baseline engine power levels for the test cycle are shown in Figure 17.

The mission considered is the weighted average of eleven typical missions for various usages supplied by Sikorsky Aircraft. A graphical representation of the composite mission is shown in Figure 18. Contingency power is activated during pilot proficiency training, and is used four times on each of 36 flights giving a total time at contingency power of approximately 45 minutes. The total mission life over 20 years is 7,200 hours.

The distributions of power usage for the baseline engine used in the life analysis for the qualification test and mission are shown in Table 19.

For the engine components considered, creep rupture life was important in the high-pressure turbine first and second stage rotor airfoils and the second stage disk posts, and also the low pressure turbine first stage rotor airfoil.

Life usage curves were obtained from component material properties and the stress levels at the locations considered. Calculated metal temperatures determined percentages of life used from these curves.

TABLE 19. POWER USAGE FOR MILITARY ENGINE QUALIFICATION TEST AND MISSION

Qualification Test - 300 Hours		Mission - 7200 Hours	
Power	% Usage	Power	% Usage
Contingency (CRP)	0.056	CRP	0.01
Intermediate (IRP)	50.22	IRP	0.16
Maximum Continuous	18.61	85% IRP	0.46
80% Intermediate Rated Power (IRP)	4.44	80% IRP	0.32
65% Intermediate Rated Power (IRP)	26.67	75% IRP	10.43
		70% IRP	1.32
		65% IRP	5.87
		<60% IRP	81.43

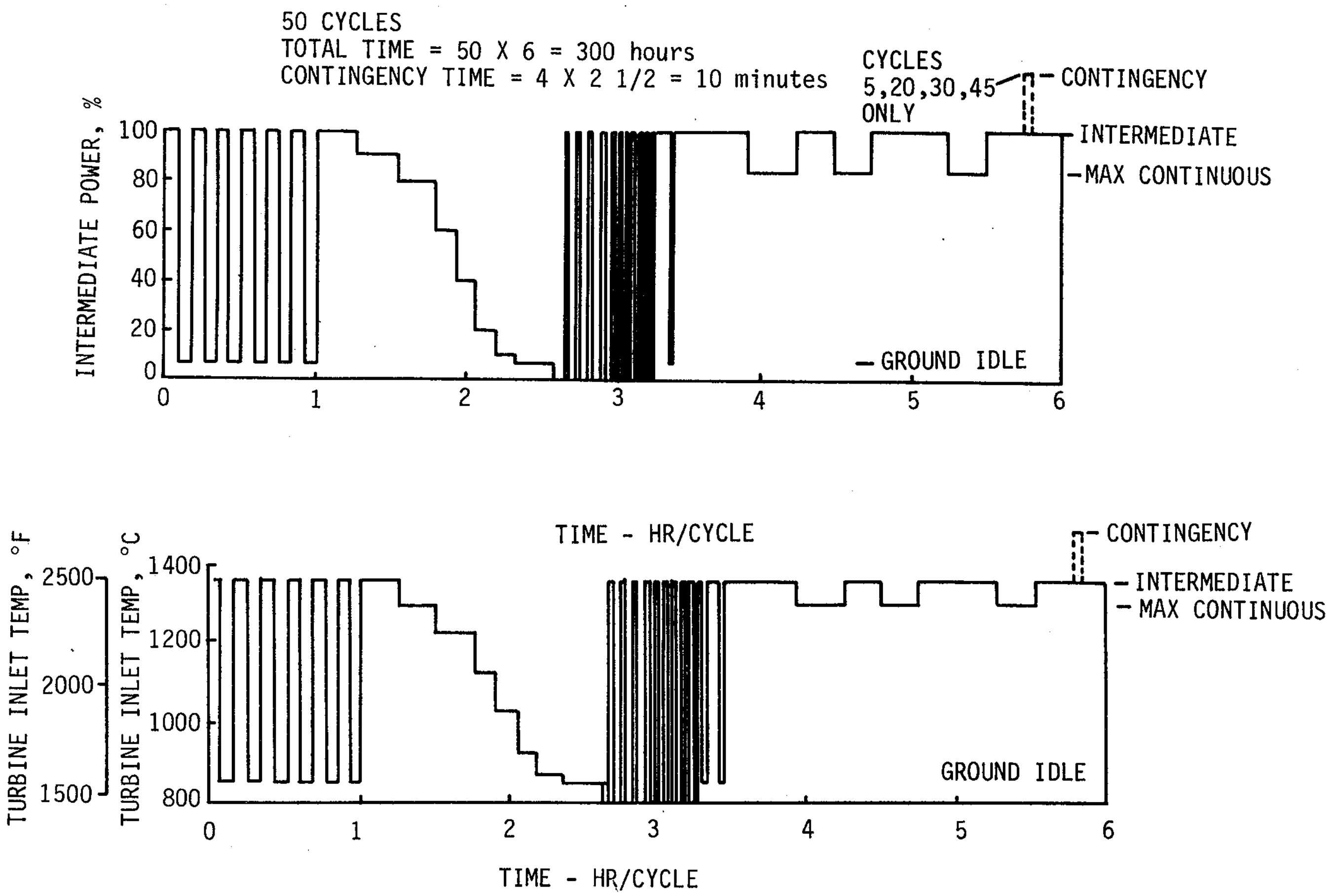

Figure 17. Military Qualification Test.

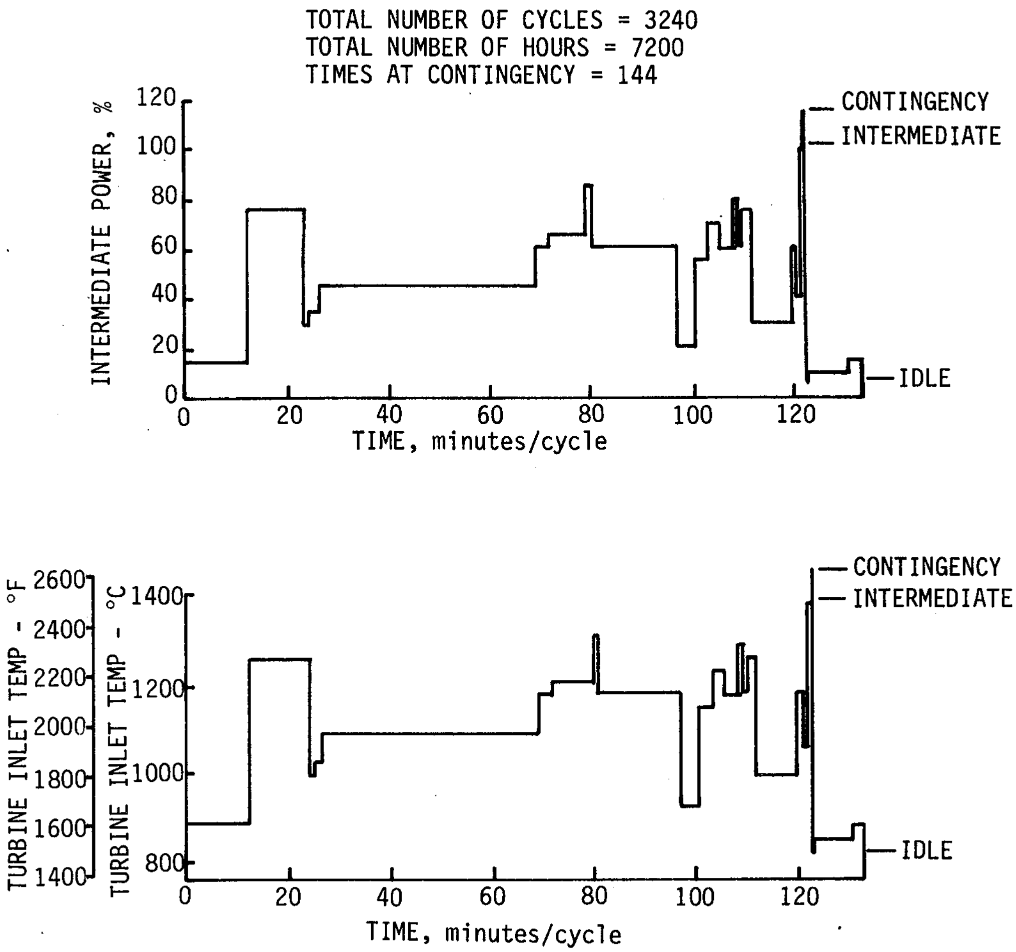

Figure 18. Military Composite Duty Cycle.

MILITARY APPLICATION - Continued

The maximum life usage is at the trailing edge of the 70% span of the first stage high-pressure turbine rotor airfoil. At this point, 100% of the design life is used in the qualification test, while only 28.6% is used in the mission. A breakdown of life usage is shown in Table 20.

TABLE 20. LIFE USAGE - BASELINE MILITARY ENGINE (High-Pressure Turbine Stage 1 Blade)

Condition	Test	Mission
Contingency Rated Power	0.56	2.37
Intermediate Rated Power	88.09	7.05
Maximum Continuous	11.35	----
Part Power 1	----	1.86
Part Power 2	----	0.59
Part Power 3	----	10.59
Part Power 4	----	0.77
Part Power 5	----	5.33
Total Life Used (%)	100.0	28.56
Total Hours	300	7,200

The life of the military engine is determined by the high-pressure turbine first stage blade life in the qualification test, which is much more demanding than the operational requirement assumed, and where Contingency power operation is only considered with one engine inoperative. It has been suggested that Contingency Rated Power could also be used on rare occasions with both engines operating for emergency overload, maneuver, or extreme ambient conditions. For the throttle push case for an engine with a Contingency Power Ratio of 1.15 and contingency operation of 2-1/2 minutes duration, life analysis shows that during the mission the engine could be taken to CRP 550 times and not exceed the life usage set by the qualification test.

Weight, Price, and Maintenance

The weight breakdown for the military engine is shown in Table 21. The nominal price was established at $555,000 for use in this study.

The depot overhaul maintenance costs were defined as follows:

Maintenance parts cost = (.03 x price)/1000 = 16.65 $/EFH
Maintenance labor cost = .12 x 30 $/HR = 3.6 $/EFH
Total depot overhaul maintenance cost = 20.25 $/EFH

MILITARY APPLICATION - Continued

Scaling Data

Weight and price scaling curves for the baseline military engine are shown in Figures 19 and 20 respectively. The depot overhaul cost scaling curve is shown in Figure 21.

TABLE 21. WEIGHT BREAKDOWN - MILITARY ENGINE

Component	Weight	
	kg	(lb)
Compressor	64.5	(142.3)
Combustor	14.3	(31.7)
High Pressure Turbine	33.8	(74.6)
Low Pressure Turbine	55.5	(122.5)
Frames, Sumps + Drives, Shafts	55.4	(122.2)
Controls + Accessories, Accessory Gearbox	66.5	(146.7)
Total	290.0	(640.0)

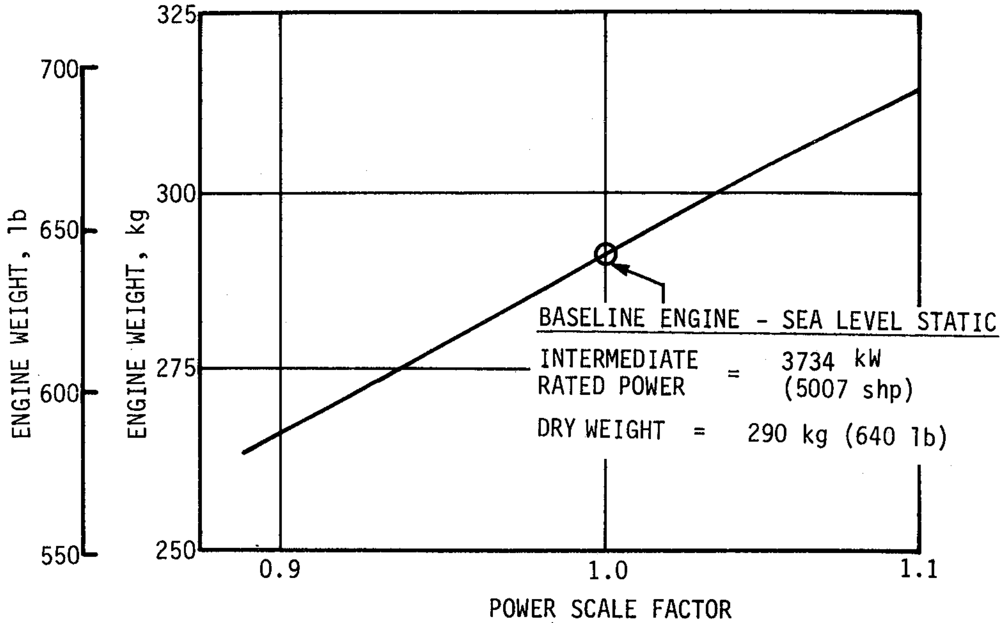

Figure 19. Weight Scaling Curves - Military Engine.

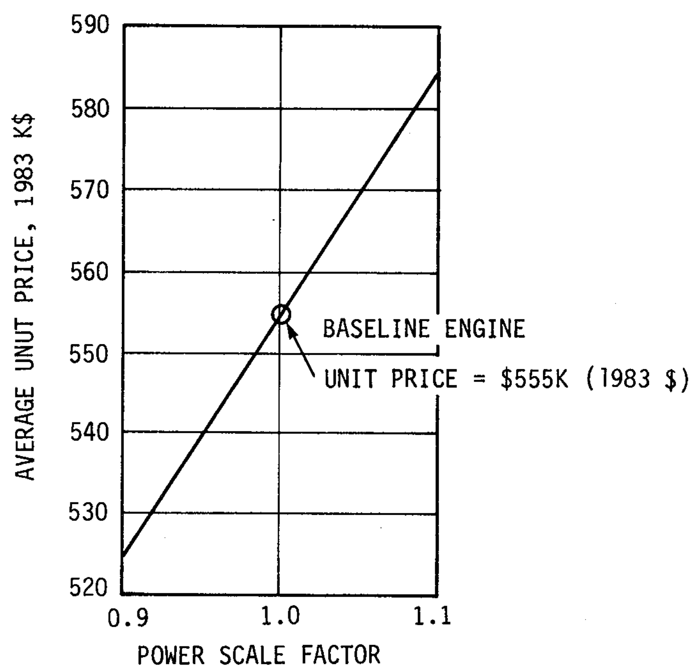

Figure 20. Production Engine Average Unit Price - Military Engine.

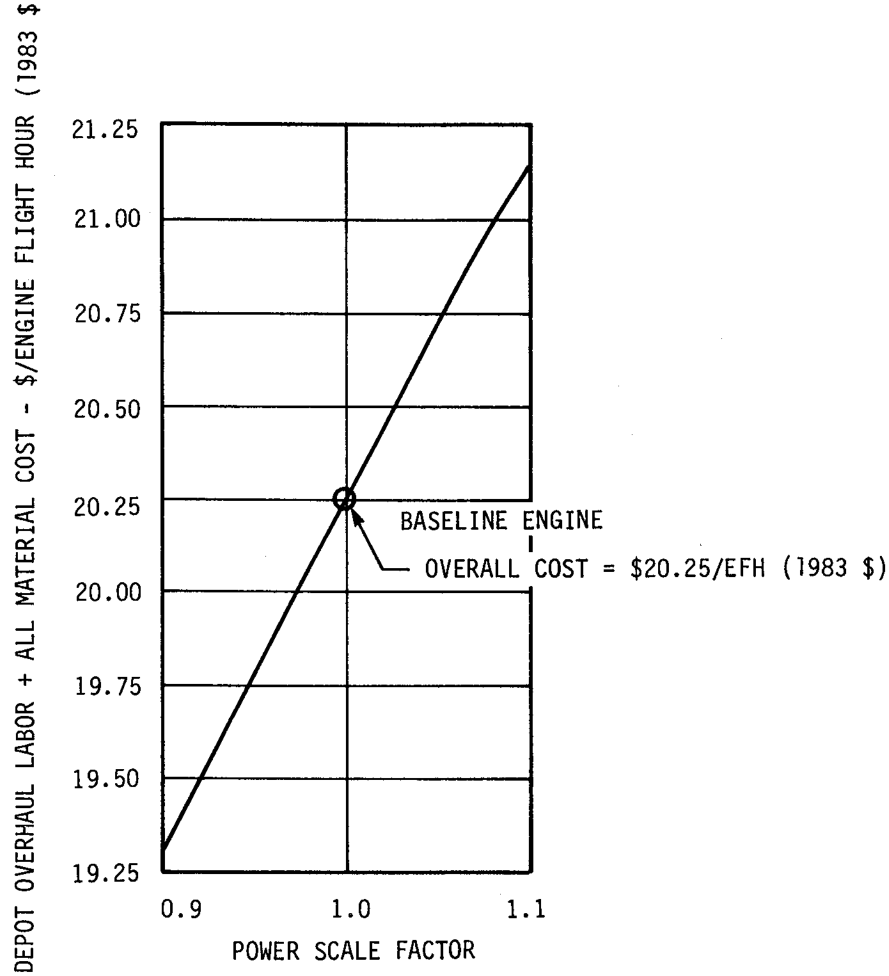

Figure 21. Depot Overhaul Cost-Labor + All Materials - Military Engine.

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TASK III

NOVEL POWER AUGMENTATION CONCEPTS CHARACTERIZATION

TASK III - NOVEL POWER AUGMENTATION CONCEPTS CHARACTERIZATION

SUMMARY AND CONCLUSION OF TASK III

This task consists of designing the system/engine for each of the concepts in the military and civil engine. The changes required to the baseline engine were defined in a qualitative manner. This included the control, accessories, hot section, and all other affected parts. The approach to quantify the necessary changes was also a part of this task, including establishing life criteria and limits.

THROTTLE PUSH

Description

For the throttle push case, additional fuel is added to obtain the required contingency power ratio. The turbine inlet temperature increases rapidly with increasing ratio together with some increase in speed. The cycle conditions are either limited by temperature or corrected speed. For this concept only, fixed geometry components similar to the baseline engine are modified to retain engine integrity at the elevated conditions and to preserve overall endurance life.

Control and System

Figure 22 shows the basic additional control logic required to operate either engine at contingency power. The system is turned on by sensing the loss of torque from one engine by comparison of the output from both engines. To avoid inadvertent operation of the contingency system, the torque from the affected engine has to be less than 50% of that at rated power, and the high-pressure turbine inlet temperature and speed of the other engine must be greater than 85% of their rated values to initiate operation. The system is shut off when the affected engine returns to an acceptable torque signal. There are also test, diagnostic, and display features.

Design Changes From Baseline

Figure 23 shows the engine components which were likely to be affected by the use of contingency power. The hot section parts are also shown in the annotated sketch (Figure 24).

The baseline civil and military engines are for Contingency/Takeoff (CRP/TOP) and Contingency/Intermediate (CRP/IRP) power ratios of 1.15 respectively. With increasing power ratios, it is necessary to modify engine components to preserve life.

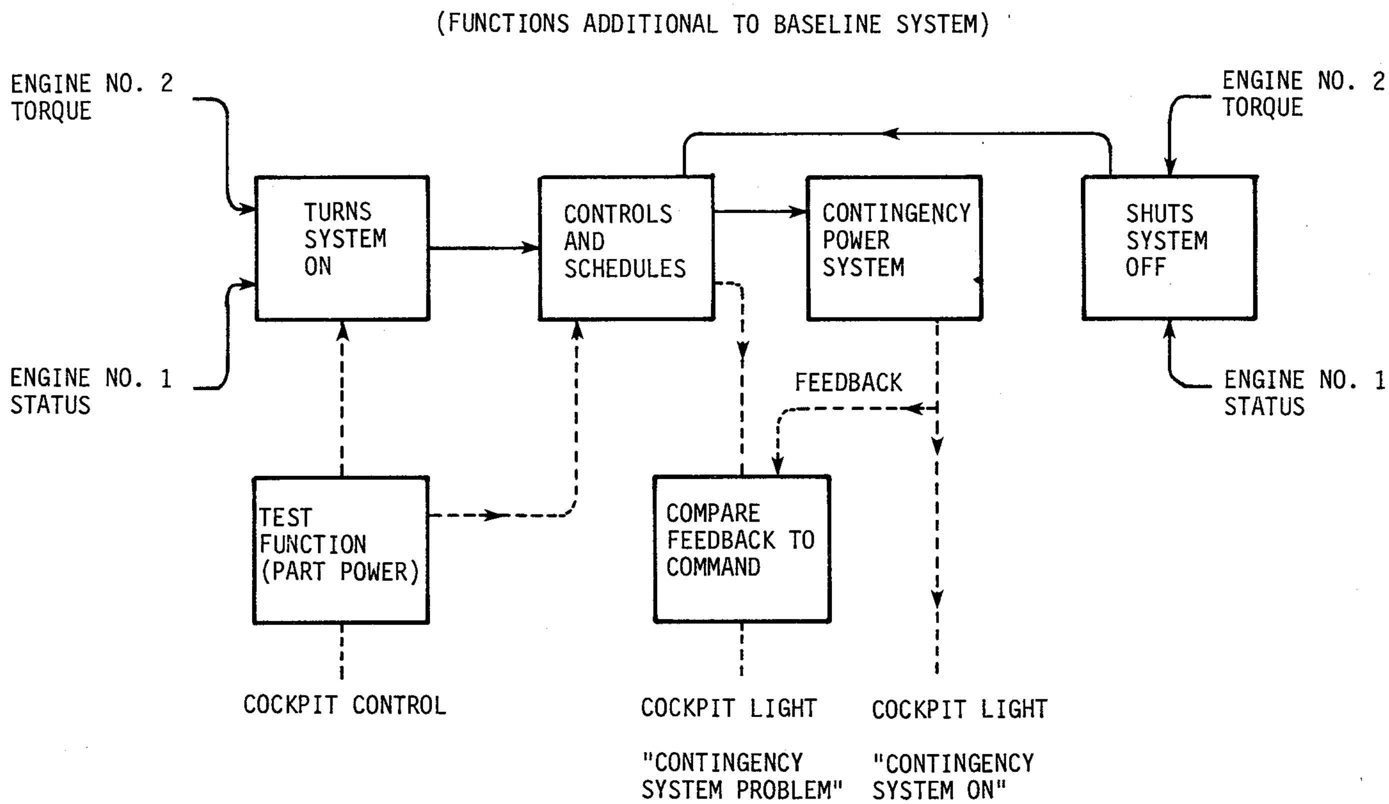

Figure 22. Engine No. 1 Contingency Control Logic.

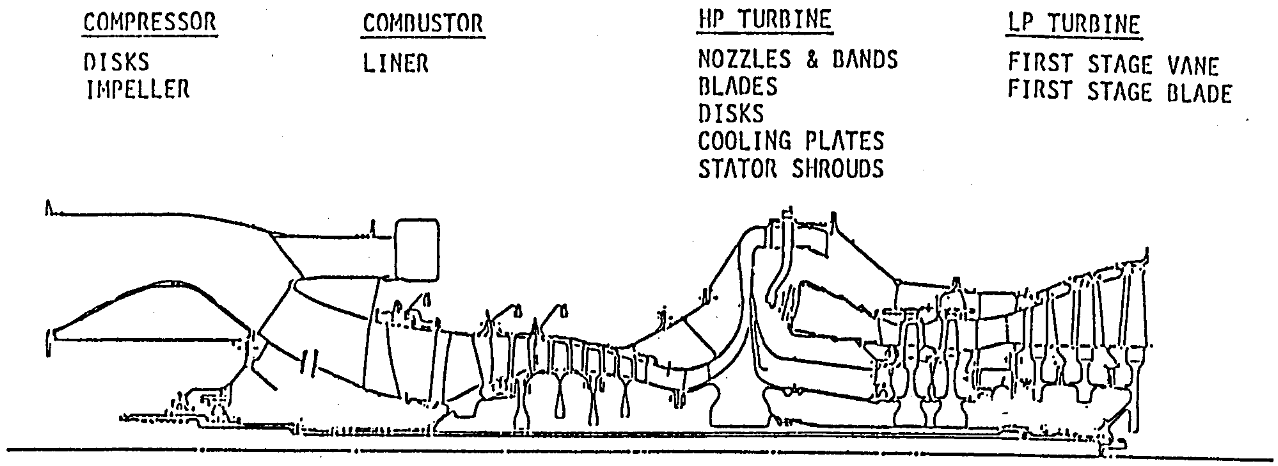

Figure 23. Components Studied.

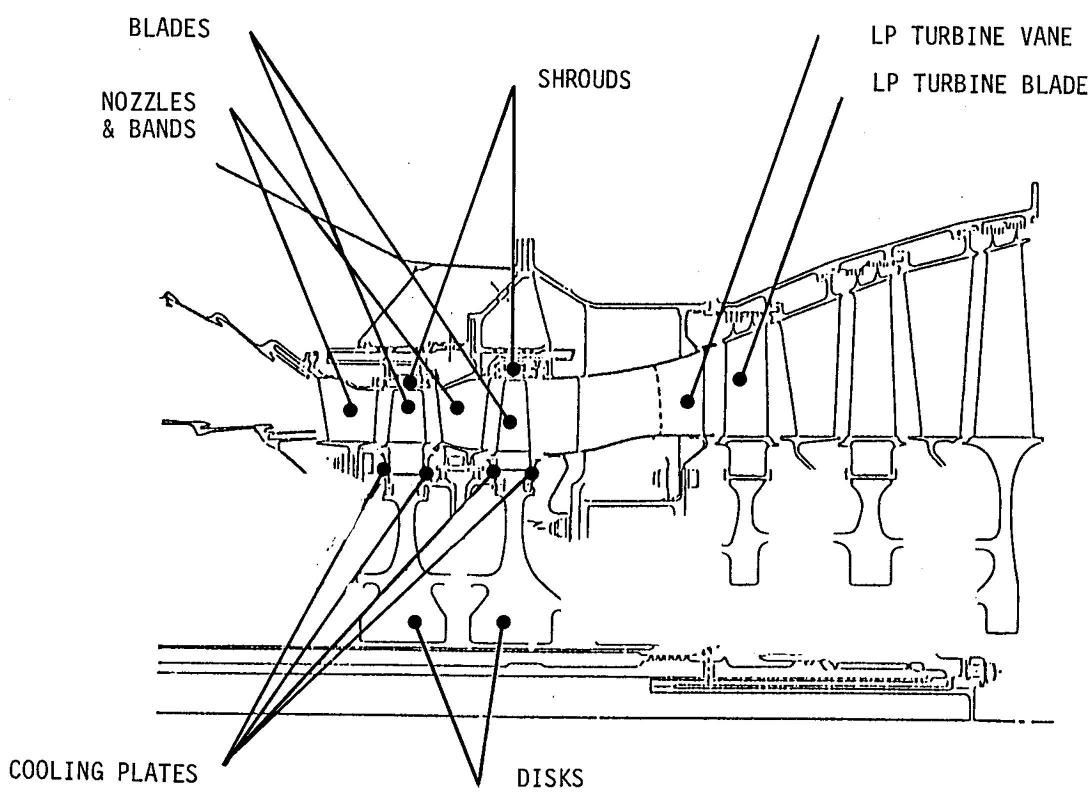

Figure 24. Hot Section Parts.

THROTTLE PUSH - Continued

To compensate for increasing speed, additional material is added to strengthen the axial and centrifugal compressor rotors and the high-pressure turbine rotor. To compensate for increasing temperature, the following actions are taken:

- Combustor Liner: Cooling pattern changed and cooling air increased to retain combustor life and discharge profile.
- HPT Rotor Blades: Increased cooling effectiveness by increasing quantity of cooling air and complexity of airfoil internal cooling passages to keep life usage acceptable.
- HPT Stator Vanes: When CRP/TOP = 1.45 for the civil engine, a small increase in cooling air is required for the first and second stage vane airfoils. Otherwise, there is no change to the airfoils. A cooling air supply has to be added for the first stage vane bands, whereas there is adequate cooling air for going to the second stage bands.
- Stage 1 Shroud (HPT): More cooling air through an increased number of impingement holes.
- Cooling Plates (HPT): With the requirement for increased cooling air for the rotor airfoils, an adequate cooling air supply is provided for the cooling plates.
- LPT First Stage Blade: With an uncooled blade a material change is required for the civil engine for contingency power ratios above the baseline. For the military engine the superior material is required even for the baseline engine to satisfy the qualification test requirements.
- Interturbine Frame: An additional air insulation shield is placed around the oil passage struts to prevent coking of the oil.

Limits

The engine components considered together with the limiting criteria and, where appropriate, the limiting locations are shown in Table 22. Stages 1 and 2 refer to the high-pressure turbine and Stage 3 is the first stage of the low-pressure turbine. The limits shown are basic for all the concepts considered. Some of the other novel concepts have further limits imposed.

TABLE 22. COMPONENT LIMITS

Component	Location	Contingency Power Limit Criteria	Mission/Qual Test Life Limit Considerations
Stage 1 Blade	Temp - 70% Span Stress - 70% Span	TE Coating Temp TE Creep Rupture	----- Creep Rupture
Stage 2 Blade	Temp - 70% Span Stress - 50% Span	TE Coating Temp TE Creep Rupture	----- Creep Rupture
Stage 3 Blade	Temp - 50% Span Stress - Root	Coating Temp Creep Rupture	----- Creep Rupture
Stage 1 Nozzle	Temp - 50% Span Stress - 50% Span	TE Coating Temp Ballooning Creep Rupture	----- Thermal Fatigue
Stage 2 Nozzle	Temp - 50% Span Stress - Root	TE Coating Temp TE Creep Rupture	----- Thermal Fatigue
Stage 3 Nozzle	Temp - 50% Span	Coating Temp	Thermal Fatigue
Stage 1 Shroud	Bondcoat	Disbonding Temp	-----
Nozzle Bands	Surface	Coating Temp	-----
Cooling Plates	Rim	Creep Rupture	Thermal Fatigue
Stage 2 Disk	Dovetail	Creep Rupture	Creep Rupture
Other GG Rotor Structure	Disks	Burst Margin	-----

THROTTLE PUSH - Continued

Limits

The rotor blade airfoils are limited by either the maximum surface temperature or the stress level, which are not necessarily at the same location. The integrity of the airfoil coating during the life of the blade determines the maximum allowable temperature. Creep rupture determines the life of the blade. In the case of the Stage 1 blade particularly, the coating temperature becomes more limiting with increasing contingency power ratio such that the creep rupture life calculated decreases with increasing ratio, due to the additional cooling required to satisfy the coating limit.

In the case of the nozzle airfoils, the limits are determined by the airfoil coating allowable temperature or by creep rupture giving rise to low cycle thermal fatigue. The nozzle blade bands are limited by the coating temperature.

The limit on the Stage 1 rotor shroud is the temperature at which the shroud segment bonding material starts to oxidize, a condition which would lead to segment separation.

The cooling plates attached to the high pressure turbine rotor disks direct cooling air into the blades on the forward sides of the disks. The rim temperature is limiting as the thermal gradient is approximately equal to the rim temperature minus the cooling air temperature and results in the rim creep rupture stress leading to thermal fatigue.

Creep rupture is limiting in the Stage 2 disk dovetail posts due to the difficulty in obtaining enough temperature differential for cooling purposes between the metal and cooling air.

The limiting consideration for the axial and centrifugal compressor rotors and also the high pressure turbine rotor is the burst margin when the speed exceeds that of the baseline engine. The high-pressure rotor was also limited in corrected speed due to the flat flow-speed characteristic of the compressor and the rapidly declining compressor efficiency. This is true for all of the novel concepts studied as well as the Throttle Push case.

TURBINE COOLING AIRFLOW MODULATION

Description

In this concept, the cooling air flow to the high pressure turbine is controlled by a two-position valve, which is in an open position for contingency power and is "closed" for all other power levels. In the "closed" position the maximum amount of cooling air flow is that required for Intermediate or Takeoff power conditions.

A sketch of the turbine rotor cooling air modulation scheme is shown in Figure 25. The cooling air originates in an annulus inside the combustor casing adjacent to the diffuser discharge. The solenoid operated modulating valve meters the flow of cooling air into a duct running down the front face of the combustor. The air then flows into a manifold inside the combustor inner wall and is transferred to the cooling air accelerator through several axial ducts. The air is then distributed throughout the high-pressure turbine rotor with the existing system.

TURBINE COOLING AIRFLOW MODULATION - Continued

In addition, modulating the cooling air to the stator, viz, the Stage 1 rotor shroud, shows some advantages. In this case, air is taken from the duct on the downstream side of the modulating valve and then ducted to the outside of the combustor at a point similar to, but circumferentially around the modulating valve. The open valve position is adjusted to give the extra flow required for the stator.

The cooling air is then piped externally to the manifold in the high pressure turbine casing and then through radial tubes into the annulus around the shroud impingement shield. There is a shut-off valve in the external tubing which is operated by the same signal as the modulating valve.

Control and System

Figure 26 shows the control requirements in addition to those already described for the throttle push concept. The dashed line represents the additions for cooling flow modulation to the stator.

The modulating valve is a pneumatic valve operated with compressor bleed air on signals from the engine control system.

A system which is only capable of one-time operation has also been considered for comparison. The modulating valve and shut-off valve in the stator cooling line would be kept in the open position for the required contingency operation time by the pressure produced by burning a pyrotechnic squib initiated by a control signal. The compressor bleed system, feedback transducer, and solenoid valve would not be required for this system. Besides the limitation of one-time operation, it will be shown that this system adversely affects the maintenance costs, especially when training flights are considered.

Design Changes From Baseline

In addition to the engine component changes for throttle push contingency power operation, this system also requires additional modifications and special parts. The modifications include the provision of a bleed port in the compressor casing, changes to the diffuser and combustor casings to mount the modulating valve and ducting for flow to the rotor and shroud, modify the high-pressure turbine casing for shroud cooling, and add the control system logic required. New parts required consist of the valves and interconnecting wiring and tubing.

Apart from the requirement for additional cooling air at contingency power, the amount of cooling air required at intermediate or takeoff power also must be increased to prevent backflow through the outer balance piston seal.

Limits

Limiting requirements for the cooling flow modulation are the same as those defined for throttle push (see Limits, pg 44). In addition, modulation range is limited because of hot gas backflow potential through seals and blades at low power operation.

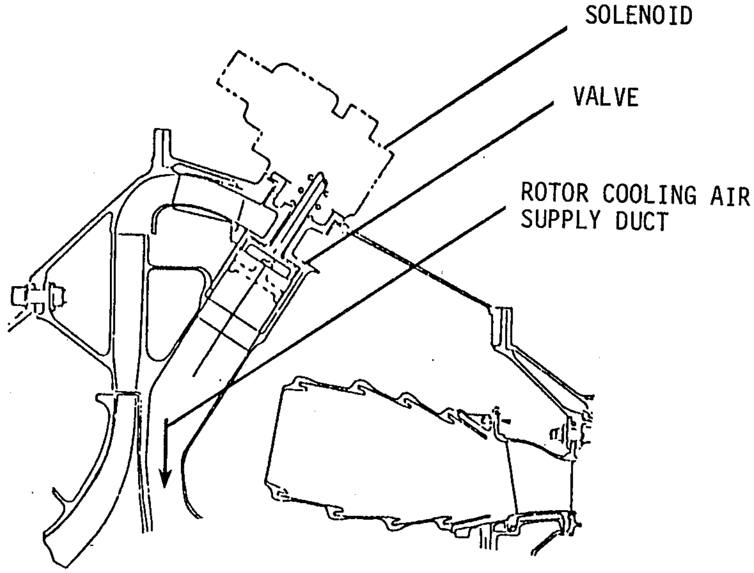

Figure 25. Turbine Cooling Airflow Modulation System.

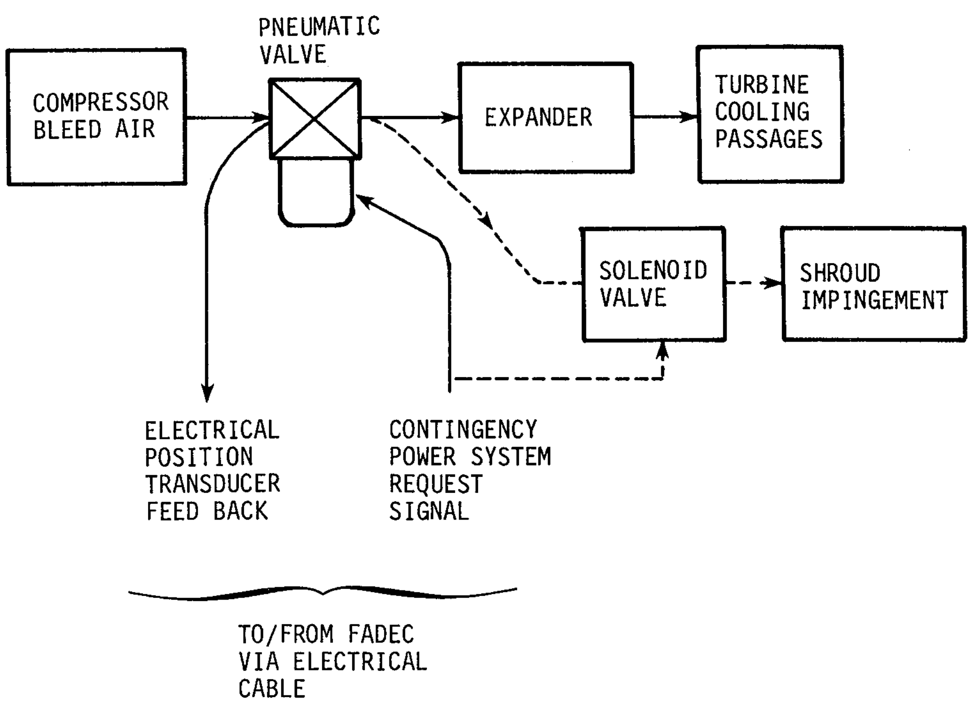

Figure 26. Turbine Cooling Airflow Modulation.

WATER INJECTION INTO TURBINE COOLING AIRFLOW

Description

This concept provides water addition to the high-pressure turbine rotor cooling air when engine contingency power is demanded. Besides providing a steam/air coolant mixture with lower temperature to the rotor, the quantity of cooling air is also increased due to the higher density of the mixture.

Water addition to the high-pressure turbine stator cooling air is not included in this concept. It is thought that any potential advantage to be gained is low and is more than offset by the degree of difficulty and risk involved. Without extensive design changes, it is not possible to change the source of cooling air to the first stage stator vanes. As the cooling air flows to the rotor shrouds and the second stage stator vanes are relatively low, there is not too much potential for gain by lowering the cooling air temperature.

The proposed concept for water cooling the turbine rotor is shown in Figure 27. Water is brought into the combustor through a strut in the diffuser exit at the bottom of the engine, and then goes into a water distribution manifold tube running 360° circumferentially inside the cooling air collection annulus in the combustor. The water is sprayed rearwards through orifices placed circumferentially around the tube into a two-part sheet metal manifold which allows dry air to enter, but prevents water from spraying onto the combustor structural parts. The steam/air mixture, probably containing water droplets, circulates to the top of the engine, and then passes down a radial duct on the back wall of the diffuser into another annulus inside the inner wall of the combustor. The mixture then passes through several axial ducts into another annulus before going through the cooling air accelerator. Any remaining water droplets will be disintegrated at this stage due to the high velocity in the accelerator. The cooling mixture is then distributed through the normal turbine rotor cooling system.

Control and System

In addition to the basic controls necessary for contingency power (see Description, section above), the additional system required for this concept is shown in Figure 28. Water/anti-freeze mixture, stored in a tank which is sized for the amount of water required for the application and contingency power ratio, is capable of being routed to either engine as required. On demand, the water is pumped through the system by an electric motor driven centrifugal pump. A pressure transducer provides a signal to the control for logic requirements, and a flow sensor provides a signal to shut down the system when the water tank is empty. Solenoid valves operated by signals from the control determine which engine receives the water. A filter and a check valve are also part of the system.

An alternate system, which is capable of one operation only, has also been considered. The motor, pump and transducer are deleted, and the required pressure is provided by a regulated inert gas supply operated by a solenoid valve with a signal from the control. In this case, the water tank requires a bladder to separate the gas and water. This system is shown in Figure 29.

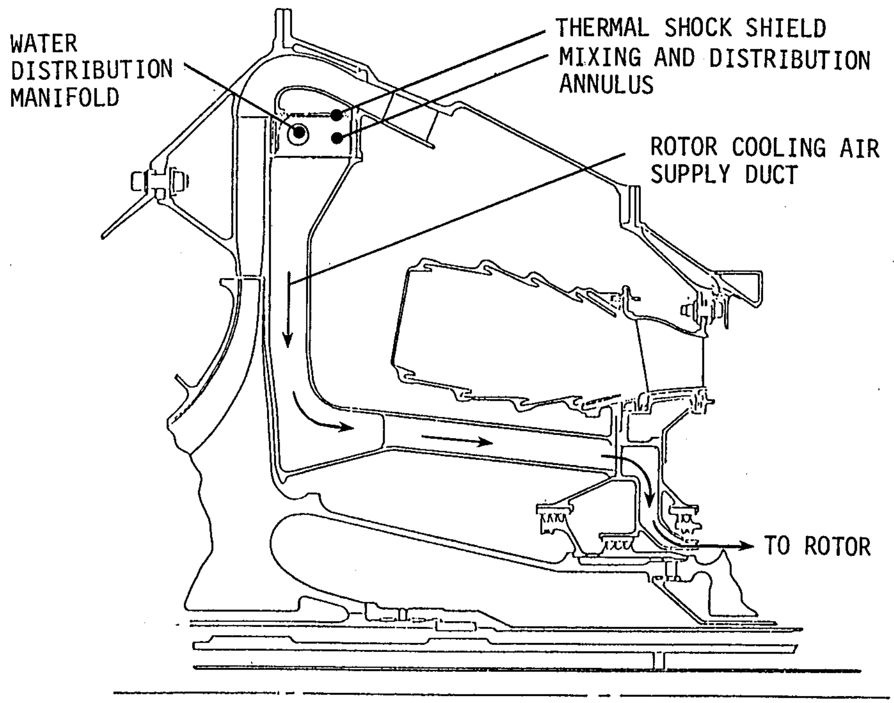

Figure 27. Water Injection into Turbine Cooling Airflow.

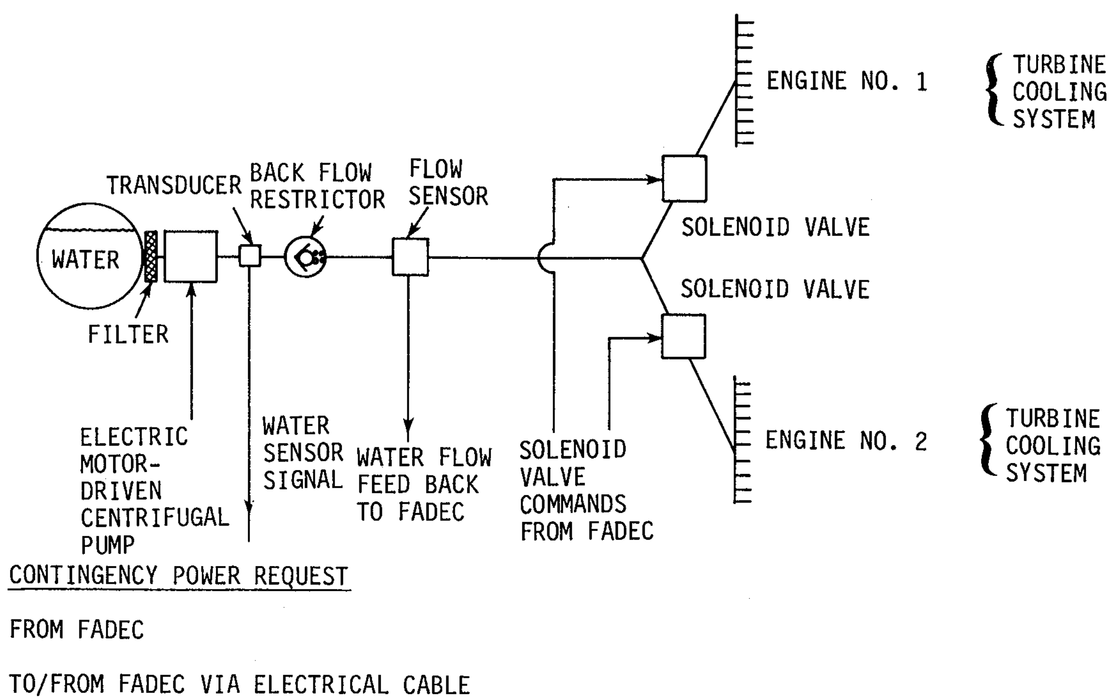

Figure 28. Water Injection into Turbine Cooling Airflow System.

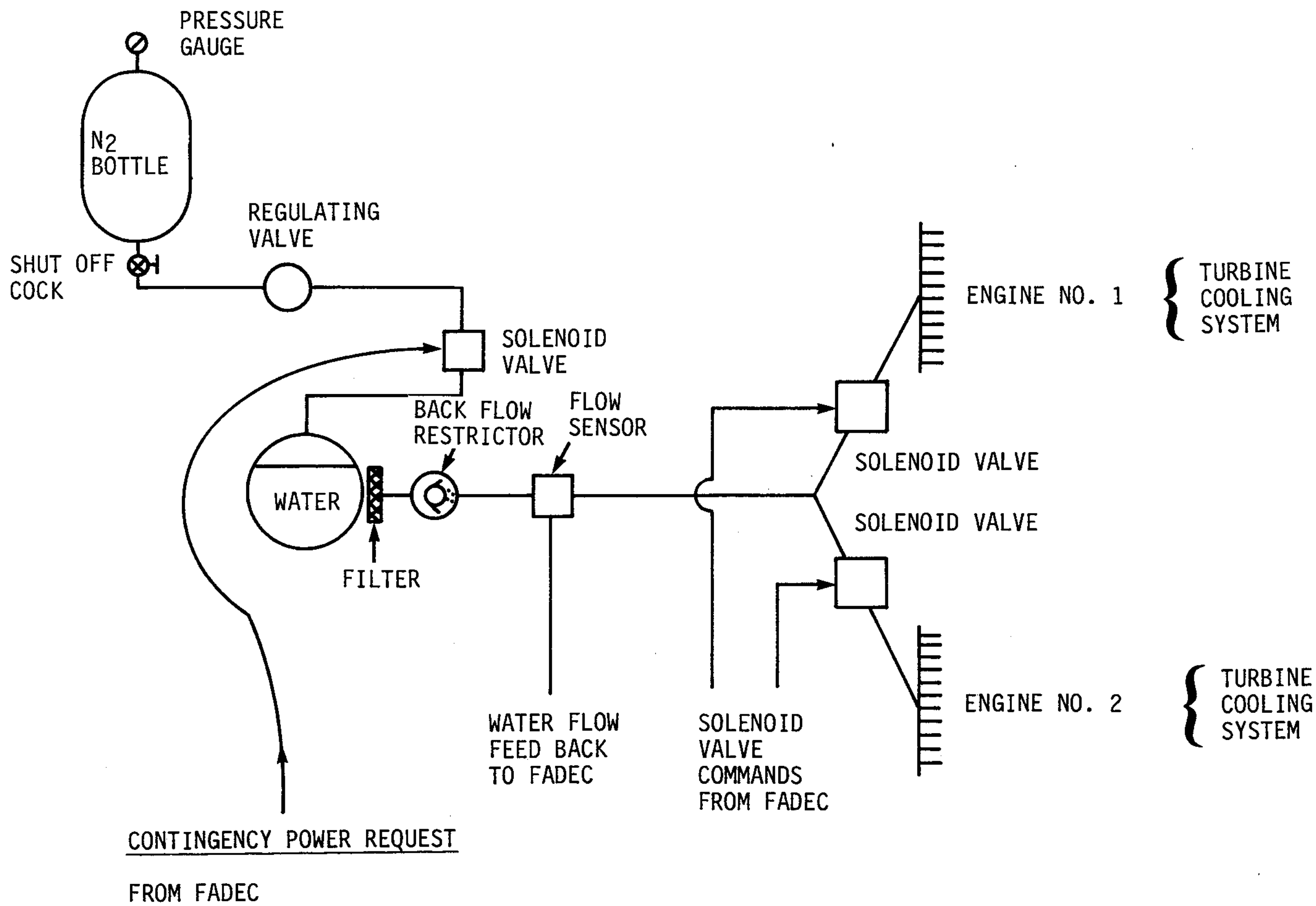

Figure 29. Water Injection into Turbine Cooling Airflow System - Alternate Gas-Pressured Scheme.

WATER INJECTION INTO TURBINE COOLING AIRFLOW - Continued

Design Changes From Baseline

For this concept, the diffuser is separated from the combustor outer casing, so that, with the water distribution tube attached to a modified combustor casing to get water into the cooling air system, it is possible to install the sheet metal annulus surrounding the tube inside the cooling air annulus. The diffuser design is also modified to get the transition from the water/air mixing annulus to the rotor cooling system.

The requirements for external components common for both engines have been covered in the last section.

Limits

In addition to the limiting requirements defined for the Throttle Push case (see Limits, pg 44), a further restraint was imposed for this concept. Theoretically, the steam/air cooling mixture could be used at a temperature just above the saturation temperature, approximately 150°C (300°F), but to lessen the possibility of thermal shock and distortion, this temperature had to be at least 260°C (500°F).

WATER INJECTION INTO COMPRESSOR INLET

Description

In this concept engine power is augmented, while keeping the same turbine inlet temperature, by spraying a water/anti-freeze mixture into the compressor inlet which will be fully evaporated before compressor discharge. To accomplish this end, the outer wall of the front frame is modified to include a circumferential manifold which feeds removable nozzles for spraying the water across and partially into the air stream. A sketch of this system is shown in Figure 30.

Control and System

In addition to the basic controls necessary for contingency power requirement and execution described for throttle push, this concept will also require the components shown in the schematic Figure 31.

As the pressure required to operate this system is much less than that required for putting water into the turbine cooling system, this system may be pressurized with air from the compressor interstage bleed. On contingency power demand, the control opens a solenoid valve to allow air from the operating engine to pressurize the water tank with a diaphragm to separate air and water. A check valve prevents the bleed air from blowing out through the non-operational engine. The system to distribute water to either engine is virtually the same as that downstream of the pump in the turbine cooling air system (see Control and System, pg 49), with the exception that, for this system, a variable orifice driven by a stepper motor is required in the line to schedule the correct water flow required for any flight condition.

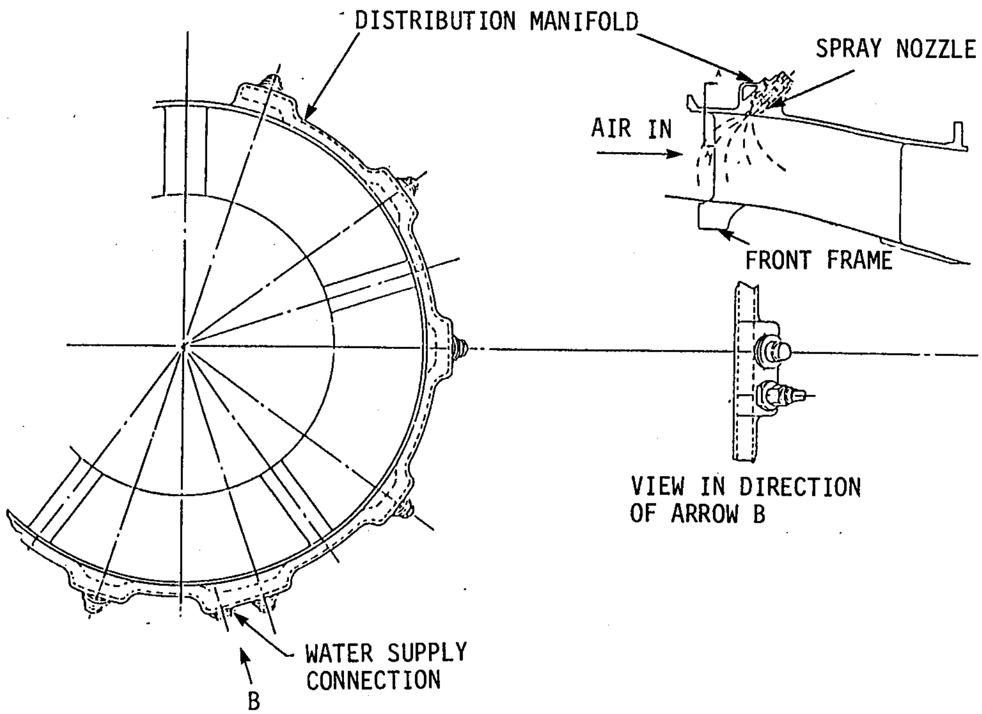

Figure 30. Water Injection into Compressor Inlet.

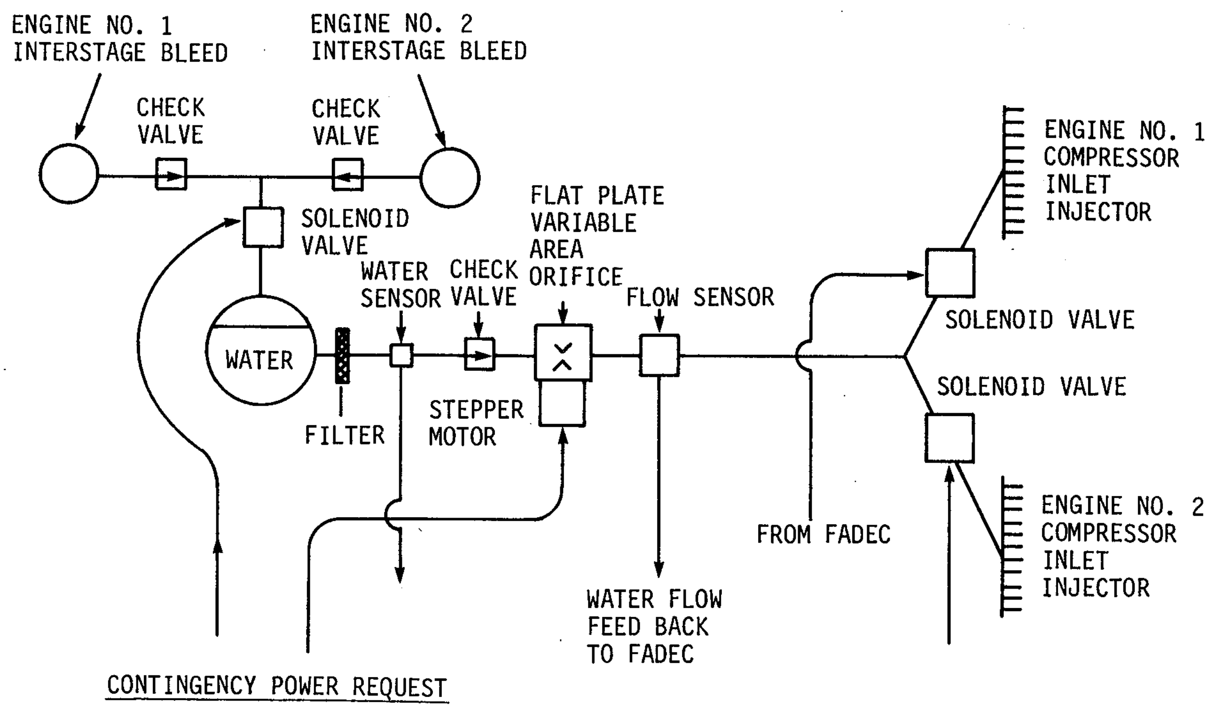

Figure 31. Water Injection into Compressor Inlet.

WATER INJECTION INTO COMPRESSOR INLET - Continued

Design Changes from Baseline

The only engine components modified for this concept are the front frame and control. The front frame has an integral manifold for water distribution including a supply connection and bosses to house the spray nozzle and seal assemblies (Figure 30).

Requirements for external components common for both engines have been covered in the last section.

Limits

In addition to the limiting requirements defined for the throttle push case (see Limits, pg 44), this concept also has a water flow limit to satisfy compressor stall margin considerations.

Addition of water to the inlet of the compressor causes some reduction in compressor stall margin resulting from the lowering of the compressor stall line to a greater extent than the compressor operating line is lowered. The stall margin appears to be adequate up to 1% water-air ratio which is more than the water used in these studies. Also, the addition of water causes an increase of compressor speed (at constant turbine inlet temperature) but the engine remained below the 104.3% corrected speed limit. This limit was selected consistent with compressor stall margin considerations and rapidly decaying compressor air flow capacity and efficiency characteristics.

WATER INJECTION INTO TURBINE COOLING AIRFLOW AND COMPRESSOR INLET

Description

Another concept which has been studied is the combination of water injection into both the compressor inlet and the turbine rotor cooling air system; a combination of the two separate systems described in the Water/Injection into Turbine Cooling Airflow and Compressor Inlet sections (pgs 52-54).

Control and System

The systems shown in the schematic Figures 28 and 31 can be combined to some extent for this concept. The system shown in Figure 28 is retained in its entirety as the pump operated scheme is required to obtain the necessary pressure for water injection into the turbine cooling air. Water injection into the compressor inlet would be provided by taking a branch line downstream of the flow sensor, then going through the variable orifice to the solenoid valves controlling the flow to each engine. In all cases the solenoid valves are placed as close as possible to the water injection points to minimize the delay time when operation is required. The higher water pressure going to the compressor inlet spray nozzles in this case would not be detrimental to the functioning of the system.

WATER INJECTION INTO TURBINE COOLING AIRFLOW AND COMPRESSOR INLET - Continued

Design Changes from Baseline

All the engine modifications and new parts required for the separate water injection schemes described in the Design Changes from Baseline section (pgs 54 and 55) are required for this combined concept. The control, however, as described in the previous section is only slightly more complicated than that for each separate system.

Limits

The limits described separately for the two systems in the Limit section (pgs 54 and 55) will also apply to this combined water injection concept.

PROPELLANT EMERGENCY POWER UNIT

Description

This concept calls for a self-contained emergency power unit to supply the entire additional horsepower required for the Contingency Rated Power level under consideration. For example, in order to achieve a Contingency Rated Power to Takeoff power ratio of 1.25, the Emergency Power Unit (EPU) would have to be designed to supply 1.25-1.15 or 10% of the basic engine output horsepower at takeoff. A solid propellant cartridge would supply the necessary flow of hot gas to the turbine assembly in the EPU. The power would be transmitted to the aircraft main rotor gearbox through reduction gears and an overrunning clutch. The total propellant weight would be determined by the flow rate multiplied by the time requirement of 2 1/2 minutes (+10% margin).

Control and System

A schematic of the EPU concept is shown in Figure 32 with the control logic depicted in Figure 33.

Referring to these two figures, the system will operate as follows: As a demand for Contingency Power is initiated by a signal from the FADEC, an electrical current will be transmitted to the cartridge, igniting the solid propellant. The resulting constant gas flow rate (produced by the double end burning design of the cartridge) will be directed into the nozzle box assembly of the EPU. This gas will be directed through the three stage turbine to produce a constant horsepower. The turbine speed will be constant since the turbine rotor drives a reduction gear set which is corrected through an overrunning clutch into the main rotor gearbox running at a fixed rotor speed. If for any reason there might be a gearing failure in the EPU which could allow the turbine to become unloaded, an overspeed sensing device would operate to blow out a rupture disc which would then allow the hot gas to bypass the turbine causing a rapid return to safe speeds. Similarly, if a cartridge failure, e.g., such as grain cracking took place which would produce an excessively high pressure, an overpressure disc would be blown also allowing the gas to bypass the turbine nozzlebox and causing the solid propellant either to be extinguished or to burn at a reduced pressure.

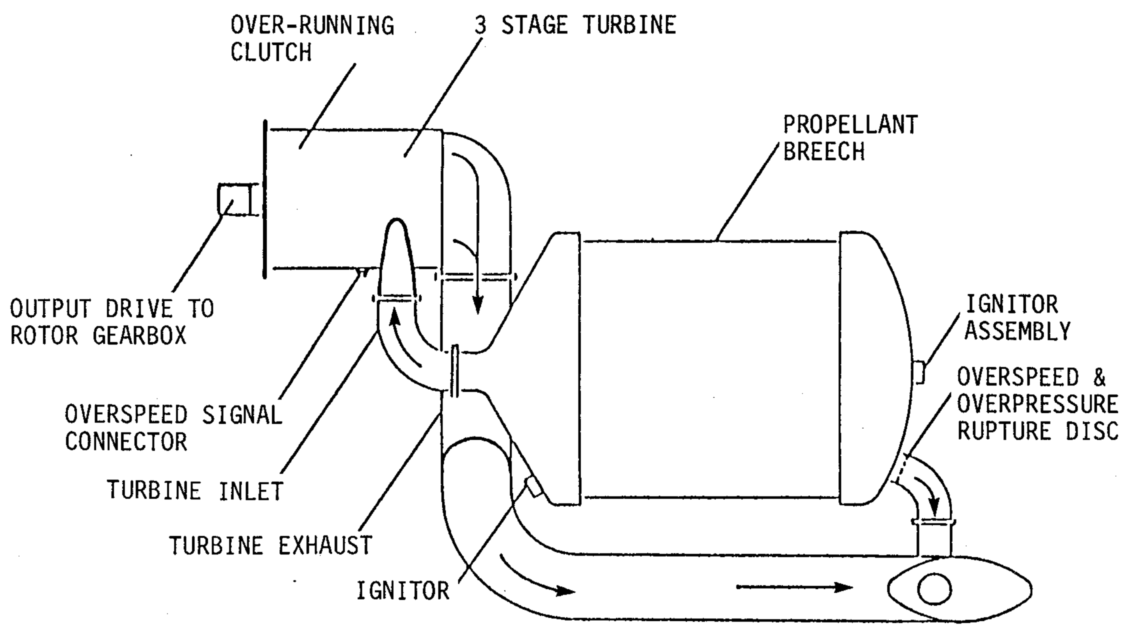

Figure 32. Solid Propellant Emergency Power Unit (Military) - CRP/IRP = 1.25.

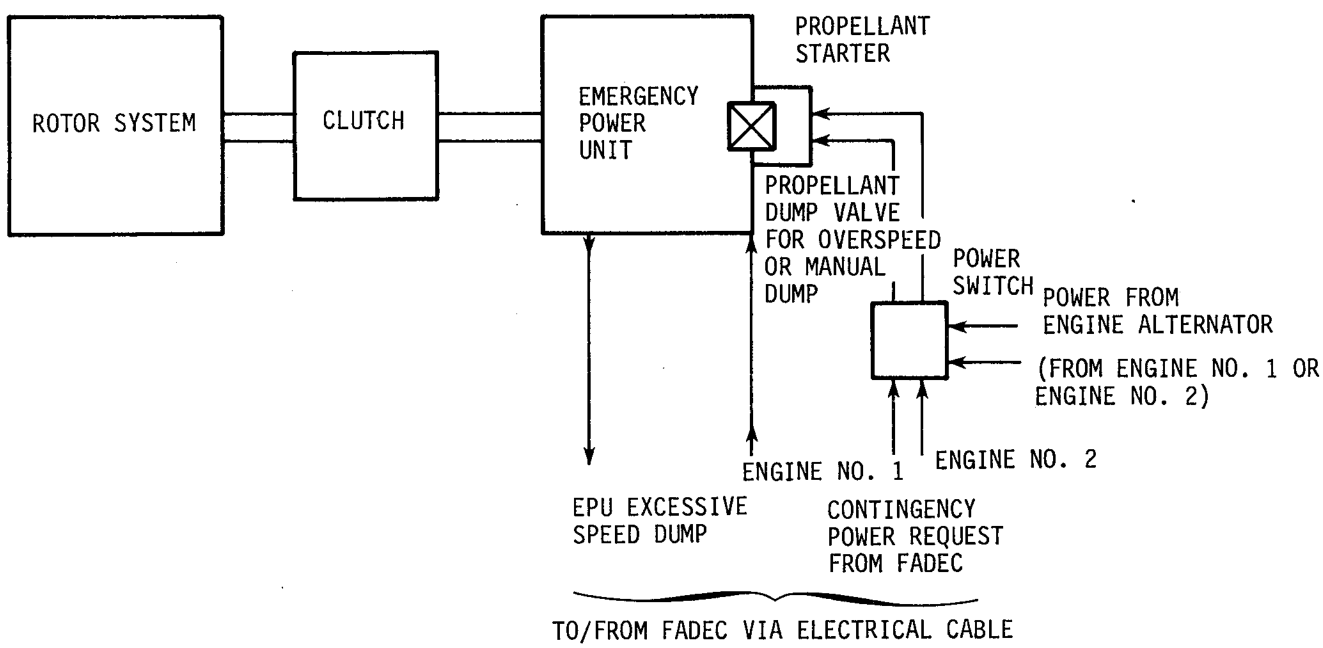

Figure 33. Solid Propellant Emergency Power Unit.

PROPELLANT EMERGENCY POWER UNIT - Continued

Control and System - Continued

Assuming that neither of the above occurs, then the EPU would accelerate from zero speed up to the speed at which the overruning clutch would engage. It would deliver design horsepower, for at least 2 1/2 minutes and then as gas flow is stopped, it would declutch and decelerate to zero speed. After each use in service, maintenance action to replace consumables would be required.

Design Changes from Baseline

As stated earlier the EPU is designed to produce the incremental horsepower required to reach the contingency rated power level. Therefore, no changes have to be made to the baseline engine, which is one of the major advantages of this systems, compared to the other concepts. Since no engine changes are specified, there will be no penalties for added engine, weight, cost or maintenance to account for those design changes which would otherwise have been needed to bring the engine back to its original horsepower, life capabilities.

Limits

No changes are made to the baseline engine design, so all performance and mechanical limits will remain the same as those for the baseline engine. However, downsizing the engine will result in a more severe duty cyle, i.e., more time spent at higher powers. With regards to the EPU, the only limits will be those of size, weight, development and production cost of the solid propellant cartridges since the unit will be relatively small, 0.3 m (12 in.) long with an OD of 0.2 m (8 in.). For a CRP/IRP ratio of 1.25 on the military rotorcraft, the cartridge would weigh 60 kg (132 lb) with an OD of 0.35 m (13.8 in.) and a length of 0.41 m (16.2 in.). Since this cartridge must be stored, shipped and then handled in unprepared locations, the physical size takes on major importance. Also development and production cost will go hand in hand with physical size so minimizing the cartridge will be of extreme importance. In addition, the cartridge is necessarily loaded into a high strength metal pressure vessel (commonly called a breech) for firing. Keeping the cartridge as small as possible will also keep the breech size/weight/cost to a minimum.

System Evaluation

As this concept was studied in detail, it became apparent that the cartridge/breech size to achieve a reasonable contingency rated power level was excessive. The physical size, weight, and cost levels were of a magnitude which considerably outweighed the advantages obtained by downsizing the engine. Therefore, this concept was eliminated from the detailed analysis and studies specified in Task IV.

COMBINATION: TURBINE COOLING AIRFLOW MODULATION AND WATER INJECTION INTO TURBINE COOLING AIRFLOW SYSTEM

Description

This combination system was considered as an approach to obtaining high CRP ratios in the event that either concept by itself fails to reach the maximum ratios. A review of the penalties in both systems showed that there was no synergism between them. Specifically, the extra equipment added for the water system and for the cooling flow modulation system are both required for the combination system. Therefore, the only reason for considering the combination system would be to raise the CRP ratio for either system.

For descriptions of the Turbine Cooling Airflow Modulation (rotor only) and the Water Injection Turbine Cooling Airflow systems, see Task IV (pgs 71-82). Each of these concepts presents a viable system with no restrictions or limits requiring another concept to extend its range. Therefore, study of their simultaneous use was discontinued to permit in-depth study of each individual system.

PERFORMANCE BENEFIT OF ENGINE DOWNSIZING

The benefits of designing an engine with greater Contingency Rated Power to Intermediate Rated Power ratio come from downsizing the engine and result in a smaller, lighter and less expensive engine to buy and maintain. In addition, there is a SFC benefit associated with the downsizing. Figure 34 indicates that the primary effect of a 10% smaller engine (10% smaller in design value of airflow) is to shift the SFC characteristic to the left by 10% in shaft horsepower. At constant cruise power, the SFC for the smaller engine is improved. In this analysis, the components have not been degraded due to engine size because the effect is too small for the range considered. Also, the impact of the design changes required to achieve the greater Contingency Power Ratio is considered separately. These considerations were applied to all Novel Concepts under study.

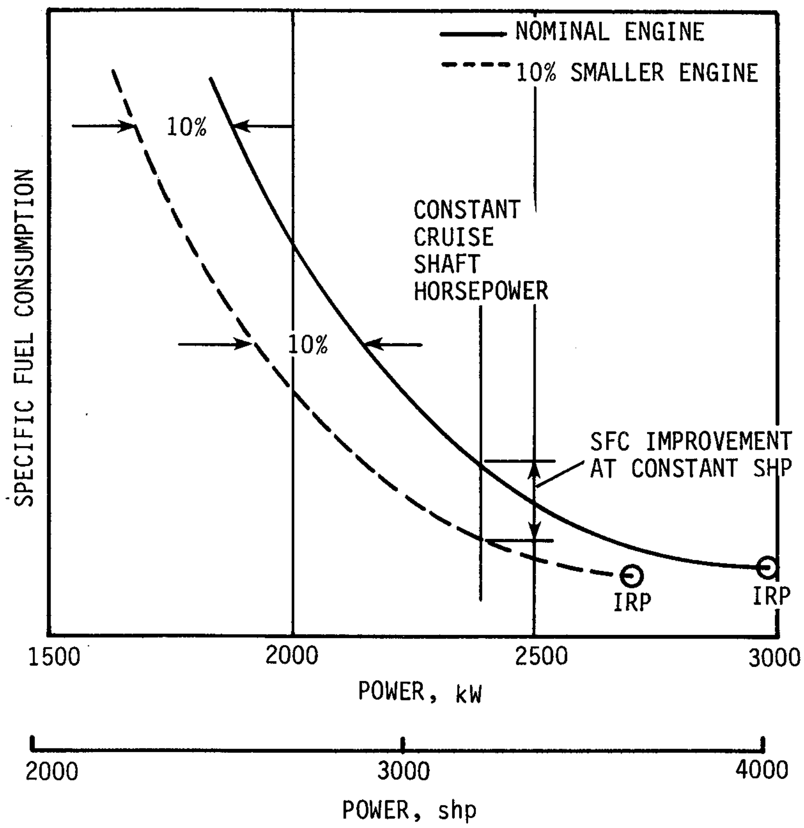

Figure 34. Specific Fuel Consumption vs Power Comparison for Nominal Size and 10% Smaller Engines.

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TASK IV

CONCEPT ANALYSIS

TASK IV - CONCEPT ANALYSIS

The following summarizes the procedures used to analyze and to evaluate the relative capabilities of each concept when installed on either the civil or the military engine.

ENGINE COMPONENT INTEGRITY STUDY

The engine components studied for each concept and the design limits and criteria used were the same as for the Throttle Push concept listed in Table 22. For the parts studied, the following characteristics and parameters were considered:

1. Stress Rupture/Creep Limits: The time at temperature and at stress levels to achieve a life equivalent to that of the Baseline engine.

2. Limit Temperatures: Temperatures associated with short time blade coating oxidation and disbonding.

3. Low Cycle Fatigue: As there are only a few cycles to Contingency Power, this effect is small. Nevertheless, the cooling requirements for some components are set by thermal fatigue considerations.

4. Gas Generator Rotor Speeds: For Contingency Power speeds in excess of that for the Baseline engine, the rotor structure is resized to retain the original stress levels. The physical locations chosen for investigation of creep rupture life are also tabulated for each component. These locations were selected by experience with baseline engine life analysis. The cooling flow effectiveness curves used for the airflows were also derived from cooling analyses for the baseline engine.

   Component metal temperatures were determined using average cycle turbine inlet gas temperatures modified with an adder to account for engine-to-engine quality variations and a combustor pattern factor.

LIFE USAGE DETERMINATIONS

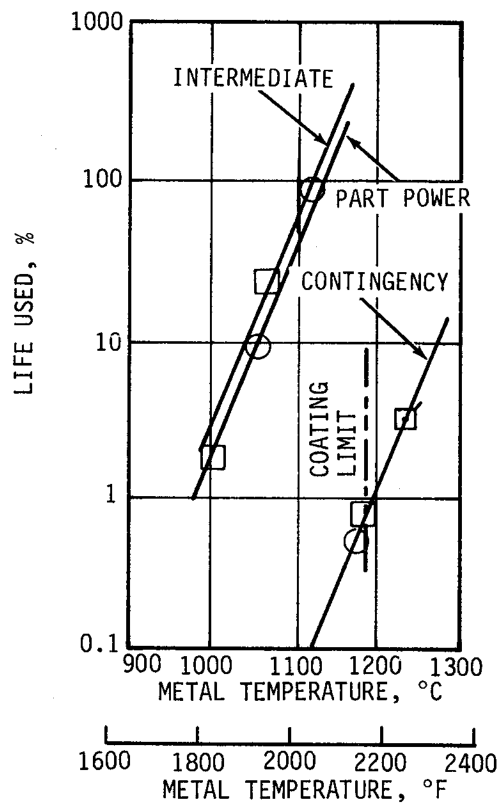
Relationships between turbine blade life usage and metal bulk temperatures were developed from General Electric Design Practice Handbook data on material properties plus power/time profiles from specific mission and qualification test schedules. It was possible to plot this relationship in linear form on a semi-log scale, for both mission and test conditions.

LIFE USAGE DETERMINATIONS - Continued

Figure 35 shows an example of this life usage plot as it applies to the Stage 1 blade military qualification test. Power usage has been divided into three categories: Contingency, Intermediate, and part power. The part power component is a combination of all life usages for powers below Intermediate, and is expressed as a percentage of Intermediate Rated Power. At different Contingency Power Ratios, this percentage is allowed to vary so that the equivalent time at part power can be kept constant, thus enabling the part power life usage to be represented by a single line on the semi-log plot. This representation of life usage with only three linear expressions facilitate the calculations of the cooling flow requirement. This calculation involves an iterative process consisting of assuming a cooling air flow, determining the cooling effectiveness from a curve, calculating metal temperatures at the three power levels, and in turn, calculating the total percentage life usage. This iteration will generally provide the cooling flow requirement to obtain 100% life usage for the contingency power ratio being considered. However, as described in detail for each concept where applicable, there were combinations of mission, test, and augmentation level where 100% total life usage could not be achieved. In such cases, maintenance figures were adjusted to reflect the reduced frequency of replacing turbine blades since 100% life was not being used.

The example shown in Figure 35 for Throttle Push demonstrates how life usage at a Contingency Power Ratio of 1.35 would compare with that of the baseline engine. Both life usages at Contingency Power are relatively small due to the short operating time at this condition but life usage for the 1.35 CRP ratio would have been 4.3% compared to 0.54% at 1.15, or 8 times as much. However, the Stage 1 blade coating limit must be observed which means that the cooling flow must be increased. This reduces the life usage at CRP to 0.9% and since this additional flow will occur at all times, the IRP and PP metal temperatures will also be reduced. As a result, the life usage values will reduce from 81.2 to 18 and from 9.4 to 2.3% respectively. The total life usage will therefore decrease from 100% at 1.15 to 21.2% at 1.35.

In all life calculations, a speed increase at contingency power above that of the baseline engine is also accounted for. For every 1% increase in gas generator speed, the allowable metal temperature was decreased by 1.9^{o}C (3.5^{o}F).



LOG_{10} (% LIFE USED) = $C_1 \times T_{METAL} + C_2$

ALLOWABLE TEMPERATURE REDUCTION FOR SPEED:

1.9°C (3.5°F) T_{METAL}/1% GG SPEED

PART POWER LEVELS

CRP/IRP	1.15	1.25	1.35	1.45
% IRP	87.9	87.9	86.8	86.45

LEGEND

○ CRP/IRP = 1.15 (BASELINE)

□ CRP/IRP = 1.35 (WITH COATING LIMIT OBSERVED)

⊡ CRP/IRP = 1.35 (WITHOUT COATING LIMIT OBSERVED)

Figure 35. Military Qualification Test for Stage 1 Blade - % Life Used.

NON-TIME DEPENDENT TEMPERATURE LIMITS

Certain static parts have temperature limits independent of usage time. For example the Stage 1 shroud incorporates ceramic bonding. Since there is an absolute temperature limit for this bonding interface required cooling flows to stay within limits were calculated for each Contingency Power Ratio. Other static parts were also reviewed and where necessary, cooling flows increased. As these studies progressed, it was determined that the rotor blades were also exposed to a non-time dependent temperature limit due to the blade coating technique on materials used in this design. In a number of cases, the blade cooling flow requirement was established by this temperature limit rather than by the temperature/life use criterion.

HIGH-PRESSURE TURBINE BLADE COOLING DESIGN LIMITS

In order to proceed with detailed studies involving calculations of cooling flow requirements for each hot part, cooling effectiveness curves were generated for each turbine component scheduled for study. These curves were drawn up using computer models reflecting the technology level assigned to the Baseline engine.

Preliminary design estimates based on effectiveness levels would mean more cooling flow and increased engine scale-up to meet the constant TOP horsepower requirement. The increase in weight, cost, and maintenance resulting from this course of action would have to be evaluated against DOC penalties resulting from the option of redesigning the blade for a more complex and more costly cooling design.

TURBINE EFFICIENCY CHANGES

Changes Due to Secondary Flow Changes: As turbine cooling flows are varied, the loss or addition of these flows to the main flow stream will affect the absolute turbine efficiency due to available energy changes and mixing losses. In some instances, the detrimental effect on overall cycle performance brought on by an increase in cooling flow will be partially offset by the improvement in turbine efficiency caused by this same increased flow. Therefore as various cooling flows were varied to satisfy life or peak temperature limits, changes in turbine efficiency were also determined in order to calculate final performance levels available from each modified engine configuration.

Turbine Efficiency Changes Due to Tip Clearance Changes Caused by Bulk Temperature Variations: Hot tip clearance is usually calculated as the difference between the static shroud inner diameter at its bulk temperature, minus the running Outside Diameter (O.D.) of the turbine stage with all rotating parts at their average bulk temperature. However if the blade has been cooled to a significantly lower bulk temperature than expected at Contingency Power, the OD will be somewhat reduced. If the static parts have not been cooled, then the clearance will be increased and lower turbine efficencies will result. However if the static parts have been cooled more than normal, they will also shrink inwards, thus helping to reduce the increase in tip clearance.

TURBINE EFFICIENCY CHANGES - Continued

The high pressure turbine efficiency is a 2-stage group efficiency defined on the basis of flow and thermodynamic conditions at the Stage 1 rotor inlet. All secondary cooling flows with the exception of the Stage 1 vane and band cooling flows, which reenter upstream of the Stage 1 rotor inlet plane are termed "chargeable cooling flows." The various effects of the reentering cooling flows on the overall efficiency are treated as follows:

1. The Stage 1 vane and band flow mixing losses occur at the point of reentry with the main gas stream. The mass flow and available energy are accounted for in the rotor inlet reference station, hence there is a net loss term.

2. Stage 1 shroud, Stage 1 blade and Stage 2 vane flows are reintroduced into the gas stream downstream of the reference station and will do work downstream at their reentry points as well as cause mixing losses. The net effect is an apparent increase in the 2 stage group efficiency.

3. The Stage 2 blade flow reenters too far downstream for energy recovery and the mixing losses dominate causing a net efficiency decrease.

4. Outer Balance Piston (OBP) seal flow reenters forward of the Stage 1 wheel, causing mixing and pumping losses. However, the recoverable work outweighs these losses, resulting in a small net efficiency gain.

The following Table (Table 23) illustrates secondary flow and clearance effects on turbine efficiency for the cooling flow modulation concept applied to the civil engine at a CRP = 1.45.

PERFORMANCE EFFECT

As cooling flows are increased and turbine efficiency is affected as described earlier, the horsepower at the IRP or TOP gas generator inlet temperature will decrease with an increase in SFC. Since the economic sensitivities developed by Sikorsky Aircraft are based on rotorcraft with constant horsepower at IRP or TOP, the engine must be scaled up to meet this requirement before these economic trade factors can be assessed.

CONTINGENCY RATED POWER RATIO CHANGES

For each of the concepts under study, a series of calculations were made to cover a range of CRP ratios. However, with the exception of Throttle Push, the nominal CRP ratio was reduced since some of the performance decrements which occurred at Contingency Power did not occur at the IRP or TOP level and vice versa. Therefore, when the engine was scaled to meet the IRP or TOP horsepower level, a shift occurred in the Contingency Power level causing a decrease in CRP ratio.

TABLE 23. CIVIL TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD) AT CRP/TOP = 1.45

	Takeoff Power (TOP)	Contingency Rated Power (CRP)
	Metal Temperature, °C (°F)	
Stage 1 Disk	566 (1051)	630 (1166)
Stage 1 Blade	1093 (2000)	1188 (2171)
Stage 1 Shroud	976 (1788)	1038 (1900)
	$\Delta\eta$ Due to Cooling Flows, %	
Stage 1 Vane	-.032	-.032
Stage 2 Bands	-.053	-.053
Stage 1 Shroud	.093	.290
Stage 1 Blade	.130	.340
Stage 2 Vane	.080	.080
Stage 2 Blade	-.130	-.130
OBP Seal	0	.012
Total $\Delta\eta$ - Cooling Flow Effects	+.088	+.507
Total $\Delta\eta$ - Clearance Effects	0	+.150
Overall $\Delta\eta$	+.088	+.657

* - Clearance Change Details

		TOP	CRP
Stage 1 Disk O.D.	- MILS	-	-3.2
Stage 1 Blade Height	- MILS	-	- .6
Stage 1 Shroud ID	- MILS	-	-6.6
Stage 1 Tip Clearance	- MILS	-	-1.2

EVALUATION OF THROTTLE PUSH CONCEPT FOR CIVIL ROTORCRAFT

The procedures listed in the Engine Component Integrity Study section (pg 61) were used to carry out the evaluation of each concept at four Contingency Rated Power/Takeoff Power ratios, namely 1.25 and 1.30 for the baseline engine cycle and 1.357 and 1.465 for the rematched engine cycle. (As described earlier, it was necessary to rematch the cycle to keep the percent gas generator rotor speed and turbine inlet temperatures to realistic levels.) The effect on the engine, including system changes and engines and component performance differences are shown in tabular form for only two representative ratios; one for the standard cycle, and one for the rematched cycle.

The results for the Throttle Push concept are shown in Tables 24 and 25 (A and B). In order to observe the Stage 1 blade coating temperature limit, it was necessary to increase this cooling flow by 0.3% and by 1.50% at the higher CRP ratio. Stage 1 shroud flow was increased similarly by 0.4% and 0.82% and Stage 2 vane flow was also increased by 0.3% to satisfy peak temperature limits. Finally, the Stage 2 blade cooling flow will increase by 0.14 and 0.34% to accomplish the objective of 100% life usage for this component. Turbine efficiency changes brought about by these flow changes were also estimated and are listed in Table 24.

Cycle derivatives were then used to calculate the effect of these increased cooling flows and changes in turbine efficiency on the horsepower and SFC at Takeoff power as shown in Tables 25 (A and B). Then the engine was scaled up to produce the baseline horsepower so that the engine weight could be determined. This power scale factor also permitted cost and maintenance increases to be calculated using cost and maintenance factors appearing in Tables 46 and 48.

As can be seen from Table 24, all changes were made to satisfy the Contingency Rated Power requirements and are constant for the lower power levels. This is the result of the fixed geometry throttle push engine. This results in more Stage 1 blade cooling flow than required at horsepower less than or equal to Takeoff power and therefore only 88% and 57% of its life was used, respectively. This deviation from the 100% objective was accounted for by proportionate decrease in the base maintenance factors mentioned above.

TABLE 24. COMPONENT PERFORMANCE CHANGES FOR THROTTLE PUSH CONCEPT

CIVIL APPLICATION

	BASE		THROTTLE PUSH			
	TOP	CRP	TOP	CRP	TOP	CRP
CRP/TOP	---	1.15	---	1.25	---	1.47
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+.84	+.84	+2.96	+2.96
ΔStage 1 Blade Cooling, %	BASE	BASE	+.30	+.30	+1.50	+1.50
ΔStage 1 Shroud Cooling, %	BASE	BASE	+.40	+.40	+0.82	+0.82
ΔStage 2 Blade Cooling, %	BASE	BASE	+.14	+.14	+0.34	+0.34
ΔStage 2 Vane Cooling, %	BASE	BASE	0	0	+0.30	+0.30
ΔOBP Seal Cooling, %	BASE	BASE	0	0	0	0
$\Delta\eta$HP Turbine, pt	BASE	BASE	+.10	+.10	+0.49	+0.49
$\Delta\eta$ Compressor, pt	BASE	BASE	-.5	-.1	-.5	-.1
			Mission	Test	Mission	Test
Stage 1 Blade Life Used	100	---	88	11	57	6
Stage 2 Blade Life Used	100	---	100	11	100	9

TABLE 25A. CYCLE SUMMARY FOR THROTTLE PUSH CONCEPT

CONSTANT TAKEOFF POWER AT 305m/0/28.0°C

CIVIL APPLICATION - SI UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		THROTTLE PUSH					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, kW	2005	2310	2005	2505	2005	2720	2005	2940
CRP/TOP	---	1.15	---	1.25	---	1.36	---	1.47
ΔT_{41}, °C	1315	1395	1315	1470	1315	1515	1315	1550
ΔT coolant, °C	BASE	+25	BASE	+49	-13	+49	-24	+49
Δ% NH	BASE	+1.5	BASE	+3.2	-0.8	+3.2	-1.6	+3.2
Δ% SFC	BASE	---	+.72	---	+1.6	---	+2.8	---
Δ% Design Flow	BASE	---	+1.7	---	+5.3	---	+10.3	---
Δ% Weight	BASE	---	+2.1	---	+5.0	---	+9.1	---
Δ% Price	BASE	---	+2.0	---	+4.2	---	+7.2	---
Δ% Maintenance	BASE	---	+2.2	---	+5.1	---	+13.7	---
Δ% DOC Penalty	BASE	---	+1.2	---	+2.5	---	+4.8	---

TABLE 25B. CYCLE SUMMARY FOR THROTTLE PUSH CONCEPT

CONSTANT TAKEOFF POWER AT 1K/0/82.4°F

CIVIL APPLICATION - ENGLISH UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		THROTTLE PUSH					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, hp	2690	3095	2690	3360	2690	3650	2690	3940
CRP/TOP	---	1.15	---	1.25	---	1.36	---	1.47
ΔT_{41}, °F	2400	2540	2400	2680	2400	2755	2400	2825
ΔT coolant, °F	BASE	+45	BASE	+89	-24	+89	-44	+89
Δ% NH	BASE	+1.5	BASE	+3.2	-0.8	+3.2	-1.6	+3.2
Δ% SFC	BASE	---	+.72	---	+1.6	---	+2.8	---
Δ% Design Flow	BASE	---	+1.7	---	+5.3	---	+10.3	---
Δ% Weight	BASE	---	+2.1	---	+5.0	---	+9.1	---
Δ% Price	BASE	---	+2.0	---	+4.2	---	+7.2	---
Δ% Maintenance	BASE	---	+2.2	---	+5.1	---	+13.7	---
Δ% DOC Penalty	BASE	---	+1.2	---	+2.5	---	+4.8	---

EVALUATION OF TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY) CONCEPT FOR CIVIL ROTORCRAFT

Tables 26 and 27 (A and B) show similar information to that shown for the Throttle Push concept. However, review of the data for CRP versus Takeoff power, show the implementation of the flow modulation system. Stage 1 blade flow is set at CRP to satisfy coating limit and then is cut back for all powers less than or equal to Takeoff power to a value such that a 100% blade life can be expended. This reduced cooling reduces the SFC penalty and increases Takeoff power such that a smaller engine is possible.

TABLE 26. COMPONENT PERFORMANCE CHANGES FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY) CONCEPT

CIVIL APPLICATION

	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY)			
	TOP	CRP	TOP	CRP	TOP	CRP
CRP/TOP	---	1.15	---	1.24	---	1.45
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+0.72	+1.61	+2.03	+3.47
Δ Stage 1 Blade Cooling, %	BASE	BASE	+0.18	+0.80	+0.57	+1.50
Δ Stage 1 Shroud Cooling, %	BASE	BASE	+0.40	+0.40	+0.82	+0.82
Δ Stage 2 Blade Cooling, %	BASE	BASE	+0.14	+0.14	+0.34	+0.34
Δ Stage 2 Vane Cooling, %	BASE	BASE	0	0	+0.30	+0.30
Δ OBP Seal Cooling, %	BASE	BASE	0	+0.27	0	+0.51
$\Delta\eta_{HPT}$, pt	BASE	BASE	+0.07	-0.02	+0.29	+0.23
			Mission	Test	Mission	Test
Stage 1 Blade Life Used	100	---	100	10	100	9
Stage 2 Blade Life Used	100	---	100	11	100	9

TABLE 27A. CYCLE SUMMARY FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY) CONCEPT

CONSTANT TAKEOFF POWER AT 305m/0/28.0°C

CIVIL APPLICATION - SI UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY)					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, kW	2005	2310	2005	2490	2005	2690	2005	2910
CRP/TOP	---	1.15	---	1.24	---	1.34	---	1.45
ΔT_{41}, °C	1315	1395	1315	1470	1315	1515	1315	1550
ΔT coolant, °C	BASE	+25	BASE	+48	-13	+47	-24	+47
Δ% NH	BASE	+1.5	BASE	+3.2	-0.8	+3.2	-1.6	+3.2
Δ% SFC	BASE	---	+.64	---	+1.3	---	+2.2	---
Δ% Design Flow	BASE	---	+1.4	---	+4.5	---	+8.6	---
Δ% Weight	BASE	---	+2.6	---	+4.9	---	+8.3	---
Δ% Price	BASE	---	+3.1	---	+5.0	---	+7.6	---
Δ% Maintenance	BASE	---	+4.2	---	+7.0	---	+15.3	---
Δ% DOC Penalty	BASE	---	+1.5	---	+2.6	---	+4.6	---

TABLE 27B. CYCLE SUMMARY FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY) CONCEPT

CONSTANT TAKEOFF POWER AT 1K/0/82.4°F

CIVIL APPLICATION - ENGLISH UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY)					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, hp	2690	3095	2690	3340	2690	3610	2690	3900
CRP/TOP	---	1.15	---	1.24	---	1.34	---	1.45
ΔT_{41}, °F	2400	2540	2400	2680	2400	2755	2400	2825
ΔT coolant, °F	BASE	+45	BASE	+86	-24	+85	-44	+84
Δ% NH	BASE	+1.5	BASE	+3.2	-0.8	+3.2	-1.6	+3.2
Δ% SFC	BASE	---	+.64	---	+1.3	---	+2.2	---
Δ% Design Flow	BASE	---	+1.4	---	+4.5	---	+8.6	---
Δ% Weight	BASE	---	+2.6	---	+4.9	---	+8.3	---
Δ% Price	BASE	---	+3.1	---	+5.0	---	+7.6	---
Δ% Maintenance	BASE	---	+4.2	---	+7.0	---	+15.3	---
Δ% DOC Penalty	BASE	---	+1.5	---	+2.6	---	+4.6	---

EVALUATION OF TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD) CONCEPT FOR CIVIL ROTORCRAFT

Tables 28 and 29 (A and B) for this system show the effect of modulating the Stage 1 shroud cooling in the same fashion as was done for the Stage 1 blade. Comparison with Table 26 shows the reduced shroud cooling flow level used for all non-Contingency operation. It also shows the gain in turbine efficiency due to the active clearance control function obtained when the extra cooling flow is turned on at contingency.

With these reduced performance decrements, the engine to be used for the rotor and stator evaluation at CRP/TOP = 1.45 will have smaller differences from the Baseline engine than the rotor only cooling engine. W_{2R} = 7.7 vs 8.6% and the higher CRP ratio. The SFC used in this evaluation will be 0.4% smaller; 1.8 vs 2.2% and the design flow increase will be 7.7%.

TABLE 28. COMPONENT PERFORMANCE CHANGES FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD) CONCEPT

CIVIL APPLICATION

	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD)			
	TOP	CRP	TOP	CRP	TOP	CRP
CRP/TOP	---	1.15	---	1.24	---	1.45
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+.32	+1.61	+1.48	+3.47
Δ Stage 1 Blade Cooling, %	BASE	BASE	+.18	+0.80	+0.57	+1.50
Δ Stage 1 Shroud Cooling, %	BASE	BASE	0	+0.40	+0.27	+0.82
Δ Stage 2 Blade Cooling, %	BASE	BASE	+.14	+0.14	+0.34	+0.34
Δ Stage 2 Vane Cooling, %	BASE	BASE	0	0	+0.30	+0.30
Δ OBP Seal Cooling, %	BASE	BASE	0	+0.27	0	+0.51
$\Delta\eta$HPT, pt	BASE	BASE	+.07	+0.24	+0.09	+0.66
			Mission	Test	Mission	Test
Stage 1 Blade Life Used	100	---	100	10	100	9
Stage 2 Blade Life Used	100	---	100	11	100	9

TABLE 29A. CYCLE SUMMARY FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD) CONCEPT

CONSTANT TAKEOFF POWER AT 305m/0/28.0°C

CIVIL APPLICATION - SI UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD)					
TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP	
SHP, kW	2005	2310	2005	2490	2005	2685	2005	2900
CRP/TOP	---	1.15	---	1.24	---	1.34	---	1.45
ΔT_{41}, °C	1315	1395	1315	1470	1315	1515	1315	1550
ΔT coolant, °C	BASE	+25	BASE	+47	-13	+47	-24	+46
Δ% NH	BASE	+1.5	BASE	+3.2	-0.8	+3.2	-1.6	+3.2
Δ% SFC	BASE	---	+.40	---	+.93	---	+1.8	---
Δ% Design Flow	BASE	---	+.74	---	+2.1	---	+7.7	---
Δ% Weight	BASE	---	+2.4	---	+4.6	---	+8.1	---
Δ% Price	BASE	---	+3.0	---	+5.0	---	+7.5	---
Δ% Maintenance	BASE	---	+4.2	---	+6.9	---	+15.2	---
Δ% DOC Penalty	BASE	---	+1.3	---	+2.4	---	+4.4	---

TABLE 29B. CYCLE SUMMARY FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD) CONCEPT

CONSTANT TAKEOFF POWER AT 1K/0/82.4°F

CIVIL APPLICATION - ENGLISH UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD)					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, hp	2690	3095	2690	3335	2690	3600	2690	3890
CRP/TOP	---	1.15	---	1.24	---	1.34	---	1.45
ΔT_{41}, °F	2400	2540	2400	2680	2400	2755	2400	2825
ΔT coolant, °F	BASE	+45	BASE	+85	-24	+84	-44	+83
Δ% NH	BASE	+1.5	BASE	+3.2	-0.8	+3.2	-1.6	+3.2
Δ% SFC	BASE	---	+.40	---	+.93	---	+1.8	---
Δ% Design Flow	BASE	---	+.74	---	+2.1	---	+7.7	---
Δ% Weight	BASE	---	+2.4	---	+4.6	---	+8.1	---
Δ% Price	BASE	---	+3.0	---	+5.0	---	+7.5	---
Δ% Maintenance	BASE	---	+4.2	---	+7.0	---	+15.3	---
Δ% DOC Penalty	BASE	---	+1.3	---	+2.4	---	+4.6	---

EVALUATION OF WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT FOR CIVIL ROTORCRAFT

Tables 30 and 31 (A and B) summarize the component and cycle changes associated with this concept, where water is injected to cool the available cooling flow instead of simply adding additional cooling flow such as was done in the Turbine Cooling Airflow Modulation (Rotor Only) concept (pgs 80-86). Performance of this concept falls between cooling flow modulation (rotor only) and cooling flow modulation (rotor and shroud point). However, when system hardware, water, tank and pump weight are accounted for, it ranks lower than either of these concepts.

TABLE 30. COMPONENT PERFORMANCE CHANGES FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

CIVIL APPLICATION

	BASE		TURBINE COOLING AIR WATER INJECTION			
	TOP	CRP	TOP	CRP	TOP	CRP
CRP/TOP	---	1.15	---	1.24	---	1.45
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+.68	+.88	+1.84	+2.11
Δ Stage 1 Blade Cooling, %	BASE	BASE	+.14	+.34	+0.38	+0.65
Δ Stage 1 Shroud Cooling, %	BASE	BASE	+.40	+.40	+0.82	+0.82
Δ Stage 2 Blade Cooling, %	BASE	BASE	+.14	+.14	+0.34	+0.34
Δ Stage 2 Vane Cooling, %	BASE	BASE	0	0	+0.30	+0.30
Δ OBP Seal Cooling, %	BASE	BASE	0	0	0	0
$\Delta\eta$ HPT, pt	BASE	BASE	+0.06	-1.79	+0.26	-1.77
Water for 2.5 min at CRP, kg (lb)	---	0 (0)	---	2.7 (6.0)	---	3.6 (8.0)
			Mission	Test	Mission	Test
Stage 1 Blade Life Used	100	---	100	9	100	6
Stage 2 Blade Life Used	100	---	100	11	100	9

TABLE 31A. CYCLE SUMMARY FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

CONSTANT TAKEOFF POWER AT 305m/0/28.0°C

CIVIL APPLICATION - SI UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		TURBINE COOLING AIR WATER INJECTION					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, kW	2005	2310	2005	2490	2005	2690	2005	2910
CRP/TOP	---	1.15	---	1.24	---	1.35	---	1.45
ΔT_{41}, °C	1315	1395	1315	1470	1315	1515	1315	1550
ΔT coolant, °C	BASE	+25	BASE	-134	-13	-103	-24	-166
Δ% NH	BASE	+1.5	BASE	+3.2	-0.8	+3.2	-1.6	+3.2
Δ% SFC	BASE	---	+.58	---	+1.2	---	+2.0	---
Δ% Design Flow	BASE	---	+1.3	---	+4.4	---	+8.0	---
Δ% Weight	BASE	---	+4.2	---	+6.6	---	+9.9	---
Δ% Price	BASE	---	+3.3	---	+5.1	---	+7.6	---
Δ% Maintenance	BASE	---	+4.3	---	+6.5	---	+14.7	---
Δ% DOC Penalty	BASE	---	+1.9	---	+3.0	---	+4.9	---

TABLE 31B. CYCLE SUMMARY FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

CONSTANT TAKEOFF POWER AT 1K/0/82.4°F

CIVIL APPLICATION - ENGLISH UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		TURBINE COOLING AIR WATER INJECTION					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, hp	2690	3095	2690	3340	2690	3610	2690	3900
CRP/TOP	---	1.15	---	1.24	---	1.35	---	1.45
ΔT_{41}, °F	2400	2540	2400	2680	2400	2755	2400	2825
ΔT coolant, °F	BASE	+45	BASE	-241	-24	-186	-44	-298
Δ% NH	BASE	+1.5	BASE	+3.2	-0.8	+3.2	-1.6	+3.2
Δ% SFC	BASE	---	+.58	---	+1.2	---	+2.0	---
Δ% Design Flow	BASE	---	+1.3	---	+4.4	---	+8.0	---
Δ% Weight	BASE	---	+4.2	---	+6.6	---	+9.9	---
Δ% Price	BASE	---	+3.3	---	+5.1	---	+7.6	---
Δ% Maintenance	BASE	---	+4.3	---	+6.5	---	+14.7	---
Δ% DOC Penalty	BASE	---	+1.9	---	+3.0	---	+4.9	---

EVALUATION OF WATER INJECTION INTO COMPRESSOR INLET CONCEPT FOR CIVIL ROTORCRAFT

Water injection into the inlet of the compressor reduces the engine temperatures and permits an increase in engine speed and power while holding the high pressure turbine rotor inlet temperature (T41) nearly constant. Tables 32 (A and B) show that water injection of 0.9% of compressor inlet airflow produces a +25% power increase over TOP at essentially the same T41 1396°C (2545°F) vs 1393°C (2540°C) as +15% power increase without the addition of water. Note that the addition of water at CRP permits an additional 3°C (5°F) increase in T41 which results from the 22°C (40°F) reduction in compressor discharge temperature (T3). The increased compressor clearance at TOP results in 0.6 pt loss in compressor efficiency which requires a 1.0% increase in engine flow size to hold Takeoff Power constant. The increase in fuel consumption associated with the open compressor clearance is a penalty on the system. Further studies of water injection into the compressor inlet at CRP/TOP greater than 1.25 were not evaluated because the benefit analysis did not show promise for this novel system.

TABLE 32A. CYCLE SUMMARY FOR WATER INJECTION INTO COMPRESSOR INLET CONCEPT

CONSTANT TAKEOFF POWER AT 305m/0/28.0°C

CIVIL APPLICATION - SI UNITS

	Nominal CRP/TOP = 1.15 BASE		Nominal CRP/TOP = 1.25 COMPRESSOR WATER INJECTION	
	TOP	CRP	TOP	CRP
SHP, kW	2005	2310	2005	2505
CRP/TOP	---	1.15	---	1.25
ΔT_{41}, °C	1315	1395	1315	1395
ΔT coolant, °C	BASE	+25	+2	+4
Δ% NH	BASE	+1.5	BASE	+3.8
$\Delta\eta$ comp, pt	BASE	BASE 1	-0.6	-0.1
Δ% SFC	BASE	---	+.68	---
Δ% Design Flow	BASE	---	+.96	---
Δ% Weight	BASE	---	+6.8	---
Water for 2.5 min at CRP, kg		0		10.3

TABLE 32B. CYCLE SUMMARY FOR WATER INJECTION INTO COMPRESSOR INLET CONCEPT

CONSTANT TAKEOFF POWER AT 1K/0/82.4°F

CIVIL APPLICATION - ENGLISH UNITS

	Nominal CRP/TOP = 1.15 BASE		Nominal CRP/TOP = 1.25 COMPRESSOR WATER INJECTION	
	TOP	CRP	TOP	CRP
SHP, hp	2690	3095	2690	3360
CRP/TOP	---	1.15	---	1.25
ΔT_{41}, °F	2400	2540	2400	2545
ΔT coolant, °F	BASE	+45	+4	+7
Δ% NH	BASE	+1.5	BASE	+3.8
$\Delta\eta$ comp, pt	BASE	BASE 1	-0.6	-0.1
Δ% SFC	BASE	---	+.68	---
Δ% Design Flow	BASE	---	+.96	---
Δ% Weight	BASE	---	+6.8	---
Water for 2.5 min at CRP, lb		0		22.8

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EVALUATION OF WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT FOR CIVIL ROTORCRAFT

The combination of water injection into the compressor inlet and turbine cooling air is an attempt to combine the benefits of both systems and capitalize on the limited commonality of the water and control systems, thereby reducing the system penalties.

Water injection in the cooling air reduces the quantity of cooling airflow required at CRP but has no effect on the cooling airflow requirements at TOP and below. Table 33 shows that the cycle chargeable cooling flow for the civil engine increases 1.11% at 1.49 CRP/TOP relative to 1.15 CRP/TOP. This penalty coupled with the loss of compressor efficiency due to increased compressor clearances requires a 7.7% engine flow size increase to maintain TOP. Also, SFC is increased by 2.0% see Tables 34 (A and B). The engine flow size and SFC penalty are +4.2% and +1.4% respectively at 1.37 CRP/TOP. The percent water injected at 1.37 and 1.49 CRP/TOP is the same as used in the 1.25 CRP/TOP for compressor water injection only.

TABLE 33. COMPONENT PERFORMANCE CHANGES FOR WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT

CIVIL APPLICATION

	BASE		COMPRESSOR AND TURBINE COOLING AIR		WATER INJECTION	
	TOP	CRP	TOP	CRP	TOP	CRP
CRP/TOP	---	1.15	---	1.37	---	1.49
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+0.81	+1.11	+1.11	+1.36
Δ Stage 1 Blade Cooling, %	BASE	BASE	+0.23	+0.53	+0.34	+0.59
Δ Stage 1 Shroud Cooling, %	BASE	BASE	+0.38	+0.38	+0.54	+0.54
Δ Stage 2 Blade Cooling, %	BASE	BASE	+0.20	+0.20	+0.23	+0.23
Δ Stage 2 Vane Cooling, %	BASE	BASE	0	0	0	0
Δ OBP Seal Cooling, %	BASE	BASE	0	0	0	0
$\Delta\eta$ HPT, pt	BASE	BASE	+0.6	-0.42	+0.13	-0.37
$\Delta\eta$ comp, pt	BASE	BASE	-0.3	-0.1	-0.3	-0.1
Water for 2.5 min at CRP, kg (lb)	---	0 (0)	---	10.8 (23.8)	---	11.1 (24.4)
			Mission	Test	Mission	Test
Stage 1 Blade Life Used	100	---	100	15	100	17
Stage 2 Blade Life Used	100	---	100	29.	100	42

TABLE 34A. CYCLE SUMMARY FOR WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT

CONSTANT TAKEOFF POWER AT 305m/0/28.0°C

CIVIL APPLICATION - SI UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		COMPRESSOR AND TURBINE COOLING AIR WATER INJECTION					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, kW	2005	2310			2005	2750	2005	2980
CRP/TOP	---	1.15			---	1.37	---	1.48
ΔT_{41}, °C	1315	1395			1315	1475	1315	1515
ΔT coolant, °C	BASE	+25			-11	-209	-23	-200
Δ% NH	BASE	+1.5			-0.8	+5.1	-1.6	+5.1
Δ% SFC	BASE	---			+1.4	---	+2.0	---
Δ% Design Flow	BASE	---			+4.2	---	+7.7	---
Δ% Weight	BASE	---			+10.0	---	+13.1	---
Δ% Price	BASE	---			+5.5	---	+8.2	---
Δ% Maintenance	BASE	---			+7.2	---	+14.9	---
Δ% DOC Penalty	BASE	---			+3.9	---	+5.7	---

TABLE 34B. CYCLE SUMMARY FOR WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT

CONSTANT TAKEOFF POWER AT 1K/0/82.4°F

CIVIL APPLICATION - ENGLISH UNITS

	Nominal CRP/TOP = 1.15		Nominal CRP/TOP = 1.25		Cycle Rematched Nominal CRP/TOP = 1.35		Cycle Rematched Nominal CRP/TOP = 1.45	
	BASE		COMPRESSOR AND TURBINE COOLING AIR WATER INJECTION					
	TOP	CRP	TOP	CRP	TOP	CRP	TOP	CRP
SHP, hp	2690	3095			2690	3685	2690	3995
CRP/TOP	---	1.15			---	1.37	---	1.48
ΔT_{41}, °F	2400	2540			2400	2690	2400	2755
ΔT coolant, °F	BASE	+45			-21	-377	-41	-360
Δ% NH	BASE	+1.5			-0.8	+5.1	-1.6	+5.1
Δ% SFC	BASE	---			+1.4	---	+2.0	---
Δ% Design Flow	BASE	---			+4.2	---	+7.7	---
Δ% Weight	BASE	---			+10.0	---	+13.1	---
Δ% Price	BASE	---			+5.5	---	+8.2	---
Δ% Maintenance	BASE	---			+7.2	---	+14.9	---
Δ% DOC Penalty	BASE	---			+3.9	---	+5.7	---

EVALUATION SUMMARY OF CONCEPTS FOR MILITARY ROTORCRAFT

Tables 35 through 45 (A and B) show engine and component parameters for engines incorporating the six concepts under study as they would be sized to satisfy the requirements of the military rotorcraft.

Although the numerical values are different from those exhibited when these engines were installed in the civil rotorcraft, most of the statements and conclusions for the civil rotorcraft will be true for the military application.

One noticeable difference is in the Stage 1 blade life used in the military vs the civil. This is primarily the result of calculating the military life used on the basis of a 300-hour qualification test vs a civil mission of 20,000 hours.

TABLE 35 COMPONENT PERRFORMANCE CHANGES FOR THROTTLE PUSH CONCEPT

MILITARY APPLICATION

	BASE		THROTTLE PUSH			
	IRP	CRP	IRP	CRP	IRP	CRP
CRP/IRP	---	1.15	---	1.25	---	1.47
ΔΣChargeable Cooling Flow, %	BASE	BASE	+.61	+.61	+1.39	+1.39
ΔStage 1 Blade Cooling, %	BASE	BASE	+.30	+.30	+0.80	+0.80
ΔStage 1 Shroud Cooling, %	BASE	BASE	+.31	+.31	+0.49	+0.49
ΔStage 2 Blade Cooling, %	BASE	BASE	0	0	+0.10	+0.10
ΔStage 2 Vane Cooling, %	BASE	BASE	0	0	0	0
ΔOBP Seal Cooling, %	BASE	BASE	0	0	0	0
Δη HPT, pt	BASE	BASE	+.13	+.13	+0.26	+0.26
		Test	Mission	Test	Mission	
Stage 1 Blade Life Used	100	---	48	26	16	30
Stage 2 Blade Life Used	100	---	100	63	100	100

TABLE 36A. CYCLE SUMMARY FOR THROTTLE PUSH CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 915m/0/33.1°C

MILITARY APPLICATION - SI UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		THROTTLE PUSH					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, kW	2940	3380	2940	3675	2940	3985	2940	4305
CRP/IRP	---	1.15	---	1.25	---	1.36	---	1.47
ΔT_{41}, °C	1370	1445	1370	1515	1370	1560	1370	1560
ΔT coolant, °C	BASE	+23	BASE	+46	-11	+46	-38	+17
Δ% NH	BASE	+1.1	BASE	+2.6	-0.9	+2.6	-2.9	+0.7
Δ% SFC	BASE	---	+.36	---	+1.0	---	+1.8	---
Δ% Design Flow	BASE	---	+1.0	---	+4.7	---	+13.6	---
Δ% Weight	BASE	---	+1.8	---	+5.1	---	+12.1	---
Δ% Price	BASE	---	+1.7	---	+3.8	---	+8.4	---
Δ% Maintenance	BASE	---	+2.7	---	+4.8	---	+11.6	---
Δ% LCC Penalty	BASE	---	+.50	---	+1.4	---	+2.9	---

TABLE 36B. CYCLE SUMMARY FOR THROTTLE PUSH CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 3K/0/91.5°F

MILITARY APPLICATION - ENGLISH UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		THROTTLE PUSH					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, hp	3940	4530	3940	4925	3940	5345	3940	5770
CRP/IRP	---	1.15	---	1.25	---	1.36	---	1.47
ΔT_{41}, °F	2500	2635	2500	2760	2500	2840	2500	2840
ΔT coolant, °F	BASE	+42	BASE	+82	-21	+82	-69	+30
Δ% NH	BASE	+1.1	BASE	+2.6	-0.9	+2.6	-2.9	+0.7
Δ% SFC	BASE	---	+.36	---	+1.0	---	+1.8	---
Δ% Design Flow	BASE	---	+1.0	---	+4.7	---	+13.6	---
Δ% Weight	BASE	---	+1.8	---	+5.1	---	+12.1	---
Δ% Price	BASE	---	+1.7	---	+3.8	---	+8.4	---
Δ% Maintenance	BASE	---	+2.7	---	+4.8	---	+11.6	---
Δ% LCC Penalty	BASE	---	+.50	---	+1.4	---	+2.9	---

TABLE 37. COMPONENT PERFORMANCE CHANGES FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY) CONCEPT

MILITARY APPLICATION

	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY)			
	IRP	CRP	IRP	CRP	IRP	CRP
CRP/IRP	---	1.15	---	1.25	---	1.44
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+.39	+.71	+.72	+1.56
ΔStage 1 Blade Cooling, %	BASE	BASE	+.06	+.30	+.17	+0.80
ΔStage 1 Shroud Cooling, %	BASE	BASE	+.31	+.31	+.49	+0.49
ΔStage 2 Blade Cooling, %	BASE	BASE	+.02	0	+.06	0
ΔStage 2 Vane Cooling, %	BASE	BASE	0	0	0	0
ΔOBP Seal Cooling, %	BASE	BASE	0	+.10	0	+0.27
$\Delta\eta$HPT, pt	BASE	BASE	+.07	+.03	+.10	+0.02
			Test	Mission	Test	Mission
Stage 1 Blade Life Used	100	---	86	41	46	80
Stage 2 Blade Life Used	100	---	100	63	100	100

TABLE 38A. CYCLE SUMMARY FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY) CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 915m/0/33.1°C

MILITARY APPLICATION - SI UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY)					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, kW	2940	3380	2940	3660	2940	3955	2940	4235
CRP/IRP	---	1.15	---	1.25	---	1.35	---	1.44
ΔT_{41}, °C	1370	1445	1370	1515	1370	1560	1370	1560
ΔT coolant, °C	BASE	+23	BASE	+45	-11	+44	-38	+16
Δ% NH	BASE	+1.1	BASE	+2.6	-0.9	+2.6	-2.9	+0.7
Δ% SFC	BASE	---	+.25	---	+.73	---	+1.5	---
Δ% Design Flow	BASE	---	+.68	---	+3.7	---	+12.6	---
Δ% Weight	BASE	---	+2.2	---	+4.8	---	+11.9	---
Δ% Price	BASE	---	+2.6	---	+4.4	---	+8.9	---
Δ% Maintenance	BASE	---	+4.3	---	+6.3	---	+13.1	---
Δ% LCC Penalty	BASE	---	+0.60	---	+1.3	---	+2.8	---

TABLE 38B. CYCLE SUMMARY FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY) CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 3K/0/91.5°F

MILITARY APPLICATION - ENGLISH UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR ONLY)					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, hp	3940	4530	3940	4905	3940	5305	3940	5680
CRP/IRP	---	1.15	---	1.25	---	1.35	---	1.44
ΔT_{41}, °F	2500	2635	2500	2760	2500	2840	2500	2840
ΔT coolant, °F	BASE	+42	BASE	+81	-21	+80	-69	+28
Δ% NH	BASE	+1.1	BASE	+2.6	-0.9	+2.6	-2.9	+0.7
Δ% SFC	BASE	---	+.25	---	+.73	---	+1.5	---
Δ% Design Flow	BASE	---	+.68	---	+3.7	---	+12.6	---
Δ% Weight	BASE	---	+2.2	---	+4.8	---	+11.9	---
Δ% Price	BASE	---	+2.6	---	+4.4	---	+8.9	---
Δ% Maintenance	BASE	---	+4.3	---	+6.3	---	+13.1	---
Δ% LCC Penalty	BASE	---	+0.60	---	+1.3	---	+2.8	---

TABLE 39. COMPONENT PERFORMANCE CHANGES FOR TURBINE COOLING AIRFLOW MODULATION CONCEPT

MILITARY APPLICATION

	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD)			
	IRP	CRP	IRP	CRP	IRP	CRP
CRP/IRP	---	1.15	---	1.24	---	1.43
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+.08	+.71	+.28	+1.56
ΔStage 1 Blade Cooling, %	BASE	BASE	+.06	+.30	+.17	+0.80
ΔStage 1 Shroud Cooling, %	BASE	BASE	0	+.31	+.05	+0.49
ΔStage 2 Blade Cooling, %	BASE	BASE	+.02	0	+.06	0
ΔStage 2 Vane Cooling, %	BASE	BASE	0	0	0	0
ΔOBP Seal Cooling, %	BASE	BASE	0	+.10	0	+0.27
$\Delta\eta$HPT, pt	BASE	BASE	-.04	+.18	-.06	+0.25
			Test	Mission	Test	Mission
Stage 1 Blade Life Used	100	---	86	26	46	30
Stage 2 Blade Life Used	100	---	100	63	81	100

TABLE 40A. CYCLE SUMMARY FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD) CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 915m/0/33.1°C

MILITARY APPLICATION - SI UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD)					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, kW	2940	3380	2940	3655	2940	3940	2940	4200
CPR/IRP	---	1.15	---	1.24	---	1.34	---	1.43
ΔT_{41}, °C	1370	1445	1370	1515	1370	1560	1370	1560
ΔT coolant, °C	BASE	+23	BASE	+44	-11	+44	-38	+14
Δ% NH	BASE	+1.1	BASE	+2.6	-0.9	+2.6	-2.9	+0.7
Δ% SFC	BASE	---	+.11	---	+.59	---	+1.2	---
Δ% Design Flow	BASE	---	+0.2	---	+3.2	---	+11.6	---
Δ% Weight	BASE	---	+2.1	---	+4.7	---	+11.2	---
Δ% Price	BASE	---	+2.6	---	+4.4	---	+8.8	---
Δ% Maintenance	BASE	---	+4.3	---	+6.2	---	+13.1	---
Δ% LCC Penalty	BASE	---	+0.53	---	+1.2	---	+2.6	---

TABLE 40B. CYCLE SUMMARY FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD) CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 3K/0/91.5°F

MILITARY APPLICATION - ENGLISH UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD)					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP	3940	4530	3940	4900	3940	5285	3940	5630
CPR/IRP	---	1.15	---	1.24	---	1.34	---	1.43
ΔT_{41}, °F	2500	2635	2500	2760	2500	2840	2500	2840
ΔT coolant, °F	BASE	+42	BASE	+80	-21	+79	-69	+26
Δ% NH	BASE	+1.1	BASE	+2.6	-0.9	+2.6	-2.9	+0.7
Δ% SFC	BASE	---	+.11	---	+.59	---	+1.2	---
Δ% Design Flow	BASE	---	+0.2	---	+3.2	---	+11.6	---
Δ% Weight	BASE	---	+2.1	---	+4.7	---	+11.2	---
Δ% Price	BASE	---	+2.6	---	+4.4	---	+8.8	---
Δ% Maintenance	BASE	---	+4.3	---	+6.2	---	+13.1	---
Δ% LCC Penalty	BASE	---	+0.53	---	+1.2	---	+2.6	---

TABLE 41. COMPONENT PERFORMANCE CHANGES FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

MILITARY APPLICATION

	BASE		TURBINE COOLING AIRFLOW WATER INJECTION			
	IRP	CRP	IRP	CRP	IRP	CRP
CRP/IRP	---	1.15	---	1.25	---	1.42
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+.31	+.40	+.67	+.73
ΔStage 1 Blade Cooling, %	BASE	BASE	0	+.09	+.08	+.14
ΔStage 1 Shroud Cooling, %	BASE	BASE	+.31	+.31	+.49	+.49
ΔStage 2 Blade Cooling, %	BASE	BASE	0	0	+.10	+.10
ΔStage 2 Vane Cooling, %	BASE	BASE	0	0	0	0
ΔOBP Seal Cooling, %	BASE	BASE	0	0	0	0
$\Delta\eta$HPT, pt	BASE	BASE	+.07	-.94	+.14	-1.3
Water for 2.5 min at CRP, kg (lb)	---	0 (0)	---	1.8 (3.9)	---	3.5 (7.7)
			Test	Mission	Test	Mission
Stage 1 Blade Life Used	100	---	100	48	59	100
Stage 2 Blade Life Used	100	---	100	63	81	100

TABLE 42A. CYCLE SUMMARY FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 915m/0/33.1°C

MILITARY APPLICATION - SI UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		TURBINE COOLING AIRFLOW WATER INJECTION					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, kW	2940	3380	2940	3660	2940	3965	2940	4175
CRP/IRP	---	1.15	---	1.25	---	1.35	---	1.42
ΔT_{41}, °C	1370	1445	1370	1515	1370	1560	1370	1560
ΔT coolant, °C	BASE	+23	BASE	-57	-11	-96	-38	-133
Δ% NH	BASE	+1.1	BASE	-2.6	+0.9	-2.6	+2.9	+0.7
Δ% SFC	BASE	---	+.19	---	+.55	---	+1.25	---
Δ% Design Flow	BASE	---	+.53	---	+3.8	---	+12.0	---
Δ% Weight	BASE	---	+4.2	---	+6.6	---	+12.8	---
Δ% Price	BASE	---	+2.8	---	+4.3	---	+8.9	---
Δ% Maintenance	BASE	---	+3.8	---	+5.5	---	+12.3	---
Δ% LCC Penalty	BASE	---	+0.84	---	+1.4	---	+2.8	---

TABLE 42B. CYCLE SUMMARY FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 3K/0/91.5°F

MILITARY APPLICATION - ENGLISH UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		TURBINE COOLING AIRFLOW WATER INJECTION					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, hp	3940	4530	3940	4905	3940	5315	3940	5600
CRP/IRP	---	1.15	---	1.25	---	1.35	---	1.42
ΔT_{41}, °F	2500	2635	2500	2760	2500	2840	2500	2840
ΔT coolant, °F	BASE	+42	BASE	-103	-21	-173	-69	-240
Δ% NH	BASE	+1.1	BASE	+2.6	-0.9	+2.6	-2.9	+0.7
Δ% SFC	BASE	---	+.19	---	+.55	---	+1.25	---
Δ% Design Flow	BASE	---	+.53	---	+3.8	---	+12.0	---
Δ% Weight	BASE	---	+4.2	---	+6.6	---	+12.8	---
Δ% Price	BASE	---	+2.8	---	+4.3	---	+8.9	---
Δ% Maintenance	BASE	---	+3.8	---	+5.5	---	+12.3	---
Δ% LCC Penalty	BASE	---	+0.84	---	+1.4	---	+2.8	---

TABLE 43A. CYCLE SUMMARY FOR WATER INJECTION INTO COMPRESSOR INLET CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 915m/0/33.1°C

MILITARY APPLICATION - SI UNITS

	Nominal CRP/IRP = 1.15 BASE		Nominal CRP/IRP = 1.25 COMPRESSOR WATER INJECTION	
	IRP	CRP	IRP	CRP
SHP, kW	2940	3380	2940	3670
CRP/IRP	---	1.15	---	1.25
ΔT_{41}, °C	1370	1445	1370	1450
ΔT coolant, °C	BASE	+23	+2	+7
Δ% NH	BASE	+1.1	BASE	+3.7
$\Delta\eta$ comp, pt	BASE	BASE	-0.5	-0.1
Δ% SFC	BASE	---	+0.5	---
Δ% Design Flow	BASE	---	+0.8	---
Δ% Weight	BASE	---	+5.4	---
Water for 2.5 min at CRP, kg		0		11.8

TABLE 43B. CYCLE SUMMARY FOR WATER INJECTION INTO COMPRESSOR INLET CONCEPT

CONSTANT TAKEOFF POWER AT 3K/0/91.5°F

MILITARY APPLICATION - ENGLISH UNITS

	Nominal CRP/IRP = 1.15 BASE		Nominal CRP/IRP = 1.25 COMPRESSOR WATER INJECTION	
	IRP	CRP	IRP	CRP
SHP, hp	3940	4530	3940	4925
CRP/IRP	---	1.15	---	1.25
ΔT_{41}, °F	2500	2635	2500	2640
ΔT coolant, °F	BASE	+42	+4	+12
Δ% NH	BASE	+1.1	BASE	+3.7
$\Delta\eta$ comp, pt	BASE	BASE 1	-0.5	-0.1
Δ% SFC	BASE	---	+0.5	---
Δ% Design Flow	BASE	---	+0.8	---
Δ% Weight	BASE	---	+5.4	---
Water for 2.5 min at CRP, lb		0		26.0

TABLE 44. COMPONENT PERFORMANCE CHANGES FOR WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT

MILITARY APPLICATION

	BASE		COMPRESSOR AND TURBINE COOLING AIRFLOW WATER INJECTION			
	IRP	CRP	IRP	CRP	IRP	CRP
CRP/IRP	---	1.15	---	1.37	---	1.48
$\Delta\Sigma$Chargeable Cooling Flow, %	BASE	BASE	+0.30	+0.43	+.15	+.15
ΔStage 1 Blade Cooling, %	BASE	BASE	0	+0.13	+.08	+.08
ΔStage 1 Shroud Cooling, %	BASE	BASE	+0.30	+0.30	0	0
ΔStage 2 Blade Cooling, %	BASE	BASE	0	0	+.07	+.07
ΔStage 2 Vane Cooling, %	BASE	BASE	0	0	0	0
ΔOBP Seal Cooling, %	BASE	BASE	0	0	0	0
ΔHPT, pt	BASE	BASE			-.04	-.54
$\Delta\eta$comp, pt	BASE	BASE	-.5	-.1	-.5	-.1
Water for 2.5 min at CRP, kg (lb)		0 (0)		13.2 (29)	---	12.7 (28)
			Test	Mission	Test	Mission
Stage 1 Blade Life Used	100	---	92	82	59	100
Stage 2 Blade Life Used	100	---	94	96	79	100

TABLE 45A. CYCLE SUMMARY FOR WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 915m/0/33.1°C

MILITARY APPLICATION - SI UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		COMPRESSOR AND TURBINE COOLING AIRFLOW WATER INJECTION					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, kW	2940	3380			2940	4035	2940	4345
CRP/IRP	---	1.15			---	1.37	---	1.48
ΔT_{41}, °C	1370	1445			1370	1510	1370	1490
ΔT coolant, °C	BASE	+23			-10	-59	-37	-34
Δ% NH	BASE	+1.1			-0.9	+3.0	-2.9	+0.3
Δ% SFC	BASE	---			+1.1	---	+1.4	---
Δ% Design Flow	BASE	---			+4.0	---	+11.7	---
Δ% Weight	BASE	---			+9.3	---	+15.2	---
Δ% Price	BASE	---			+5.8	---	+10.1	---
Δ% Maintenance	BASE	---			+6.6	---	+13.0	---
Δ% LCC Penalty	BASE	---			+2.0	---	+3.2	---

TABLE 45B. CYCLE SUMMARY FOR WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT

CONSTANT INTERMEDIATE RATED POWER AT 3K/0/91.5°F

MILITARY APPLICATION - ENGLISH UNITS

	Nominal CRP/IRP = 1.15		Nominal CRP/IRP = 1.25		Cycle Rematched Nominal CRP/IRP = 1.35		Cycle Rematched Nominal CRP/IRP = 1.45	
	BASE		COMPRESSOR AND TURBINE COOLING AIRFLOW WATER INJECTION					
	IRP	CRP	IRP	CRP	IRP	CRP	IRP	CRP
SHP, hp	3940	4530			3940	5410	3940	5825
CRP/IRP	---	1.15			---	1.37	---	1.48
ΔT_{41}, °F	2500	2635			2500	2750	2500	2710
ΔT coolant, °F	BASE	+42			-18	-106	-66	-61
Δ% NH	BASE	+1.1			-0.9	+3.0	-2.9	+0.3
Δ% SFC	BASE	---			+1.1	---	+1.4	---
Δ% Design Flow	BASE	---			+4.0	---	+11.7	---
Δ% Weight	BASE	---			+9.3	---	+15.2	---
Δ% Price	BASE	---			+5.8	---	+10.1	---
Δ% Maintenance	BASE	---			+6.6	---	+13.0	---
Δ% LCC Penalty	BASE	---			+2.0	---	+3.2	---

WEIGHT, PRICE AND MAINTENANCE INCREASES FOR CIVIL AND MILITARY ROTORCRAFT

The increases in weight, price, and maintenance costs at different Contingency Power Ratios for each application and particular concept are expressed in non-dimensional form as percentages of the total baseline engine weight, price, and maintenance cost respectively (see Tables 46 and 47). For example, as this study is for twin-engined rotorcraft, a percentage weight increase is derived from the expression:

$$\Delta\% = \frac{(2 \times \Delta\text{Engine Weight} + \Delta\text{Common Equipment Weight}) \times 100}{(2 \times \text{Baseline Engine Weight})}$$

Weight and cost increases are estimates based on the component material additions and modifications described for each concept under the Task III study. Maintenance costs are derived from component part replacement severity rates based on similar studies, labor, and consumables used. In the case of the high-pressure turbine blade when the airfoil coating temperature is limiting and not the creep rupture stress then the replacement severity rate is modified to reflect the relative blade life usage.

Weight, price, and maintenance increases per aircraft listed in Table 46 for those concepts involving an external water storage and supply system are generally less than shown for the air modulation systems. This result is due to the fact that the water system is shared by both engines. The formula shows that any equipment, common to both engines, will only be included once when total twin-engine rotorcraft increases are calculated.

The distribution and sources of increases in weight, price, and maintenance costs throughout the engine are shown in Tables A-1 through A-8 in Appendix A.

Special Tables A-2B and A-6B also in Appendix A were developed to show the weight, price, and maintenance increases that would take place on the cooling flow modulation concept if a squib operated blowout disk were used instead of a two position electrically operated valve.

Similarly, Tables A-3B and A-7B in Appendix A were generated to show the effect on weight, price, and maintenance increases that would occur if water were introduced by a pressurized tank bladder asembly rather than by a motor/pump combination.

For each of the concepts under study, horsepower penalties were incurred due to the cycle performance changes caused by secondary cooling flow and turbine efficiency variations. However, in order to apply the economic sensitivities consistent with the approach used by Sikorsky Aircraft to generate the "ideal" data, it was necessary to scale these engines up to deliver the same horsepower at the Intermediate Rated Power for the military engine and Takeoff Power for the Civil engine. Weight, cost, and maintenance increments were generated to account for engine design changes, additional system hardware, and consumables which are required for each of the concepts (reference Tables 48 through 55). In addition, scale factors were generated which converted the engine power scale factors into weight, price, and maintenance scale factors based on Figures 12-14 and 19-21. The two scale factors multiplied together yield the total percent increase in weight, cost, and maintenance to be used in the Task V evaluation. These results are shown on Tables 46 and 47 for the civil and military rotorcraft respectively.

TABLE 46. PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE

CIVIL ROTORCRAFT

Concept	CRP/TOP*	1.25	1.30	1.357	1.465
Throttle Push	Δ% Weight	2.11	3.63	5.04	9.14
	Δ% Cost	2.0	3.1	4.2	7.2
	Δ% Maint	3.3	4.6	5 9	9.5
Cooling Flow Modulation (Rotor Only)	CRP/TOP	1.241	1.285	1.341	1.45
	Δ% Weight	2.56	3.7	4.9	8.3
	Δ% Cost	3.1	3 9	5.0	7.6
	Δ% Maint	5.3	6.5	7.7	11.1
Cooling Flow Modulation (Rotor and Shroud)	CRP/TOP	1.239	1.28	1.338	1.446
	Δ% Weight	2.35	3.1	4.6	8.1
	Δ% Cost	3.0	3.7	4.95	7.5
	Δ% Maint	5.3	6.2	7.7	11.0
Water Injection Turbine Cooling Airflow	CRP/TOP	1.243	1.295	1.351	1.453
	Δ% Weight	4.2	5.7	6.6	9.9
	Δ% Cost	3.3	4.0	5.1	7.6
	Δ% Maint	5.3	5.9	7.2	10.6
Water Injection Compressor Inlet and Turbine Cooling Airflow	CRP/TOP			1 37	1.485
	Δ% Weight			10.0	13.1
	Δ% Cost	N/A	N/A	5.5	8.2
	Δ% Maint			7.4	10.7

*Δ% = Percent Increase

TABLE 47. PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE

MILITARY ROTORCRAFT

Concept	CRP/IRP*	1.25	1.30	1.357	1.465
Throttle Push	Δ% Weight	1.76	2.82	5.05	12.08
	Δ% Cost	1.7	2.3	3.8	8.4
	Δ% Maint	2.7	3.3	4.8	9.8
Cooling Flow Modulation (Rotor Only)	CRP/IRP	1.246	1.292	1.347	1.442
	Δ% Weight	2.21	2.77	4.79	11.93
	Δ% Cost	2.6	3.1	4.4	8.9
	Δ% Maint	4.3	4.8	6.3	11.3
Cooling Flow Modulation (Rotor and Shroud)	CRP/IRP	1.245	1.292	1.350	1.422
	Δ% Weight	2.13	2.53	4.69	11.22
	Δ% Cost	2.6	3.2	4.4	8.8
	Δ% Maint	4.3	4.9	6.2	11.2

*Δ% = Percent Increase

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TASK V

BENEFIT ASSESSMENT

TASK V - BENEFIT ASSESSMENT

The procedures used to determine the weight, SFC, price, and maintenance changes required to bring each concept to the objectives of 100% life usage and constant IRP or TOP horsepower at CRP ratios up to the maximum usable levels were discussed in Task IV. The resulting changes are shown as %'s in Tables 46 and 47. As specified in the Statement of Work, the ranking of the various concepts was scheduled to be carried out by utilizing DOC and LCC as the primary parameters with consideration also to gross weight, weight of fuel burned, acquisition cost, overall empty weight, reliability, and logistics. To translate the results of Task IV into these categories, sensitivities generated by Sikorsky Aircraft were used and this data is shown in Tables 6 and 12.

CIVIL

The benefits of incorporating promising contingency concepts on vehicle economics (DOC), gross weight, and fuel burned are shown in Figures 36 through 38 respectively, for the civil rotorcraft application. As can be seen, the various augmented air cooling schemes along with the water addition into turbine coolant concept are viable competitive systems having maximum DOC benefits of 2.3 to 2.7%. The throttle push concept optimized at a contingency of about 35% while the others continued to show increasing benefits with increasing contingency. Figures 39 through 41 show how the net benefit curve (Figure 36) was obtained. For each concept and at each CRP ratio the "ideal" value is reduced by the maintenance weight, cost, and SFC penalties. These penalties were obtained by multiplying each engine effect listed in Tables 46 and 47 by the appropriate sensitivity shown in Tables 6 and 12. A similar method was used to obtain the net benefit curves for the other criteria shown in Figures 37 and 38.

MILITARY

Evaluation criteria for the military rotorcraft are shown in Figures 42 through 44. As in the civil application, the concepts are very competitive. Besides the parameters shown, other factors such as simplicity, reliability, and logistics have to be considered. Due to the trend reversal of the economic trade factors, it is doubtful if a CRP ratio above 1.30-1.35 should be considered.

The method for obtaining these benefit curves is the same as for the civil engine and are shown in Figures 45 through 47. Each penalty is subtracted from the "ideal" curve to display finally the actual benefit.

The military "ideal" curves show a much less positive slope than the civil "ideal" curves, based on the studies at higher CRP ratios conducted by Sikorsky Aircraft. Therefore, even though the military penalties are of similar magnitudes to the civil penalties, the military benefit curves tend to exhibit negative slopes. On the basis of this trend, it appears that the military rotorcraft at its maximum usable CRP ratio will not benefit as much as the civil rotorcraft at its maximum usable CRP ratio.

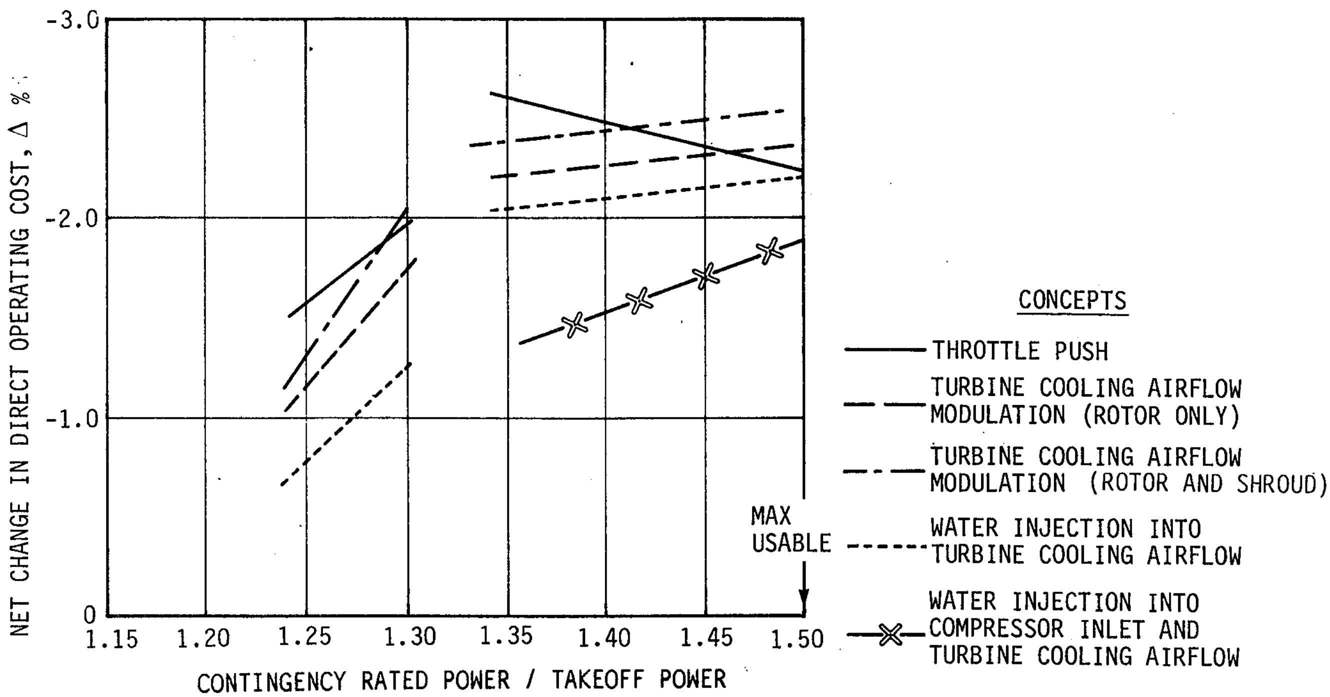

Figure 36. Net Change in Direct Operating Cost vs Contingency Rated Power Ratio for Civil Rotorcraft.

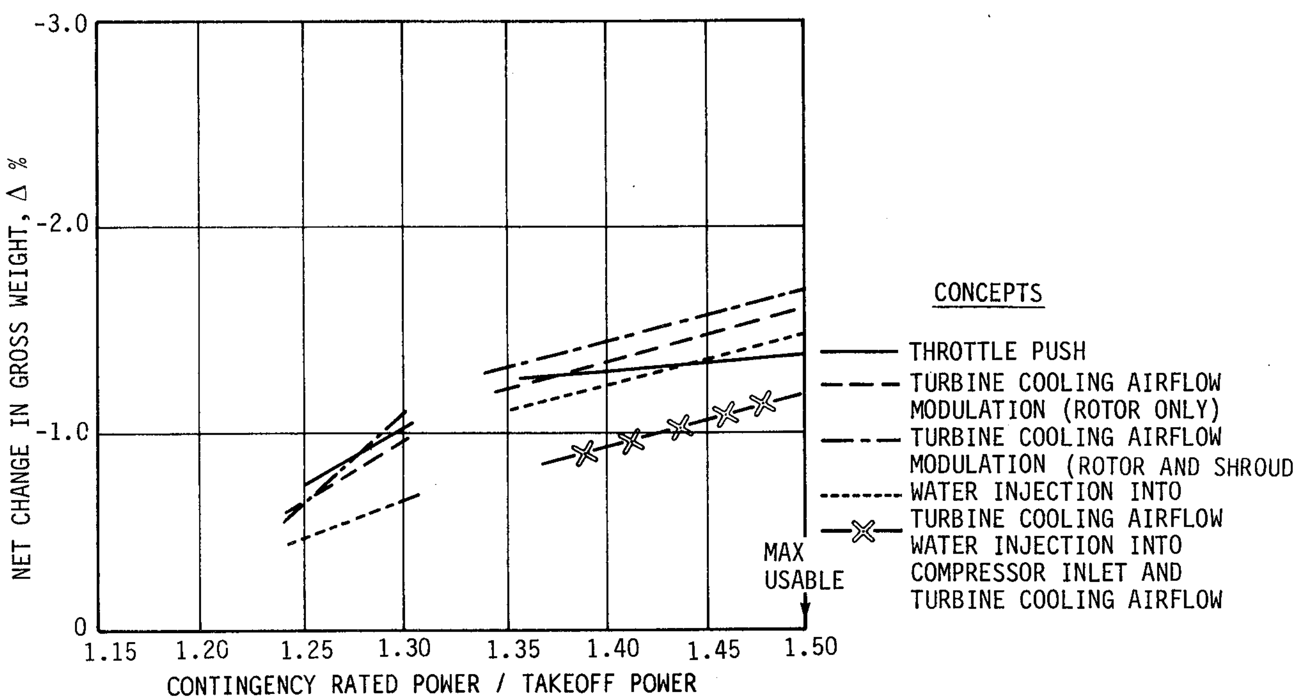

Figure 37. Net Change in Gross Weight vs Contingency Rated Power Ratio for Civil Rotorcraft Concepts.

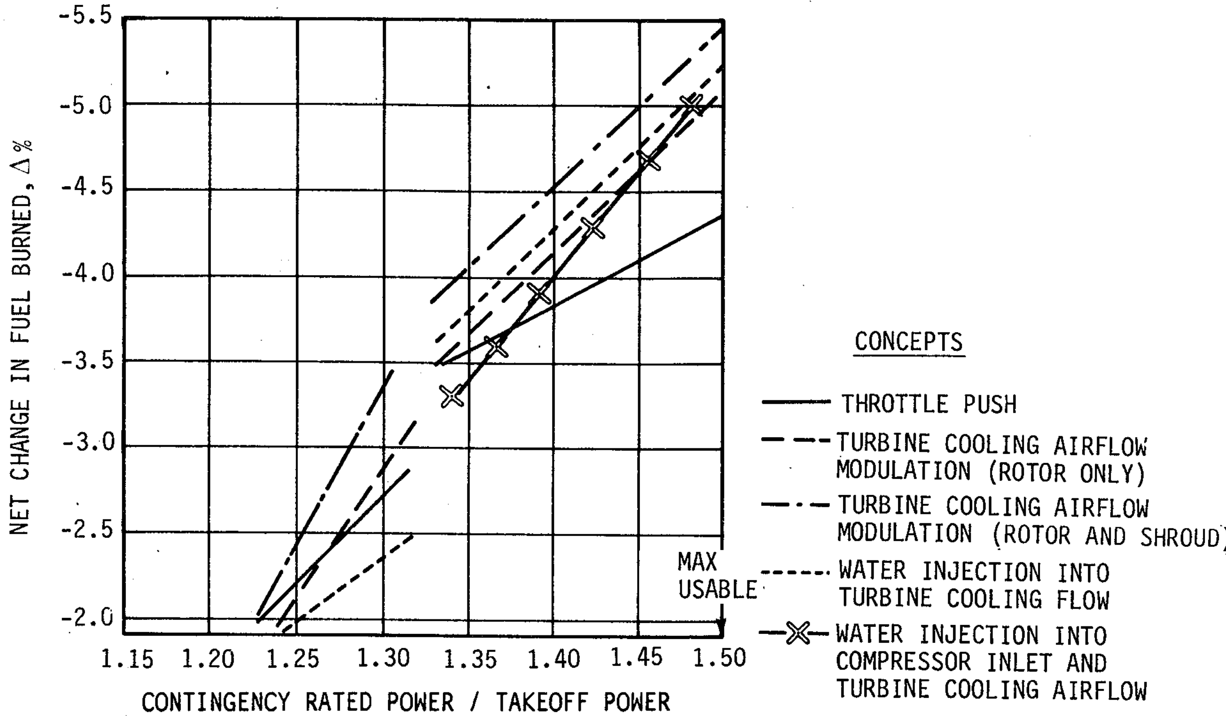

Figure 38. Net Change in Fuel Burned for Civil Rotorcraft Concepts.

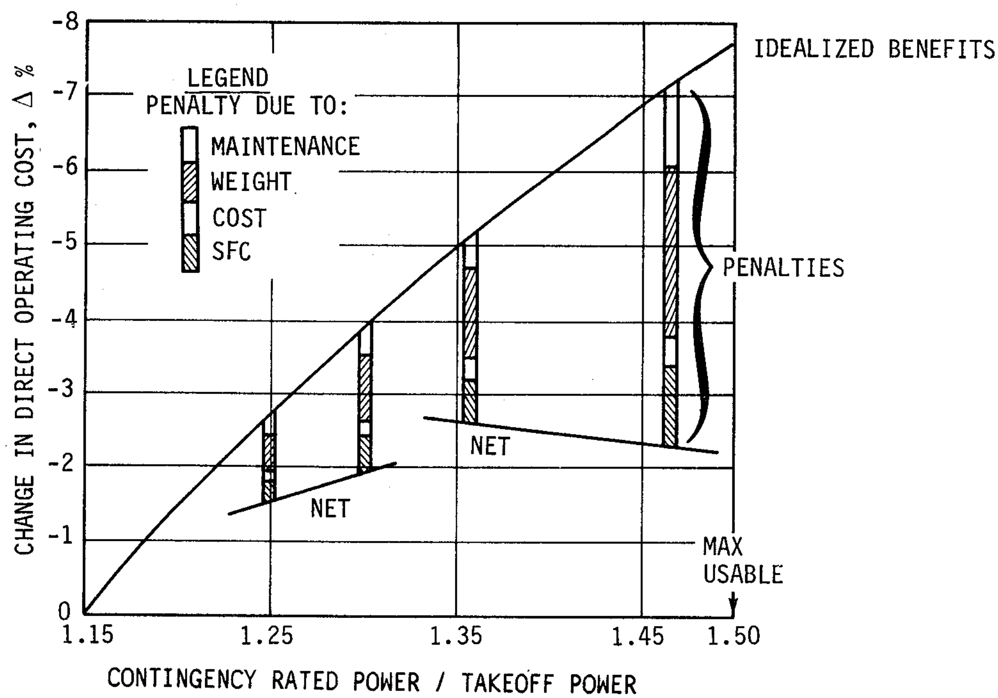

Figure 39. Mission Trade Factors for Civil Rotorcraft Throttle Push Concept.

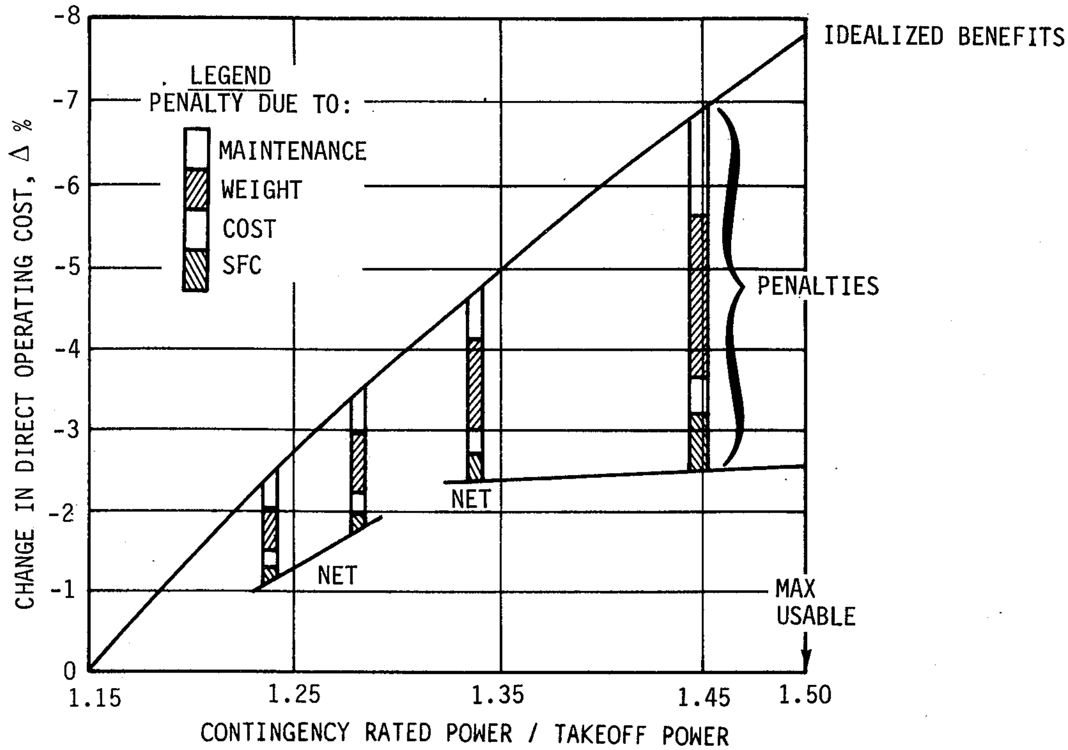

Figure 40. Mission Trade Factors for Civil Rotorcraft Cooling Airflow Modulation (Rotor and Shroud) Concept.

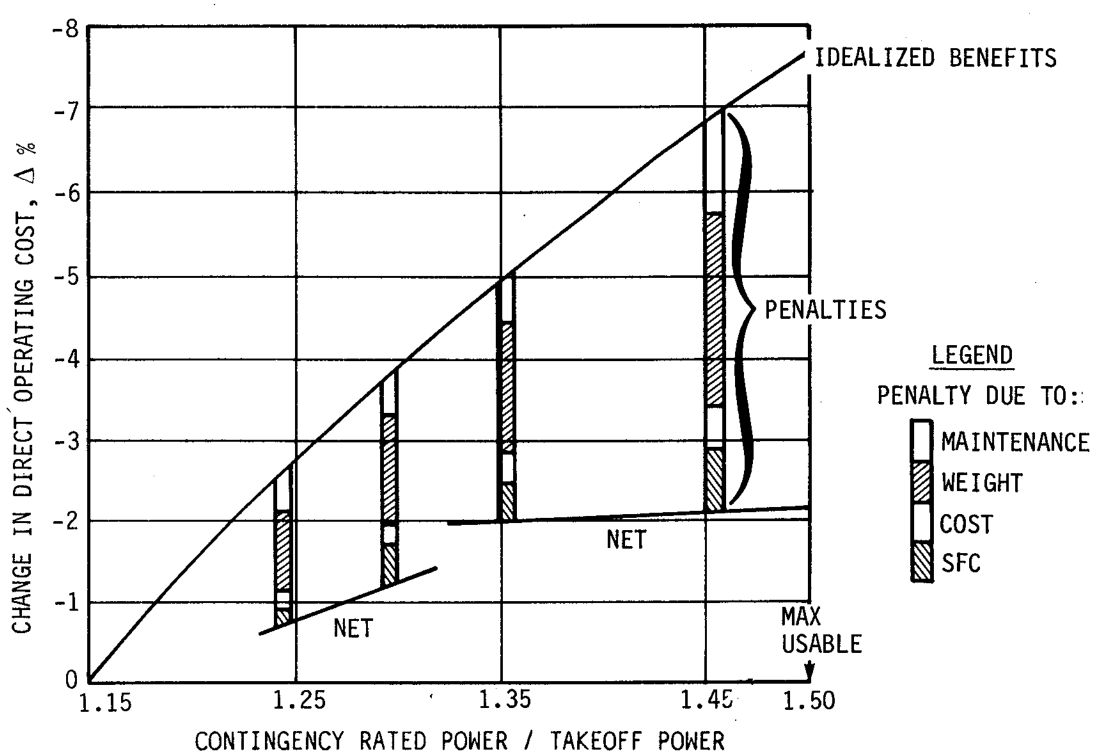

Figure 41. Mission Trade Factors for Water Injection for Civil Rotorcraft Water Injection into Turbine Cooling Airflow Concept.

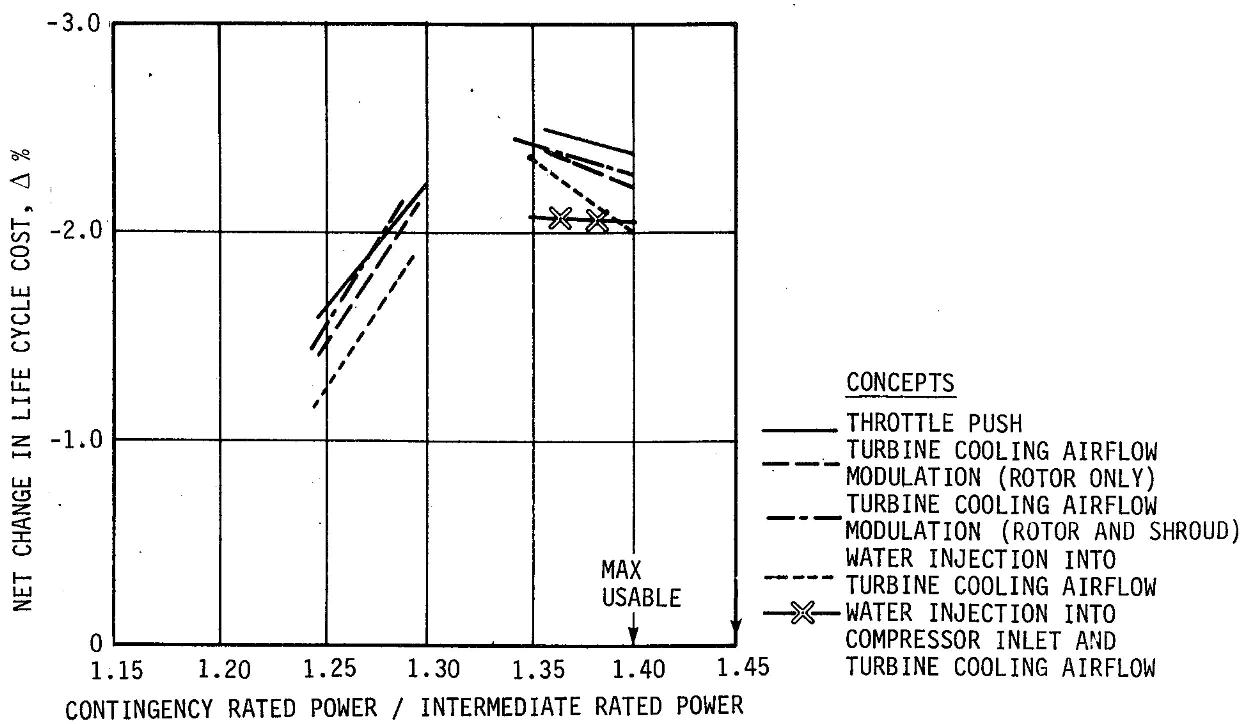

Figure 42. Net Change in Life Cycle Cost vs Contingency Rated Power Ratio for Military Rotorcraft Concepts.

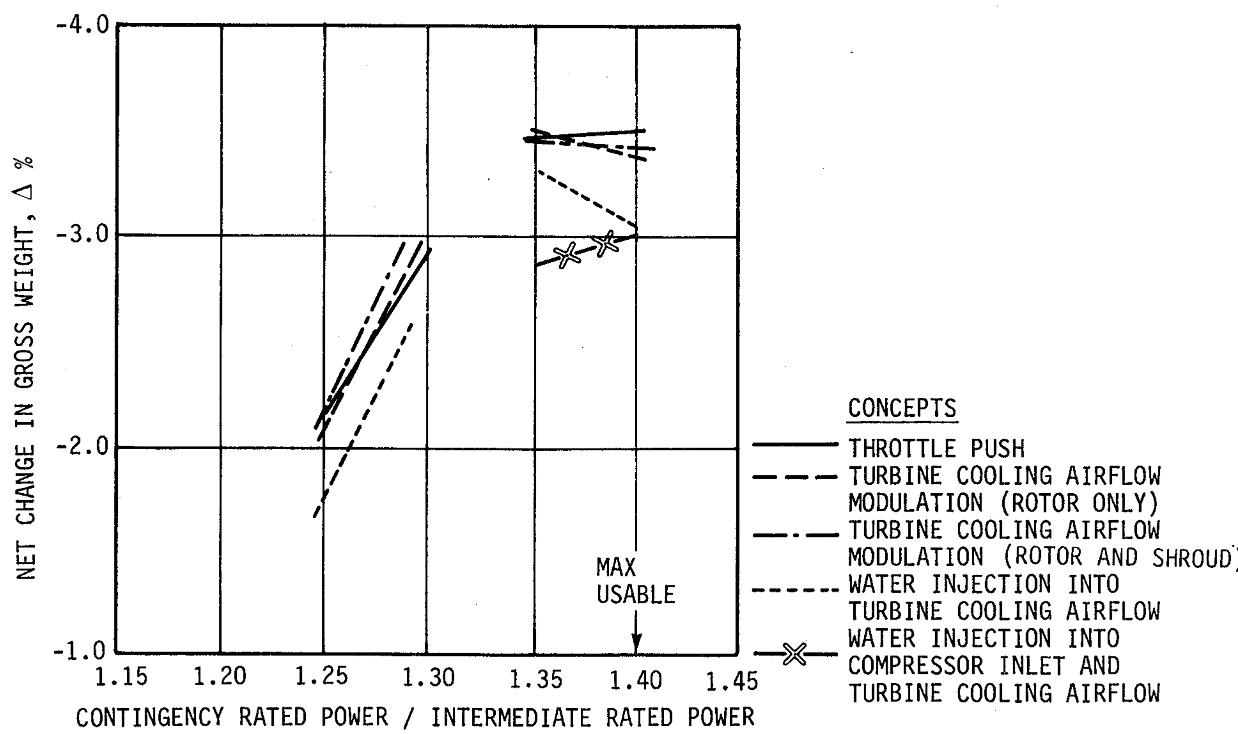

Figure 43. Net Change in Gross Weight vs Contingency Rated Power Ratio for Military Rotorcraft Concepts.

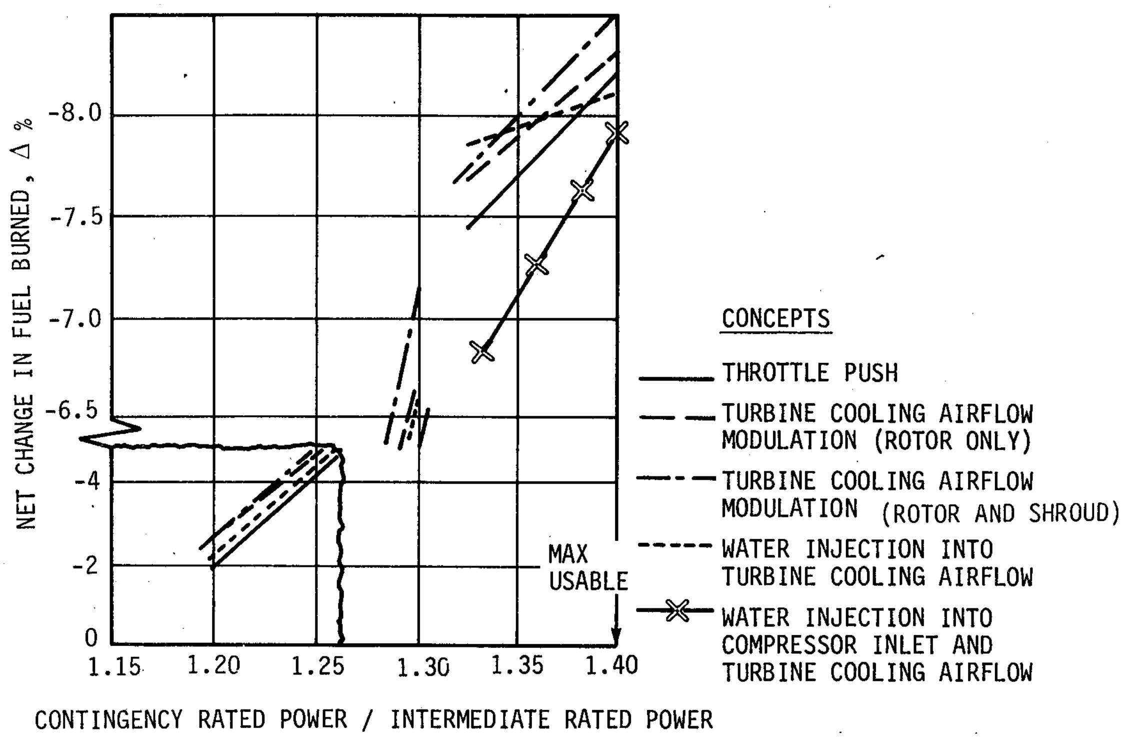

Figure 44. Net Change in Fuel Burned vs Contingency Rated Power Ratio for Military Rotorcraft Concepts.

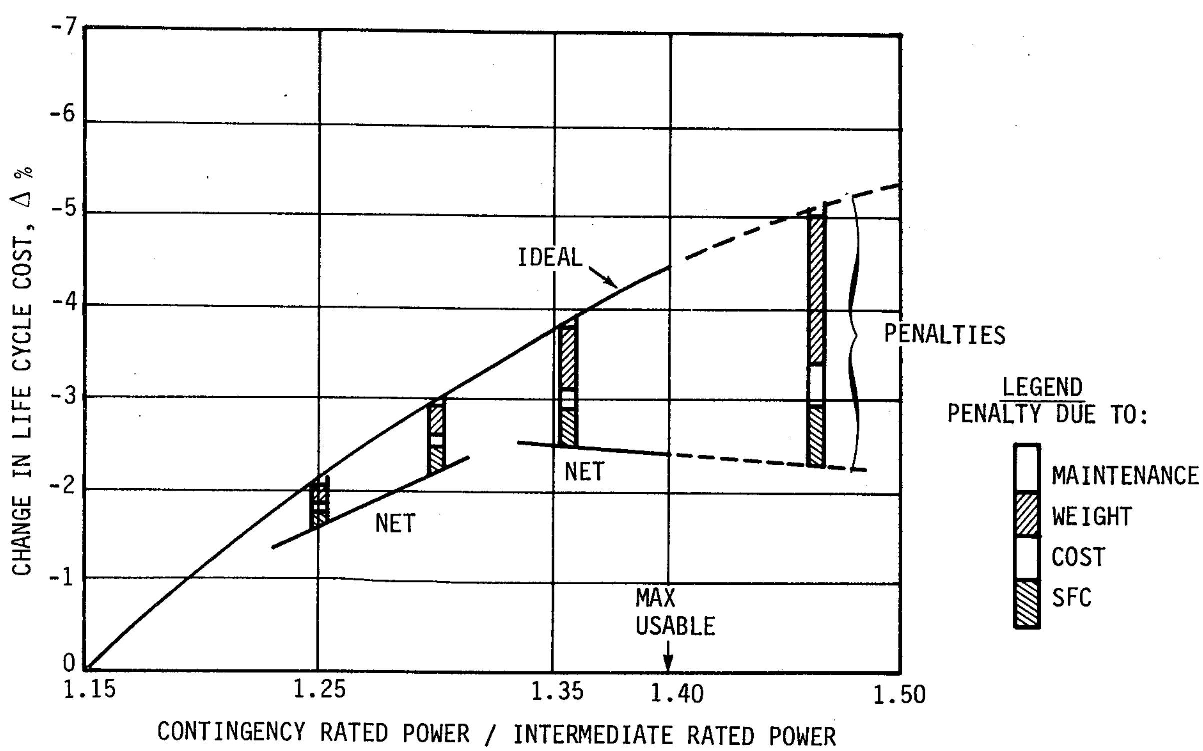

Figure 45. Mission Trade Factors for Military Rotorcraft Throttle Push Concept.

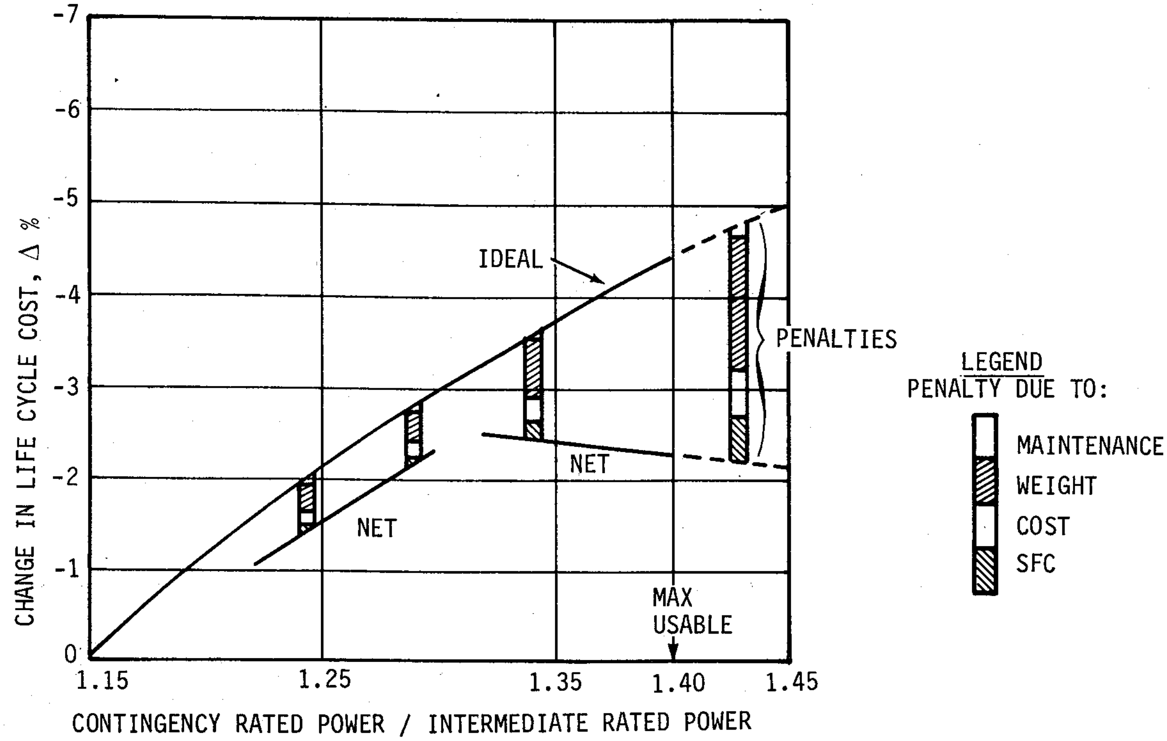

Figure 46. Mission Trade Factors for Military Rotorcraft Turbine Cooling Airflow Modulation (Rotor and Shroud) Concept.

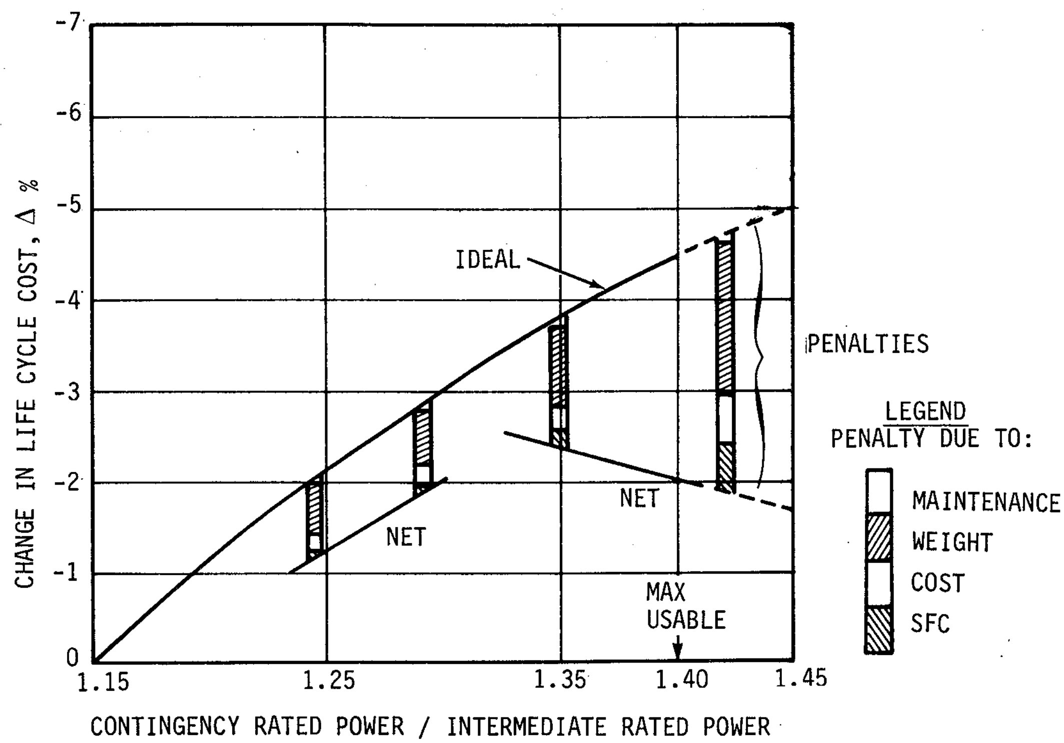

Figure 47. Mission Trade Factors for Military Rotorcraft Water Injection into Turbine Cooling Airflow Concept.

DISCUSSION

The %DOC and %LCC net benefits versus CRP/TOP and CRP/IRP results shown in Figures 40 and 46 show some characteristics which require explanation. First, as shown in these figures, the idealized curves are slightly nonlinear with the military LCC curve showing lower levels and a lower rate of increase than the civil DOC curve. This effect is primarily the result of the reduced utilization rate for the military rotorcraft (360 versus 2000 flight hours per year). Even though the higher power loading of the military rotorcraft will have a larger favorable impact on the gross weight, the aquisition cost, and the weight of fuel burned than on the civil rotorcraft; the associated effect on the economic benefit will be less favorable than on the civil rotorcraft. This occurs since the major cost items on the military rotorcraft are fixed costs and a lesser utilization will mean a reduced effect on the other costs associated with operating and support (O&S) functions, both of which will result in a decreasing economic benefit with increasing CRP ratio.

In regard to engine related penalties, cooling flow increases at higher T41 levels, i.e. higher CRP ratios, will mean larger losses. These losses will result in SFC increases, specific HP reductions due to less efficient cycles in addition to the effects of rematching the compressor at a lower speed. The rematching losses become larger as the CRP ratio increases; an example of this is shown in Figure 48. This effect is a major contributor to the discontinuities in the net benefit curves and to the reduced slopes as the CRP ratio increases further.

This effect is more pronounced for the Throttle Push concept due to the fact that the cooling flow increases will be constant at all power settings. As shown in Table 48 for the Turbine Cooling Airflow Modulation concept, the cooling flows can be reduced from the CRP levels thus reducing the penalties incurred with the modulation systems. The Water Injection into the Turbine Cooling Airflow concept will also have this same advantage (Reference Table 33A). However, for the Throttle Push concept, these penalties must be fixed at the CRP level. Even after addition of the hardware used to modulate the cooling flows, the DOC benefit for the modulation systems still shows an ascending characteristic when compared to the Throttle Push concept.

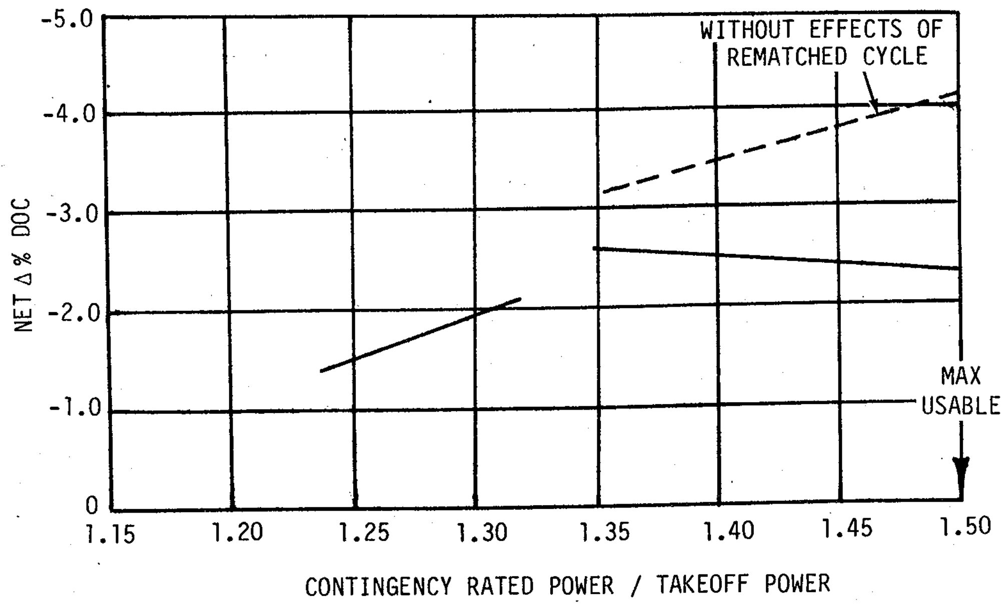

Figure 48. Effect of Rematching Cycle on Direct Operating Cost for Civil Rotorcraft.

TABLE 48. COMPARISON OF NET CHANGE IN DIRECT OPERATING COSTS - THROTTLE PUSH VERSUS TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD) CONCEPT								
	Civil Rotorcraft							
	Throttle Push				Turbine Cooling Airflow (Rotor and Shroud) Modulation			
Normal CRP Ratio	1.35		1.45		1.35		1.45	
	CRP	TOP	CRP	TOP	CRP	TOP	CRP	TOP
Δ% Chargeable Cooling Flow	1.72	1.72	2.96	2.96	2.86	.77	3.47	1.48
Horsepower Decrement	3.17	3.17	5.25	5.25	5.0	1.55	6.0	2.8
Δ% SFC	1.61	1.61	2.82	2.82	2.13	.93	2.84	1.81
Δ% Weight		5.04		9.14		4.58		8.08
Δ% DOC Penalty		2.52		4.79		2.37		4.29
Δ% Benefit		2.61		2.39		2.35		2.54

RELIABILITY AND LOGISTICS

The competitive systems on the basis of quantitative benefit analysis were Throttle Push, Cooling Flow Modulation and Water Injection into the Turbine Cooling Airflow system. These systems were compared to the Baseline engine for other factors such as reliability and logistics.

For the purpose of reliability analysis, each of the systems was considered relative to the Baseline engine, considering only the elements necessary to obtain Contingency Power. This includes the control, sensors, and special elements such as the water injection system. All engines are designed for equal life, so that failure rates and reliability under normal operating conditions are common to all. There are, however, differences in the reliability of the engine to attain Contingency Power, on demand.

Failure rate estimates were made for each component involved in the Contingency Power system, based on field experience for similar parts. These were then compiled statistically into the expected engine failure rate to produce Contingency Power.

	Failure rate/ 1,000,000 Engine Flight Hours
Baseline engine - from all causes	2,300
Baseline engine - contingency system only	5
Throttle Push - contingency system only	5
Turbine Cooling Airflow Modulation - contingency system only	73
Water Injection into Turbine Cooling Airflow - contingency system only	305

Based on these factors, the combined reliability of the twin engine-powered helicopter to attain Contingency Power on the remaining engine after failure of an engine during a 2.2-hour flight is as follows:

	Reliability	Failure Rate/ 1,000,000 Flights
Baseline	.999999	1
Throttle Push	.999999	1
Turbine Cooling Airflow Modulation	.999999	1
Water Injection into Turbine Cooling Airflow	.999997	3

RELIABILITY AND LOGISTICS - Continued

The failure rate of the Contingency Power systems is only life threatening if it is combined with the failure of an engine during the same flight. Short of this highly improbable event, the failure of the Contingency Power system will lead to flight delays if discovered during preflight checks. To put the rates into perspective, for one civil commuter aircraft over its 10-year life, the Water Injection into Turbine Cooling Airflow system failure rate of 305/1,000,000 LFM means approximately 7 system malfunctions.

This is a deficiency of the water system relative to either Throttle Push or Turbine Cooling Airflow Modulation, and probably undesirable, at least for the high utilization civil environment.

The effect on logistics of the additional components required by the Contingency Power systems has been taken into account in the maintenance portion of the DOC and LCC analysis. There is, however, no additional penalty inherent in the Water Injection into Turbine Cooling Airflow system requirement for a demineralized water-antifreeze mixture to be available at all flight line locations.

OTHER FACTORS

There are practical considerations beyond the pure numerical comparisons of DOC and LCC. Reliability factors favor Throttle Push over Turbine Cooling Airflow Modulation and Water Injection. However, the reliability reduction would not be serious enough to rule out either system. The logistics of the special water supply is a clear disadvantage to those systems requiring it, but it is in the nuisance category and as a matter of judgment does not eliminate it from consideration. The ground rules for this study specified new, advanced engines for the application for Contingency Power Systems. Therefore, conceptual designs were considered requiring large cooling flow increases and in the case of Turbine Cooling Airflow Modulation, system changes are necessary to incorporate this feature. If however, the concepts were to be applied to current and derivative engines, the use of Throttle Push or Turbine Cooling Airflow Modulation would be limited without major engine redesign. Water into the turbine cooling system is probably adaptable without major modifications - to the blade for example.

Another factor of interest is the applicability of these study results to other size engines. The civil and military engines are 6.4 kg/s (14 lb/sec) and 14.5 kg/s(32 lb/sec), respectively. There is no limit in the direction of larger engines. The results would probably not be the same if much smaller sizes, say 2.3 - 4.5 kg/s (5-10 lb/sec) are considered. It becomes more difficult to execute the cooling flow increases associated with Turbine Cooling Airflow Modulation or Throttle Push. Water injection will continue to be an efficient cooling approach and perhaps this concept could be desirable for engines in this size range.

GROUND RULE VARIATIONS

Duration of Contingency Power

In the Statement of Work, the Contingency Power interval was specified as 2-1/2 minutes. However, it was stated that lesser durations should be studied to determine if any concept would benefit by reducing this requirement down to as low as 30 seconds.

1. Solid Propellant EPU

   As stated in the System Evaluation section (pg 57), this concept was eliminated from further consideration after the initial conceptual design studies indicated that the cartridge and breech weight, size, and cost were excessive. However, since reducing the duration of Contingency Power would significantly decrease the required size and weight of the propellant and breech, this concept was resubmitted for further evaluation. A 30-second duration was selected for study since this would mean an 80% reduction in the propellant weight from the 2-1/2 minute weight. Since horsepower output of the EPU is established by the propellant flow rate, the cartridge would have to retain its original diametral dimensions, since the end burn area sets the flow rate. The length however would decrease in the same proportion as the time required for Contingency Power decreased. Although this would mean the same percent decrease in propellant or cartridge weight, the breech weight would only decrease by its shorter length, which would be a much smaller percent weight decrease. For example, for the EPU system designed to give a CRP ratio of 1.25 for the military rotorcraft, reducing the time to 30 seconds would reduce the cartridge weight of 60 kg (132 lb) to 11.8 kg (26 lb) by 80% but the breech would only be reduced from 50 kg (110 lb) to 25.8 kg (57 lb) by 48%. Various combinations of CRP ratios and times were investigated but in each case, the weight, size, and cost remained at a high level ruling out EPU even for short durations.

2. Throttle Push

   Since this concept is based on a fixed cooling flow system with no consumables, reducing the time at Contingency Power would only affect the blade life used while at that power. For example, the civil engine at a CRP/TOP ratio of 1.465 uses 36% of the Stage 1 blade life at CRP, 21% during other power points for a total of 57% for the total mission. Reducing to a 30-second Contingency requirement would mean that only 7.2% life would be used at Contingency for a total of only 28% life used. Reducing Stage 1 blade cooling flow would result in bringing the life used back to the objective of 100% but this cannot be done since the blade 1 average bulk temperature is already at the coating limit. Therefore, the only advantage here is that fewer blade replacements will be required and maintenance cost will decrease. This factor is taken into account in the evaluation.

   Since the Stage 2 blade is not at the coating limit, a reduced cooling flow in this case - 0.11% can be set to use up 100% blade life with the reduced Contingency time. Reducing the cooling flow gives more horsepower and less SFC and a reduced engine size. Figure 53 shows a net decrease in DOC of 0.13%.

GROUND RULE VARIATIONS - Continued

Duration of Contingency Power - Continued

3. Turbine Cooling Flow Modulation (Rotor and Shroud)

   Since this concept has the advantage of adjusting cooling flow between Contingency Power and the powers at or less than Takeoff power, it can reduce the flow at non-contingency powers so as to use 100% of the Stage 1 blade life. Applying a reduced flow to this configuration results in a net decrease in DOC of 0.35% as shown in Figure 49.

4. Water Injection into Turbine Cooling Airflow

   This concept will benefit by the reduction in consumables, in this case water, that will result from reducing the time at Contingency Power. However, in this case, the water used amounted to only 1% of the engine weight. Reducing this by 80%, meant a reduction of 0.8% in engine weight or a gain of 0.9 in percent of DOC. Reducing the Stage 2 blade cooling flow to use up 100% life will give another 0.10% gain in percent of DOC or a total gain of 0.29% as shown in Figure 49.

In conclusion, referring to Figure 49, it can be seen that Turbine Cooling Airflow Modulation concept will have the most gain from a duration decrease to 30 seconds. In addition, the change in net DOC advantage of the Turbine Cooling Airflow Modulation concept over the Throttle Push will increase by another 0.35-0.13 = 0.23%.

Fuel Cost

For this study, a fuel cost of $0.264/l ($1.00/gal) was assumed based on information continuously being collected and evaluated by both the Sikorsky Aircraft and the General Electric Co. All economic factors such as DOC and LCC were calculated using this fuel cost. However, for a study involving aircraft operation 10 to 15 years in the future, it is wise to examine the effect of the fuel cost on these economic factors to determine, at least, if there would be any change in the ranking of the concepts, if world conditions caused a sudden rise in fuel cost.

This type of investigation was made for the leading concepts for each rotorcraft namely the Throttle Push and the Turbine Cooling Airflow Modulation (Rotor and Shroud) concepts. A fuel cost of $0.396/l (1.50/gal) was selected as a realistic value based on recent trends.

As the first step in this study, the economic trade factor data generated by Sikorsky Aircraft was redone with this higher fuel cost. One result shown in Figure 50 indicates that a higher fuel cost will give an increase in the ideal benefit at each Contingency Rated Power ratio. Similarly, the effect of weight and SFC changes on the economic factors was recalculated incorporating the higher fuel cost.

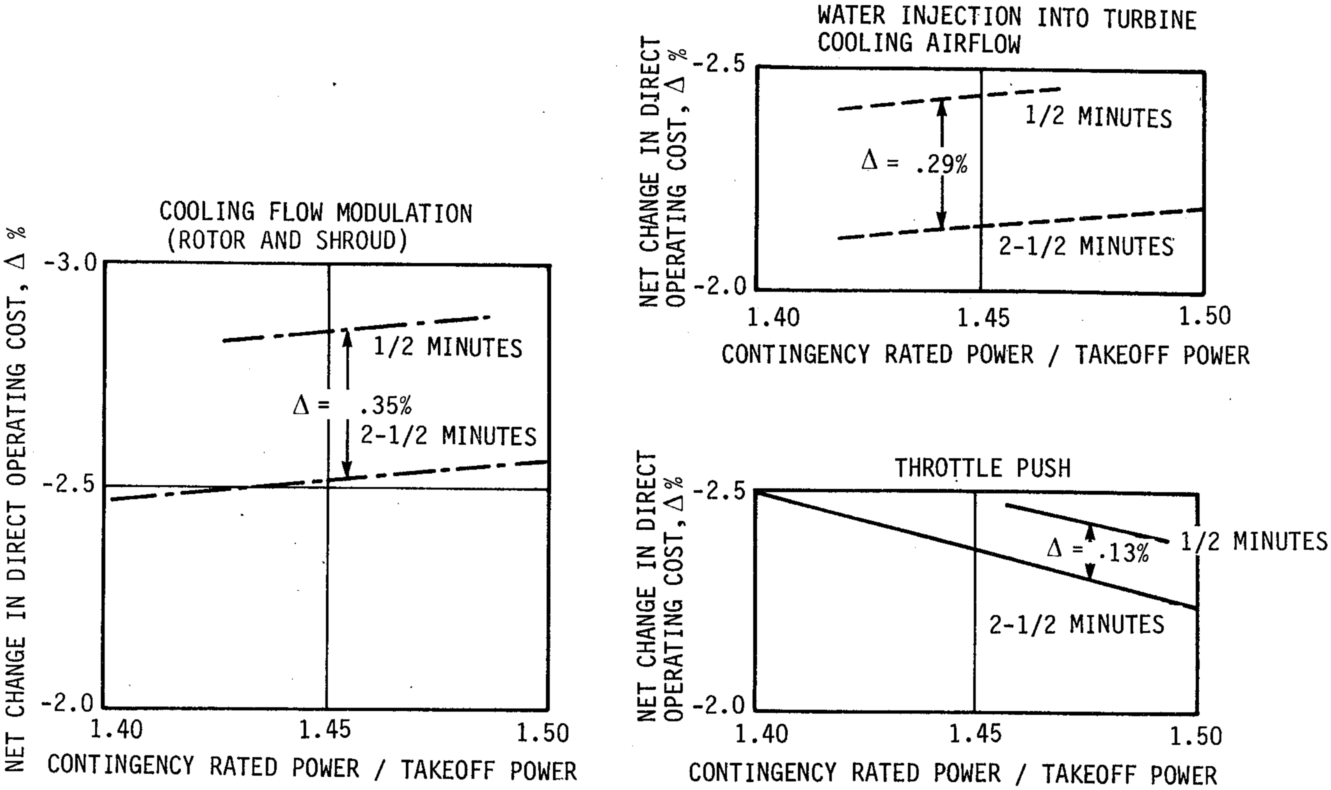

Figure 49. Effect of Reducing Time at Contingency Rated Power on Net Change in Direct Operating Cost for Civil Rotorcraft.

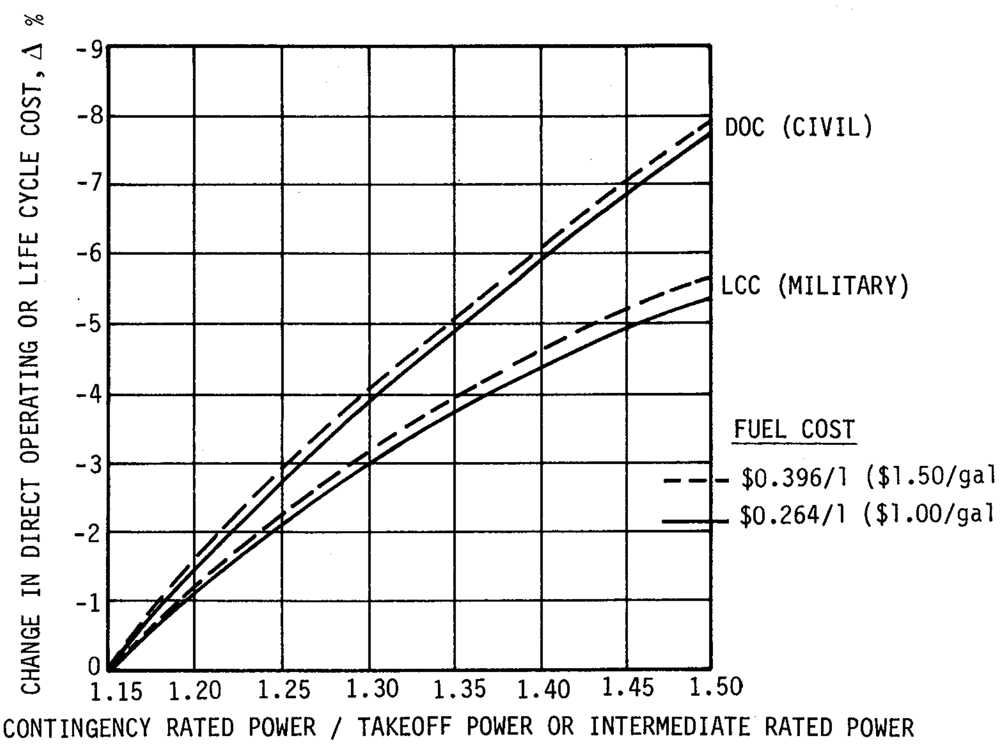

Figure 50. Effect of Fuel Cost on Direct Operating Cost and Life Cycle Cost for Civil and Military Rotorcraft.

GROUND RULE VARIATIONS - Continued

Fuel Cost - Continued

The overall results are shown in Figure 51. As evident from these curves, there is a proportionate gain, for both concepts net decrease in DOC for the civil rotorcraft and net decrease in LCC for the military rotorcraft with the higher fuel cost. The major point to be made here is that the relationship or ranking of concepts did not change, so that the concept selected for the \$0.264/l (\$1.00/gal) fuel cost would still be chosen at the higher fuel cost.

Rotorcraft Design Parameters

The selection of the rotorcraft mission and design parameters were made by Sikorsky on the basis of their best forecast of advanced but conventional rotorcraft for the 1990's. The sensitivity of the results to changes in some of the input assumptions was examined on a qualitative basis. Tables 49 and 50 summarize these results qualitatively. They indicate that neither flight speed nor payload are expected to change the Contingency Power benefits comparison between concepts in a significant way as long as the changes in flight speed or payload are modest. Reduced range will tend to reduce the benefit, but in a similar fashion for Throttle Push and Turbine Cooling Airflow Modulation.

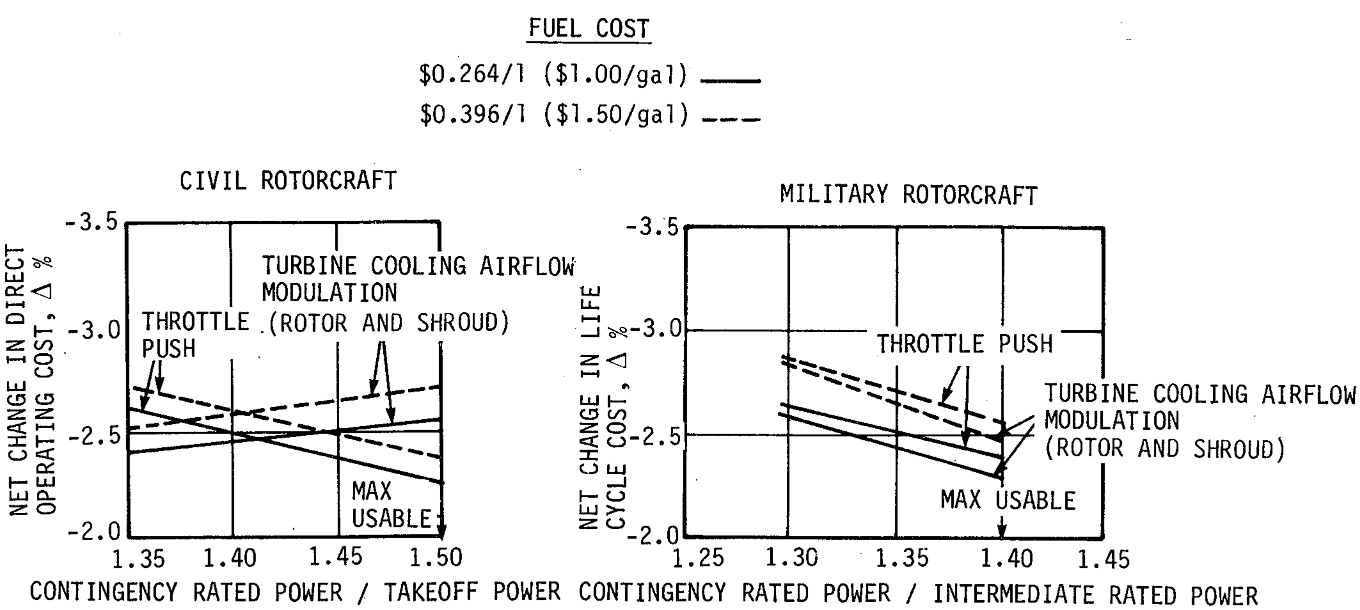

Figure 51. Effect of Fuel Cost on Net Direct Operating and Life Cycle Cost for Throttle Push and Turbine Cooling Airflow Modulation Concepts - Civil and Military Rotorcraft.

TABLE 49. SENSITIVITY OF STUDY RESULTS TO ROTORCRAFT DESIGN PARAMETERS

CIVIL ROTORCRAFT

	EFFECT OF:			
	Cruise Speed 296 km/h (160 kt)*		Payload (30 PAX)*	
	Reduced	Increased	Reduced	Increased
EFFECT ON				
Gross Weight	Decreased	Increased	Decreased	Decreased
Max Usable CRP ratio	Increased	Decreased	Minor Effect	Minor Effect
(% GW)/(% CPR)	Minor Effect	Minor Effect	Small Increase	Small Decrease
(% DOC)/(% CPR)	Minor Effect	Minor Effect	Small Increase	Small Decrease
(% GW)/(% SFC)	Minor Effect	Minor Effect	Minor Effect	Minor Effect
(% DOC)/(% SFC)	Minor Effect	Minor Effect	Minor Effect	Minor Effect
(% GW)/(% Engine Weight)	Minor Effect	Minor Effect	Minor Effect	Minor Effect
(% DOC)/(% Engine Weight)	Minor Effect	Minor Effect	Minor Effect	Minor Effect
Throttle Push, Net Benefit	Minor Effect	Minor Effect	Small Increase	Small Decrease
Turbine Cooling Airflow Modulation, Net Benefit	Minor Effect	Minor Effect	Small Increase	Small Decrease
Water Injection into Turbine Cooling Airflow, Net Benefit	Minor Effect	Minor Effect	Small Increase	Small Decrease

*Base Values

TABLE 50. SENSITIVITY OF STUDY RESULTS TO ROTORCRAFT DESIGN PARAMETERS

MILITARY ROTORCRAFT

	EFFECT OF:				
	Cruise Speed 333 km/h (180 kt)*		Payload 2615 kg (5760 lb)*		Range 370 km (200 nm) Radius*
	Reduced	Increased	Reduced	Increased	Reduced
EFFECT ON:					
Gross Weight	Reduced	Increased	Reduced	Increased	Reduced
Max. Usable CPR ratio	Increased	Reduced	Same	Same	Small Change
(% GW)/(% CPR)	Small Change	Small Change	Small Change	Small Change	Small Reduction
(% LCC)/(% CPR)	Small Change	Small Change	Small Change	Small Change	Small
(% GW)/(% SFC)	Small Change	Small Change	Small Change	Small Change	Small
(% LCC)/(% SFC)	Small Change	Small Change	Small Change	Small Change	Small
(% GW)/(% Engine Weight)	Small Change	Small Change	Small Change	Small Change	Small Change
(% LCC)/(% Engine Weight)	Small Change	Small Change	Small Change	Small Change	Small Change
Throttle Push, Net Benefit	Small Change	Small Change	Small Change	Small Change	Small Reduction
Turbine Cooling Airflow Modulation	Small Change	Small Change	Small Change	Small Change	Small Reduction
Water Injection into Turbine Cooling Airflow	Small Change	Small Change	Small Change	Small Change	Reduction

*Base Values

GROUND RULE VARIATIONS - Continued

Proposed FAA Rules

As a result of AIA and SAE committee studies, some changes in helicopter rules for one engine inoperative (OEI) or Contingency Power Requirements are being proposed for industry and FAA review. In general, these include a 30-second OEI, a 2-minute OEI, and a continuous enroute OEI. The specific level of each of the OEI powers as a percentage of the normal Takeoff power will be determined by the helicopter-engine combination seeking certification. Typical levels in the draft being circulated are shown in Table 51. A 30-minute certification test will be scheduled to demonstrate this OEI capability. The certification test schedule is shown in Table 52. A requirement for "no sign of imminent failure" after certification test has been proposed with some damage allowed which is judged to permit completion of the mission.

In order to gain some indication of what effect these proposed changes might have on the evaluation criteria, mechanical design studies were carried out to determine the effect of permitting certain hot parts to suffer some non-catastrophic damage. These studies resulted in an increase in allowable peak temperature limits for some static parts but no change in limits for rotating parts.

These temperature limit changes were applied to the Turbine Cooling Airflow Modulation concept for the civil engine since it showed the greatest potential at the higher CRP/TOP ratios. The results are shown in Figure 52. Due to the higher allowable metal temperatures, the static part cooling flows could be reduced.

It was assumed, after consultation with Sikorsky Aircraft, that under the proposed FAA rule changes, a change in the methods used to demonstrate Contingency Power during training flights was required. This change involved off-loading the rotorcraft so that power on one engine could be decreased to a reasonable part power level. Then the Contingency exercise could take place with that engine being accelerated up to no more than Takeoff power. With this procedure actual power would not be used during training flights and no damage would occur. This would also mean that more blade life could be consumed during revenue missions thus permitting a decrease in blade cooling flows at power less than or equal to Takeoff power.

The results of applying the above changes to the Turbine Cooling Airflow Modulation (Rotor and Shroud) concept is shown in Figure 52. At the maximum usable CRP ratio, the net decrease in DOC is approximately 0.8% which represents a very significant improvement.

For the Throttle Push system, where cooling flows are sized at Contingency and cannot be decreased at other powers, it is impossible to take advantage of this change in the conduct of training flights. Therefore, the potential gain for this concept is less than that for the Turbine Cooling Airflow Modulation concept, and the ranking of the Turbine Cooling Airflow Modulation concept versus the Throttle Push concept would be further improved.

TABLE 51. PROPOSED FAA RULES FOR ONE ENGINE INOPERATIVE (OEI) OR CONTINGENCY POWER REQUIREMENTS (CPR)

• 30-Second OEI	125% of Normal Takeoff
• 2-Minute OEI	110% of Normal Takeoff
• Continuous Enroute OEI	100% of Normal Takeoff

- 30-Minute Certification Test Covers OEI Ratings
- "No Sign of Imminent Failure" after Certification Test, but Degree of Allowable Damage Not Established
- Inspection Required after In-Service Use

TABLE 52. PROPOSED CERTIFICATION TEST SCHEDULE

- 150-hour block test schedule to combine FAA and CAA requirements with no 2 1/2 minute rating as follows:

Takeoff	18 hours: 45 minutes
Enroute OEI Power	20 hours: 0 minutes
MAX Continuous	37 hours: 30 minutes
Incremental Powers	50 hours: 0 minutes
Idle	23 hours: 45 minutes
Tear Down and Inspect	150 hours

- Additional test on the engine that has accomplished the above schedule as follows:

Takeoff	1 minute
30-Second Power (Limited use)	30 seconds
2-Minute (Limited use)	2 minutes
Idle	1 minute
30-Second Power (Limited use)	30 seconds
Idle	1 minute
TOTAL	6 minutes

Run a total of 5 cycles - inspect - no imminent failure.

TOTAL TEST TIME 150 hours 30 minutes

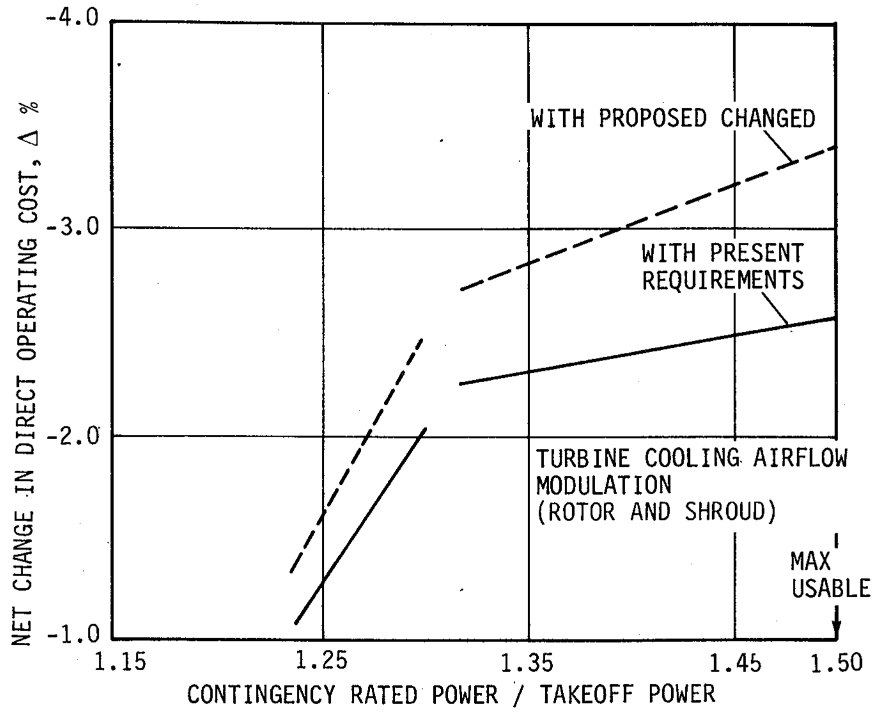

Figure 52. Effect of Proposed FAA Regulations on Turbine Cooling Airflow Modulation (Rotor and Shroud) Concept.

GROUND RULE VARIATIONS - Continued

Alternate Baseline for Cooling Flow Modulation

Figure 53 shows the percent change in DOC for the civil engine for Turbine Cooling Airflow Modulation, (Rotor Only and Rotor and Shroud) concepts. These curves (labeled "B") are identical to the curves shown in Figure 36. The curves labeled "A" are calculated with the weight and cost penalties associated with the Turbine Cooling Airflow Modulating concept removed. This alternate evaluation is based on the hypothesis that cooling flow modulation at part power is part of the Baseline engine and also part of the higher Contingency Power engine being evaluated. The implication is that if these weight and cost penalties were already included in the Baseline engine (i.e., the Baseline engine included a Turbine Cooling Airflow Modulation system for part power SFC improvement) then the net DOC benefit at increased CRP/TOP ratios would improve. The "A" curves in Figure 53 show an idealized maximum benefit since the impact of Turbine Cooling Airflow reduction at part power and associated decrease in the life of certain parts was not included in the calculation. The resulting net DOC improvement is superior to any of the novel systems studied by a minimum of 0.4%.

Figure 54 provides the same results for the military engine in terms of percent change in LCC. Again, the results are idealized maximum benefit since the impact of more frequent parts replacement is not included. The resulting net LCC improvement is 0.2% better than the Turbine Cooling Airflow Modulation (Rotor and Shroud) with the weight and cost penalties included but is only about 0.1% better than Throttle Push concept. Overall, the resulting net LCC is better than any system studied.

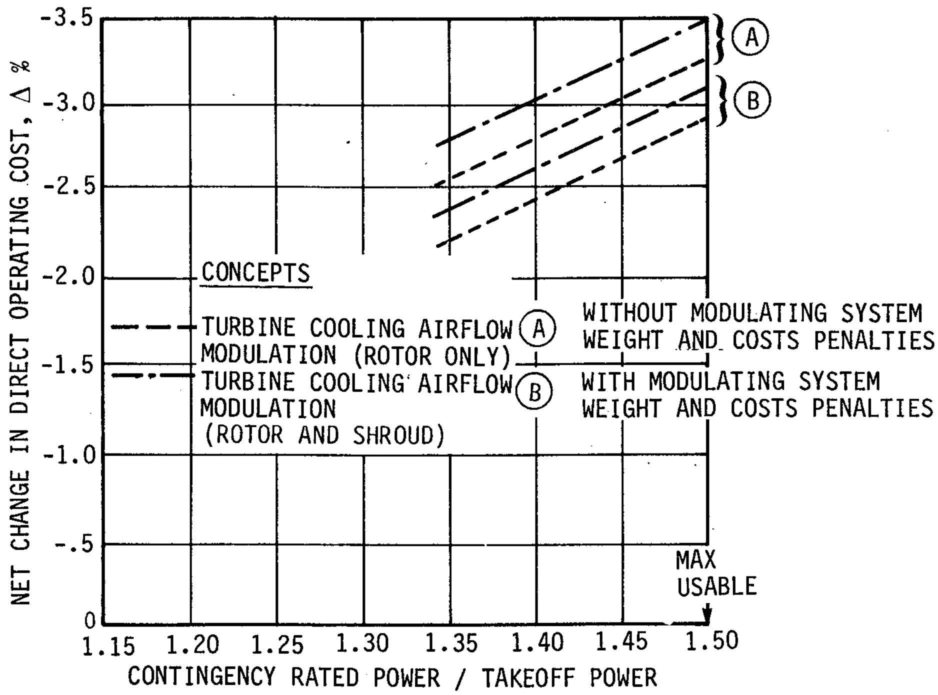

Figure 53. Idealized Potential of Turbine Cooling Airflow Modulation Concept for Civil Rotorcraft.

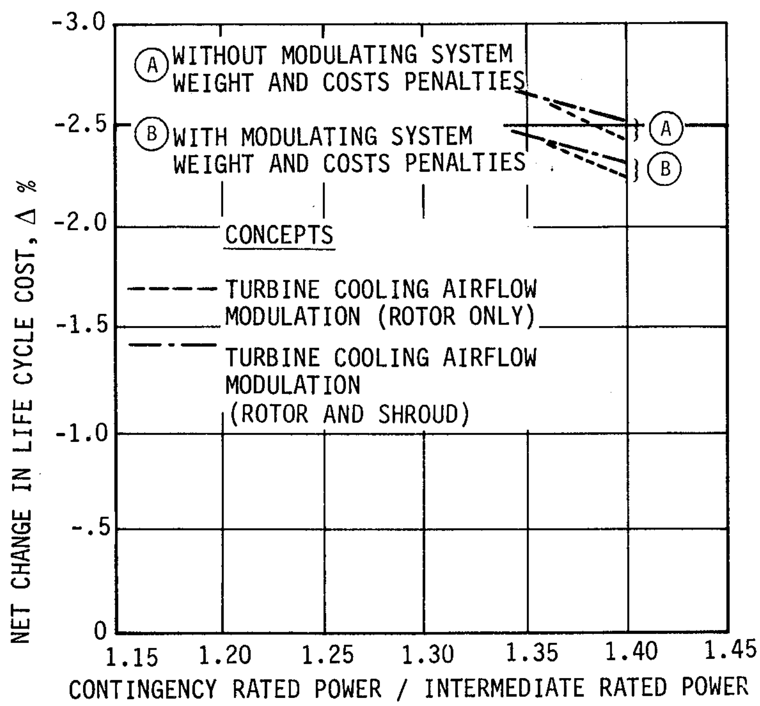

Figure 54. Idealized Potential of Turbine Cooling Airflow Modulation Concepts for Military Rotorcraft.

GROUND RULE VARIATIONS - Continued

One-Time Only Systems

The Throttle Push and Turbine Cooling Airflow Modulation concepts were evaluated assuming that the system could be operated as many times as desired without any maintenance, refilling or reloading as would be the case for those concepts having consumables such as a cartridge or a water supply. However, in order to reduce the penalty of the Turbine Cooling Airflow Modulation system it was restudied with a squib-operated burst disk to open up an increased area to supply additional Stage 1 blade and shroud cooling flow at Contingency Power. This component would replace the electrically operated solenoid valve and associated plumbing installed in the original system.

This modification was evaluated at two Contingency Rated Power/Takeoff power ratios for the civil rotorcraft. A detailed design study showed a 1.1 kg (2.4 lb) decrease in weight and a $1750 reduction in cost for this alternate one-time-only system. The effect of these changes on the net percent change in DOC is shown in Table 53. It appears that only a minor improvement in DOC would be possible and one which might not be worth the limited usefulness of the system.

TABLE 53. EFFECT OF "ONE SHOT" CAPABILITY SYSTEM*
TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD)

CIVIL ROTORCRAFT

	System			
	Multiple Use		"One Shot"	
CRP/TOP	1.30	1.50	1.30	1.50
NET Δ% DOC	-2.36	-2.63	-2.42	-2.70
Δ%	BASE	BASE	-.06	-.07

* No Use of Contingency Power in Training Assumed.

CIVIL ENGINE MISSION EVALUATION

One civil (and one military) novel engine concept was selected for detailed analysis and comparison with the results generated by trade factors. The novel concept selected for comparison was Turbine Cooling Airflow Modulation (Rotor and Shroud) at the nominal 1.45 value of CRP/TOP. Engine performance data, weight, and economic data for this engine was provided to Sikorsky Aircraft. The rotorcraft was designed using this data and off-design DOC was generated. Table 54 shows the difference between the detailed analysis and the results generated by trade factors.

TABLE 54. COMPARISON OF DETAILED ANALYSIS AND TRADE FACTORS FOR TURBINE COOLING AIRFLOW MODULATION (ROTOR AND SHROUD)

CIVIL ENGINE - CRP/TOP = 1.45

	Differences Between Detailed Analysis and Trade Factor Results
Change in Vehicle Gross Weight, Δ%	+0.1
Change in Direct Operating Cost, Δ%	-0.5

The results of the detailed analysis indicate that the vehicle gross weight is essentially the same as the weight determined by the trade factors and the DOC is 0.5% better (lower) than that obtained with the trade factors. These results confirm the expected accuracy of the trade factors.

MILITARY ENGINE MISSION EVALUATION

A military engine at increased CRP/IRP was also selected for detailed analysis and comparison with the results generated by trade factors. The selected concept was Throttle Push at a CRP/IRP nominal value of 1.35. Engine performance data, weight and economic data for this engine was provided to Sikorsky Aircraft. Table 55 provides a comparison of the rotorcraft characteristics resulting from the Sikorsky detailed analysis with the results generated by trade factors.

TABLE 55. COMPARISON OF DETAILED ANALYSIS AND TRADE FACTORS FOR THROTTLE PUSH CONCEPT

MILITARY ENGINE - CRP/IRP = 1.36

	Differences Between Detailed Analysis and Trade Factor Results
Net Change in Vehicle Gross Weight, Δ%	-0.4
Net Change in Life Cycle Cost, Δ%	-0.3

The results of the detailed analysis indicate that the vehicle gross weight is 0.4% less than the weight determined by the trade factors and the LCC is 0.3% better (lower) than that obtained with the trade factors. These results are close and within the expected accuracy of the trade factors.

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TASK VI

TECHNICAL BARRIERS

TASK VI - TECHNICAL BARRIERS

The two concepts which offer the greatest promise to advance the state of the art of Contingency Power Ratings are Throttle Push and Turbine Cooling Airflow Modulation. Both concepts could be further enhanced by raising design limits; thus reducing the penalties associated with a Contingency Power Rating capability.

Key barrier problems are listed in Table 56 with an identification of those problems for which Research and Technology (R&T) programs are recommended.

The blade cooling flow is often set by the coating temperature limit rather than stress rupture life. Raising the coatings limit allows cooling flow reductions. Similarly, shroud cooling flow is set by the ceramic bonding limit. An increase here would also reduce cooling and the penalty for Contingency Power.

Contingency Power is used for a relatively short time during the life of an engine. Material property data for short-time/high-temperature is needed for accurate design estimates of temperature cooling airflow requirements. An R&T program is recommended to obtain data, especially for monocapital turbine blade materials.

Cooling airflow Modulation systems would be enhanced if low power modulation could be combined with high power modulation at Contingency Power. Current technology of cooling airflow supply systems, limited by seal and blade back flow margins prevents this approach. A program to better define these limits and to improve the technology of turbine cooling airflow supply system is recommended.

Compressor flow capacity and high speed stall margin and efficiency are barriers to Contingency Power Ratings, since increases in engine airflow above normal ratings are a requirement of each of the systems. However, no compressor development program was recommended because this barrier is common to all engine designs and not unique to Contingency Power Ratings.

A follow-on systems study is also recommended to evaluate the best approaches in the context of derivative or current engines where more restrictions to design concepts apply than in the advanced "rubber" turboshaft engines of this study.

RECOMMENDED R&T PROGRAMS

Table 57 contains some detail on the R&T programs recommended in four areas. Two of them are in materials development to extend current limits which inhibit Contingency Power Ratings.

The Turbine Cooling Airflow Modulation study addresses some fundamental design issues in cooled turbine design, and innovative approaches may pay off here to permit a variable geometry not heretofore used.

The follow-on systems study to apply what has been learned in this study on hypothetical advanced engines, to current/derivative engines should be considered for the breadth of possible applications.

TABLE 56. KEY BARRIER PROBLEMS AND RECOMMENDATIONS

Barrier Problems	Recommended R&T Programs	Limits/Barriers
• Blade Coating Limit	X	Temp Limits Required Cooling Flow Increase Penalty
• Shroud Ceramic Bonding Limits	X	Temp Limits Required Cooling Flow Increase Penalty
• Knowledge of Short Time Material Properties/Limits	X	Extrapolated Data Base
• Compressor Flow Capacity and High Speed Efficiency		
• Turbine Blade Cooling System Backflow Margins (Turbine Cooling Airflow Modulation Range)	X	Conventional Systems Limit Modulation Magnitude

TABLE 57. RECOMMENDED R&T PROGRAMS

Program	Approach
• Blade Coating Development	Lab evaluation of chemical modifications and process changes to increase high temperature capability of overlay coatings by 28°C (50°F) to 55°C (100°F) and to improve their compatibility with specific substrate alloys such as Mono N4.
• Shroud Ceramic Bonding Development	NiCr alloy derivative TBC systems having bond coats with known Superior oxidation resistance based on preliminary lab test will be exposed to more simulative thermal shock and high velocity tests. To evaluate degradation modes.
• Short Time Material Properties Testing	Systematic materials testing on DS or Mono to include: very high temp, short time rupture, very high temp stressed exposure followed by rupture tests at normal temp and normal rupture tests for comparison.
• Cooling Flow Modulation	Study novel approaches to turbine cooling supply systems which allow a wide range of cooling flow modulation from part power to Contingency Power. Consider seal and blade back flow margin limitations. Evaluate the merits to select most promising system for practical application.
• Contingency Power Systems Study Applied to Current/Derivative Engines	Conduct preliminary design and systems study to apply the most promising concepts developed from the current study to current derivative engines. These would include Throttle Push, Turbine Cooling Airflow Modulation and Water Injection into Turbine Cooling Airflow System. Results of study lead to design and demonstration of concepts on current engines, e.g., T700 step program.

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APPENDIX A

DISTRIBUTION

OF

WEIGHT, PRICE, AND MAINTENANCE COST INCREASES

TABLE A-1. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR THROTTLE PUSH CONCEPT

CIVIL ENGINE

	Δ% Weight*				Δ% Price*				Δ% Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.377	.377	.536	1.965	2.006	2.006	2.857
Stage 1 Blade	0	0	0	0	.104	.258	.258	.486	.317	.690	.734	.850
Stage 1 Shroud	0	0	0	0	.030	.047	.048	.061	.009	.014	.014	.018
Stage 2 Vane	0	0	0	0	0	0	0	.040	0	0	0	.007
Stage 2 Blade	0	0	0	0	.040	.069	.077	.096	.028	.048	.053	.066
Compressor Rotor	.337	.587	.359	.359	.069	.119	.073	.073	.008	.014	.009	.009
HP Turbine Rotor	.094	.164	.099	.099	.083	.145	.088	.088	.003	.005	.003	.003
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
TOTAL Δ% Engine	.081	1.13	0.84	0.84	1.05	1.37	1.27	1.73	2.39	2.83	2.87	3.87
*Δ% = Percent Increase												

NOTE: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

TABLE A-2A. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR TURBINE COOLING AIRFLOW MODULATION CONCEPT

CIVIL ENGINE

	Δ% Weight*				Δ% Price*				Δ% Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.377	.377	.536	1.965	2.006	2.006	2.857
Stage 1 Blade	0	0	0	0	.258	.469	.469	.486	.787	1.429	1.429	1.480
Stage 1 Shroud	0	0	0	0	.030	.047	.048	.061	.009	.014	.014	.018
Stage 2 Vane	0	0	0	0	0	0	0	.040	0	0	0	.007
Stage 2 Blade	0	0	0	0	.040	.069	.077	.096	.028	.048	.053	.066
Compressor Rotor	.337	.587	.359	.359	.069	.119	.073	.073	.008	.014	.009	.009
HP Turbine Rotor	.094	.164	.099	.099	.083	.145	.088	.088	.003	.005	.003	.003
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
FADEC	.033	.033	.033	.033	.195	.195	.195	.195	.175	.175	.175	.175
Combustor Casing	.084	.084	.084	.084	.101	.101	.101	.101	.054	.054	.054	.054
Valves, Transducers, etc.	.470	.470	.470	.470	.727	.727	.727	.727	1.443	1.443	1.443	1.443
Tubing, Wiring, Misc.	.352	.352	.352	.352	.387	.387	.387	.387	.324	.324	.324	.324
TOTAL Δ% Engine	1.75	2.07	1.78	1.78	2.61	2.99	2.89	3.14	4.85	5.57	5.57	6.49

*Δ% = Percent Increase

NOTES: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-2B. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR TURBINE COOLING AIRFLOW MODULATION CONCEPT

CIVIL ENGINE - ONE TIME OPERATION ONLY*

	Δ% Weight*				Δ% Price*				Δ% Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.377	.377	.536	1.965	2.006	2.006	2.857
Stage 1 Blade	0	0	0	0	.258	.469	.469	.486	.787	1.429	1.429	1.480
Stage 1 Shroud	0	0	0	0	.030	.047	.048	.061	.009	.014	.014	.018
Stage 2 Vane	0	0	0	0	0	0	0	.040	0	0	0	.007
Stage 2 Blade	0	0	0	0	.040	.069	.077	.096	.028	.048	.053	.066
Compressor Rotor	337	.587	.359	.359	.069	.119	.073	.073	.008	.014	.009	.009
HP Turbine Rotor	.094	.164	.099	.099	.083	.145	.088	.088	.003	.005	.003	.003
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
FADEC	.022	.022	.022	.022	.130	.130	.130	.130	.118	.118	.118	.118
Combustor Casing	.084	.084	.084	.084	.101	.101	.101	.101	.054	.054	.054	.054
Valves, Transducers, etc.	.304	.304	.304	.304	.338	.338	.338	.338	.665	.665	.665	.665
Tubing, Wiring, Misc.*	.242	.242	.242	.242	.257	.257	.257	.257	.225	.225	.225	.225
Pyrotechnic Squib*	.022	.022	.022	.022	.130	.130	.130	.130	9.109	9.109	9.109	9.109
TOTAL Δ% Engine	1.48	1.80	1.51	1.51	2.16	2.53	2.44	2.69	13.03	13.74	13.74	14.67

*Δ% = Percent Increase

NOTES. Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-3A. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

CIVIL ENGINE - PUMPED WATER SCHEME

	Δ% Weight*				Δ% Price*				Δ% Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.377	.377	.536	1.965	2.006	2.006	2.857
Stage 1 Blade	0	0	0	0	.110	.156	.162	.210	.336	.475	.495	.641
Stage 1 Shroud	0	0	0	0	.030	.047	.048	.061	.009	.014	.014	.018
Stage 2 Vane	0	0	0	0	0	0	0	.040	0	0	0	.007
Stage 2 Blade	0	0	0	0	.040	.055	.068	.081	.028	.038	.047	.056
Compressor Rotor	.337	.587	.359	.359	.069	.119	.073	.073	.008	.014	.009	.009
HP Turbine Rotor	.094	.164	.099	.099	.083	.145	.088	.088	.003	.005	.003	.003
Interturbine Frame	293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
Combustor Casing Modification	.651	.651	.651	.651	.552	.552	.552	.552	.293	.293	.293	.293
FADEC Modification	.055	.055	.055	.055	.325	.325	.325	.325	.292	.292	.292	.292
Valves, Transducers, etc.	.210	.210	.210	.210	.253	.253	.253	.253	.455	.455	.455	.455
Tank, Filter Tubing* Wiring	.429	.402	.421	.463	.179	.173	.177	.187	.222	.218	.220	.228
Motor, Pump*	.458	.458	.458	.458	.253	.253	.253	.253	.209	.209	.209	.209
Water	.617	.501	.581	.772	.004	.003	.004	.005	.722	.653	.722	.791
TOTAL Δ% Engine	3.23	3.41	3.21	3.45	2.62	2.81	2.73	3.02	4.60	4.73	4.82	5.91

*Δ% = Percent Increase

NOTES: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-3B. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

CIVIL ENGINE - PRESSURIZED TANK ALTERNATIVE SCHEME

	Δ% Weight*				Δ% Price*				Δ% Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.377	.377	.536	1.965	2.006	2.006	2.857
Stage 1 Blade	0	0	0	0	.110	.156	.162	.210	.336	.475	.495	.641
Stage 1 Shroud	0	0	0	0	.030	.047	.048	.061	.009	.014	.014	.018
Stage 2 Vane	0	0	0	0	0	0	0	.040	0	0	0	.007
Stage 2 Blade	0	0	0	0	.040	.055	.068	.081	.028	.038	.047	.056
Compressor Rotor	.337	.587	.359	.359	.069	.119	.073	.073	.008	.014	.009	.009
HP Turbine Rotor	.094	.164	.099	.099	.083	.145	.088	.088	.003	.005	.003	.003
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
Combustor Casing Modification	.651	.651	.651	.651	.552	.552	.552	.552	.293	.293	.293	.293
FADEC Modification	033	.033	.033	.033	.195	.195	.195	.195	.175	.175	.175	.175
Valves, Transducers, etc.	.138	.138	.138	.138	.201	.201	.201	.201	.400	.400	.400	.400
Tank, Filter, Tubing Wiring	.776	.684	.748	.897	.225	.232	.247	.283	.250	.234	.244	.271
Motor, Pump	0	0	0	0	0	0	0	0	0	0	0	0
Water	.617	.501	.581	.772	.004	.003	.004	.005	.722	.653	.722	.791
TOTAL Δ% Engine	3.03	3.14	2.99	3.33	2.26	2.43	2.37	2.68	4.24	4.36	4.46	5.58

*Δ% = Percent Increase

NOTES: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-4. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT

CIVIL ENGINE

	Δ% WEIGHT*		Δ% PRICE*		Δ% MAINTENANCE COST*	
Contingency Power Ratio	1.35	1.45	1.35	1.45	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.369	.377	1.965	2.006
Stage 1 Blade	0	0	.191	.213	.582	.649
Stage 1 Shroud	0	0	.029	.040	.009	.012
Stage 2 Vane	0	0	0	0	0	0
Stage 2 Blade	0	0	.057	.065	.039	.045
Compressor Rotor	.480	.482	.097	.097	.011	.011
HP Turbine Rotor	.134	.134	.119	.119	.004	.004
Interturbine Frame	.293	.293	.351	.351	.055	.055
Combustor Casing Modification	.651	.651	.552	.552	.293	.293
Front Frame Modification	.421	.421	.426	.426	.067	.067
FADEC Modification	.088	.088	.519	.519	.468	.468
Valves, Transducers, etc.	.309	.309	.429	.429	.802	.802
Tank, Filter, Tubing Wiring	.818	.818	.301	.301	.325	.325
Motor, Pump	.459	.459	.253	.253	.209	.209
Water	2.365	2.343	.013	.013	1.203	1.203
TOTALΔ% Engine	6.10	6.08	3.71	3.76	6.03	6.15

*Δ% = Percent Increase

NOTES: Engine are rematched

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-5. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR THROTTLE PUSH CONCEPT

MILITARY ENGINE

	Δ% Weight*				Δ% Price*				Δ% Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.374	.370	.377	1.965	1.992	1.972	2.006
Stage 1 Blade	0	0	0	0	.097	.210	.258	.258	.076	.147	.173	.233
Stage 1 Shroud	0	0	0	0	.023	.034	.023	.036	.007	.010	.007	.011
Stage 2 Vane	0	0	0	0	0	0	0	0	0	0	0	0
Stage 2 Blade	0	0	0	0	0	0	0	.029	0	0	0	.020
Compressor Rotor	.535	.738	.523	0	.108	.149	.106	0	.013	.018	.013	. 0
HP Turbine Rotor	.148	.206	.145	0	.132	.183	.129	0	.004	.006	.004	0
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
TOTAL Δ% Engine	1.06	1.32	1.05	0.38	1.08	1.30	1.24	1.05	2.12	2.23	2.22	2.33

*Δ% = Percent Increase

NOTES: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-6A. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR TURBINE COOLING FLOW MODULATION CONCEPT

MILITARY ENGINE

	Δ% Weight*				Δ% Price*				Δ%Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.374	.370	.377	1.965	1.992	1.972	2.006
Stage 1 Blade	0	0	0	0	.097	.210	.258	.258	.122	.306	.413	.624
Stage 1 Shroud	0	0	0	0	.023	.034	.023	.036	.007	.010	.007	.011
Stage 2 Vane	0	0	0	0	0	0	0	0	0	0	0	0
Stage 2 Blade	0	0	0	0	0	0	0	.029	0	0	0	.020
Compressor Rotor	.535	.738	.523	0	.108	.149	.106	0	.013	.018	.013	0
HP Turbine Rotor	.148	.206	.145	0	.132	.183	.129	0	.004	.006	.004	0
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
FADEC	.033	.033	.033	.033	.195	.195	.195	.195	.175	.175	.175	.175
Combustor Casing	.084	.084	.084	.084	.101	.101	.101	.101	.054	.054	.054	.054
Valves, Transducers, etc.	.470	.470	.470	.470	.727	.727	.727	.727	1.443	1.443	1.443	1.443
Tubing, Wiring, Misc.	.352	.352	.352	.352	.387	.387	.387	.387	.324	.324	.324	.324
TOTAL Δ% Engine	2.00	2.26	1.99	1.32	2.49	2.71	2.65	2.46	4.16	4.38	4.46	4.71

*Δ% = Percent Increase

NOTES: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-6B. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR TURBINE COOLING FLOW MODULATION CONCEPT

MILITARY ENGINE - ONE TIME OPERATION ONLY*

	Δ% Weight*				Δ% Price*				Δ% Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.374	.370	.377	1.965	1.992	1.972	2.006
Stage 1 Blade	0	0	0	0	.097	.210	.258	.258	.122	.306	.413	.624
Stage 1 Shroud	0	0	0	0	.023	.034	.023	.036	.007	.010	.007	.011
Stage 2 Vane	0	0	0	0	0	0	0	0	0	0	0	0
Stage 2 Blade	0	0	0	0	0	0	0	.029	0	0	0	.020
Compressor Rotor	.535	.738	.523	0	.108	.149	.106	0	.013	.018	.013	0
HP Turbine Rotor	.148	.206	.145	0	.132	.183	.129	0	.004	.006	.004	0
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
FADEC	.022	.022	.022	.022	.130	.130	.130	.130	.118	.118	.118	.118
Combustor Casing	.084	.084	.084	.084	.101	.101	.101	.101	.054	.054	.054	.054
Valves, Transducers, etc.	.304	.304	.304	.304	.338	.338	.338	.338	.665	.665	.665	.665
Tubing, Wiring, Misc.*	.242	.242	.242	.242	.257	.257	.257	.257	.225	.225	.225	.225
Pyrotechnic Squib*	.022	.022	.022	.022	.130	.130	.130	.130	3.470	3.470	3.470	3.470
TOTAL Δ% Engine	1.74	2.00	1.72	1.05	2.04	2.26	2.19	2.01	6.70	6.92	7.00	7.25

*Δ% = Percent Increase

NOTES: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-7A. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

MILITARY ENGINE - PUMPED WATER SCHEME

	Δ% Weight*				Δ% Price*				Δ% Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.374	.370	.377	1.965	1.992	1.972	2.006
Stage 1 Blade	0	0	0	0	.029	.061	.042	.045	.041	.121	.103	.139
Stage 1 Shroud	0	0	0	0	.023	.034	.023	.036	.007	.010	.007	.011
Stage 2 Vane	0	0	0	0	0	0	0	0	0	0	0	0
Stage 2 Blade	0	0	0	0	.013	.027	.013	.013	.006	.016	.009	.009
Compressor Rotor	.535	.738	.523	0	.108	.149	.106	0	.013	.018	.013	0
HP Turbine Rotor	.148	.206	.145	0	.132	.183	.129	0	.004	.006	.004	0
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
Combustor Casing Modification	.651	.651	.651	.651	.552	.552	.552	.552	.293	.293	.293	.293
FADEC Modification	.055	.055	.055	.055	.325	.325	.325	.325	.292	.292	.292	.292
Valves, Transducers, etc.	.210	.210	.210	.210	.253	.253	.253	.253	.455	.455	.455	.455
Tank, Filter, Tubing Wiring	.341	.388	.379	.396	.158	.169	.168	.171	.207	.214	.213	.216
Motor, Pump	.458	.458	.458	.458	.253	.253	.253	.253	.209	.209	.209	.209
Water	.269	.442	.407	.475	.001	.003	.003	.003	.065	.081	.081	.081
TOTAL Δ% Engine	3.05	3.53	3.21	2.62	2.57	2.73	2.59	2.38	3.61	3.76	3.71	3.77

*Δ% = Percent Increase

NOTES: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-7B. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR WATER INJECTION INTO TURBINE COOLING AIRFLOW CONCEPT

MILITARY ENGINE - PRESSURIZED TANK ALTERNATIVE SCHEME*

	Δ% Weight*				Δ% Price*				Δ%Maintenance Cost*			
Contingency Power Ratio	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45	1.25	1.30	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.086	.086	.369	.374	.370	.377	1.965	1.992	1.972	2.006
Stage 1 Blade	0	0	0	0	.029	.061	.042	.045	.041	.121	.103	.139
Stage 1 Shroud	0	0	0	0	.023	.034	.023	.036	.007	.010	.007	.011
Stage 2 Vane	0	0	0	0	0	0	0	0	0	0	0	0
Stage 2 Blade	0	0	0	0	.013	.027	.013	.013	.006	.016	.009	.009
Compressor Rotor	.535	.738	.523	0	.108	.149	.106	0	.013	.018	.013	0
HP Turbine Rotor	.148	.206	.145	0	.132	.183	.129	0	.004	.006	.004	0
Interturbine Frame	.293	.293	.293	.293	.351	.351	.351	.351	.055	.055	.055	.055
Combustor Casing Modification	.651	.651	.651	.651	.552	.552	.552	.552	.293	.293	.293	.293
FADEC Modification	.033	.033	.033	.033	.195	.195	.195	.195	.175	.175	.175	.175
Valves, Transducers, etc.	.138	.138	.138	.138	.201	.201	.201	.201	.400	.400	.400	.400
Tank, Filter, Tubing* Wiring	.492	.636	.608	.663	.187	.221	.216	.227	.199	.224	.220	.229
Motor, Pump*	0	0	0	0	0	0	0	0	0	0	0	0
Water	.269	.442	.407	.475	.001	.003	.003	.003	.065	.081	.081	.081
TOTAL Δ% Engine	2.65	3.22	2.88	2.34	2.16	2.35	2.20	2.00	3.22	3.39	3.33	3.40

*Δ% = Percent Increase

NOTES: Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

TABLE A-8. DISTRIBUTION OF PERCENT INCREASE IN WEIGHT, PRICE, AND MAINTENANCE COST FOR WATER INJECTION INTO COMPRESSOR INLET AND TURBINE COOLING AIRFLOW CONCEPT

MILITARY ENGINE

	Δ% WEIGHT*		Δ% PRICE*		Δ% MAINTENANCE COST*	
Contingency Power Ratio	1.35	1.45	1.35	1.45	1.35	1.45
HP Turbine Stage 1 Vane	.086	.086	.369	.361	1.965	1.923
Stage 1 Blade	0	0	.042	0	.103	0
Stage 1 Shroud	0	0	.022	0	.007	0
Stage 2 Vane	0	0	0	0	0	0
Stage 2 Blade	0	0	0	0	0	0
Compressor Rotor	.523	0	.106	0	.013	0
HP Turbine Rotor	.145	0	.129	0	.004	0
Interturbine Frame	.293	.293	.351	.351	.055	.055
Combustor Casing Modification	.651	.651	.552	.552	.293	.293
Front Frame Modification	.421	.421	.426	.426	.067	.067
FADEC Modification	.088	.088	.519	.519	.468	.468
Valves, Transducers,	.309	.309	.429	.429	.802	.802
Tank, Filter, Tubing Wiring	.757	.718	.287	.278	.314	.307
Motor, Pump	.459	.459	.253	.253	.209	.209
Water	1.939	1.707	.010	.009	.175	.159
TOTAL Δ% Engine	5.67	4.73	3.50	3.18	4.48	4.28

*Δ% = Percent Increase

NOTES. Engine is rematched for 1.35 and 1.45 Contingency Power Ratios.

See Weight, Price, and Maintenance Increases for Civil and Military Rotorcraft Section (pg 109) for description of derivation.

LIST OF SYMBOLS AND ABBREVIATIONS

AC	aircraft
AEO	all engines operating
BROC	best rate of climb
CAT 'A'	FAA certification category for helicopters
CLG	cooling
CRP/IRP	Contingency Rated Power / Intermediate Rated Power
CRP/TOP	Contingency Rated Power / Takeoff Power
DOC	direct operating cost
DS	directionally solidfied
EFH	engine flight hours
EPU	emergency power unit
EXT	external
FADEC	Full Authority Digital Engine Control
GG	gas generator
GW	gross weight
HDM	Helicopter Design Model
HIGE	hover in ground effect
HOGE	hover out of ground effect
HPT	high-pressure turbine
HXM	Expanded Marine Helicopter
INT	internal
IRP	Intermediate Rated Power
ISA	International Standard Atmosphere
JVX	Experimental Joint Vertical Takeoff Vehicle
LCC	life cycle cost
LE	leading edge
MC	Maximum Cruise (or Maximum Continuous)
MCP	Maximum Continuous Power (or Maximum Cruise Power)
M_0	aircraft Mach number
NH	rotor speed
N	corrected rotorcraft speed
OBP	outer balance piston
OEI	one engine inoperative
PAX	passengers
PP	part power
pt	point (or points)
ROC	rate of climb
R&T	Research and Technology
SFC	specific fuel consumption
SLS	sea level static
Stg	stage
TBC	thermal barrier coating
TE	trailing edge
T_0	ambient temperature
T_3	compressor discharge temperature
T_{41}	turbine rotor inlet temperature
T_{45}	low-pressure turbine inlet temperature
V	velocity
W_{2R}	corrected compressor airflow
1983 $K	1983 dollars in thousands
Δ	difference
η	efficiency

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Robert Hirschkron
John F. Haynes
David N. Goldstein
Richard H. Davis

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16. Abstract

Twin helicopter engines are often sized by the power requirement of a safe mission completion after the failure of one of the two engines. This study was undertaken for NASA Lewis by General Electric Co. to evaluate the merits of special design features to provide a 2-1/2 minute Contingency Power rating, permitting an engine size reduction. The merits of water injection, turbine cooling airflow modulation, throttle push, and a propellant auxiliary power plant were evaluated using military Life Cycle Cost (LCC) and commercial helicopter Direct Operating Cost (DOC) merit factors in a rubber engine and a rubber aircraft scenario.

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