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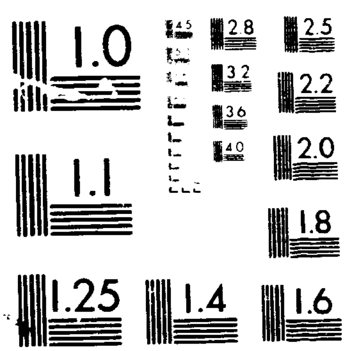

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NASA CR-145115

RESEARCH REQUIREMENTS FOR EMERGENCY POWER TO PERMIT HOVER-ONE-ENGINE-INOPERATIVE HELICOPTER OPERATION

By

James H. Yost

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Philadelphia, Pennsylvania

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ABSTRACT

This report documents the research and technology demonstration requirements to achieve emergency-power capability for a civil helicopter. The goal for emergency power for this study is the ability to hover with one engine inoperative, transition to minimum-power forward flight, and continue to a safe landing where emergency power may or may not be required. The best method to obtain emergency power identified in this study is to augment the basic engine power by increasing the engine's speed and turbine-inlet temperature, combined with water-alcohol injection at the engine inlet. Other methods, including turbine boost power and flywheel energy, offer potential for obtaining emergency power for minimum time durations. Costs and schedules are estimated for a research and development program to bring emergency power through a hardware-demonstration test. Interaction of engine emergency-power capability with other helicopter systems is examined.

FOREWORD

This report was prepared by the Boeing Vertol Company for the National Aeronautics and Space Administration, Langley Research Center, under NASA Contract NAS1-13624. William Snyder was technical monitor for this work. The Boeing Project Manager was Wayne Wiesner.

SUMMARY

The purpose of emergency power is to provide the pilot with adequate power when one engine becomes inoperative (OEI) so that forced and crash landings and load jettisoning can be minimized, and so that increased payloads can be carried safely.

Emergency power is required mainly during takeoff or landing operations. The goal for emergency power for this study is the ability to hover with one engine inoperative (HOEI), transition to minimum-power forward flight, and continue at normal rated power to a safe landing where emergency power may or may not be required.

Emergency power is required very infrequently. Chinook helicopter operations covering more than 2 million engine flight hours in over 10 years averaged one power loss in 4,400 engine flight hours (excluding battle damage). If precautionary landings are excluded from the statistics, power losses averaged only one in 15,000 engine flight hours.

Prior studies have shown that power-loss mishaps in military operations could be reduced by more than 50 percent and commercial passenger payloads could be increased up to 250 percent with adequate emergency power.

The best method to obtain 2-1/2-minute emergency power identified in this study is to augment the basic turbine powerplant by wet and dry augmentation. Combined they can provide an emergency-power capability which is more than double the 30-minute power. Dry augmentation provides increased power by increasing the engine's speed up to 8 percent and the absolute turbine-inlet temperature up to 20 percent with no weight penalty. Wet augmentation requires the addition of a water-alcohol inlet-injection system to provide increased mass flow and power without further increase in the engine's speed or temperature. The weight penalty for this wet system for a CH-47C Chinook-size helicopter is 25 percent of the installed weight of the engine. The Chinook's T55-L-11C engine has a potential 2-1/2-minute emergency-power capability of 2.43 times the 30-minute power rating.

Other methods for obtaining emergency power for HOEI have been investigated and have promise for minimum time durations (15 seconds or less) with added feasibility studies and research and development efforts. These other methods include rocket turbine-boost power and dual-flywheel (counterrotating) energy.

With emergency-power capability, the goal of being able to hover with one engine inoperative (HOEI) can be achieved with a twin-engine helicopter, thereby eliminating the need for a third engine.

The research and development cost estimates and time schedules for bringing emergency power through a hardware-demonstration test are provided.

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1.0 INTRODUCTION

The analyses in NASA CR-144953 (ref. 1) showed that meeting the requirement for hover with one engine inoperative (HOEI) penalized a 100-passenger helicopter to a considerable extent. The following table compares a three-engine, 100-passenger, short-haul helicopter having HOEI capability, but with no emergency or overrating features, to a 100-passenger, twin-engine helicopter which does not have HOEI capability:

Configuration	GW	DOC	EI
3-engine with HOEI	17 315 kg (38,160 lb)	0.0359	3.680×10^6
2-engine without HOEI	15 536 kg (34,250 lb)	0.0327	2.773×10^6

This comparison shows that the three-engine helicopter with HOEI and no emergency-rating features has an 11-percent increase in gross weight and burns 32 percent more fuel for equivalent missions. It is therefore in the best interests of civil-helicopter development that emergency-power features be investigated to minimize such penalties.

The purpose of emergency power is to provide the pilot with adequate power when one engine becomes inoperative to minimize forced and crash landings, as well as load jettisoning, and to safely carry increased payloads. These added benefits may be realized by several methods which show promise; one of these methods is by obtaining very high levels of emergency power from the engine, realizing that some hot-section damage may result and a hot-end inspection will be required following its use. Since this emergency power is very rarely required in normal operations (possibly no more than once during the total design life of the engine, if at all), the benefits derived can be very cost-effective. Prior studies (ref. 2) have shown that power-loss mishaps in military operations could be reduced by more than 50 percent and commercial passenger payloads could be increased up to 250 percent with adequate emergency power.

The need for emergency-power capability is dramatically emphasized by referring to a typical commercial rooftop helicopter operation, assuming a present-day 25-passenger helicopter. Passenger-carrying capacity is based upon safe takeoff and landing operations with one engine inoperative. If the available OEI emergency-power capability is only 8 percent above the normal takeoff rating, the passenger capacity on a 311K (100°F) day is only 6. However, if the emergency-power capability is increased to 24 percent above the normal takeoff rating, passenger capacity is more than tripled to 20. From this example, it can be seen that the cost-effective aspects of this potential payload increase with adequate emergency-power capability cannot be overemphasized in the VTOL transportation market.

Similarly, the survivability benefits to military operations by greatly reducing power-loss mishaps is very significant and cost-effective if adequate emergency power is available.

Initial investigations have shown other methods for obtaining emergency power which have promise for hover OEI, with added feasibility studies and research and development efforts. These methods would include rocket turbine-boost power and flywheel energy.

This report discusses methods of augmenting the performance of the engines: dry augmentation to obtain increased power by running at higher engine speed and turbine-inlet temperature, and wet augmentation using liquid injection at the inlet to boost power without further increase in engine speed and turbine temperature. Other methods of obtaining emergency power are discussed, including turbine-boost power and flywheel energy. Performance and weights associated with these methods, the research and technology demonstration requirements, and the corresponding costs are presented. Detailed numerical data relative to dry augmentation and wet augmentation systems and the flywheel-system calculations are incorporated in the appendixes.

2.0 LIST OF SYMBOLS

b	number of rotor blades
DOC	direct operating cost, $/seat-km
DP	design point
EI	energy intensity, J/passenger-km
FAA	Federal Aviation Administration
GW	gross weight, kg
HOEI	hover one engine inoperative
HOGE	hover out of ground effect
K	radius of gyration, m
KE	kinetic energy, J
K_1	constant (function of blade material and geometry, density, radial length, and mean radius)
N_g	gas-generator speed, rpm
$N_g/\sqrt{\theta}$	referred gas-generator speed, rpm
N_r	rotor speed, rpm
OEI	one engine inoperative
R	rotor-blade radius, m
SHP	shaft horsepower
SFC	specific fuel consumption, kg/hr/kw
T	absolute temperature, K
t_2	time duration at emergency-power level, hr
T_C	cooling-air temperature, K (compressor-exit temperature, T_3)
TIT	turbine-inlet temperature, K
T_m	blade-metal temperature, K
T_o	absolute temperature at sea-level static standard, 288.16K
$T_{m_{DP}}$	blade-metal temperature at the design point, K

ΔT_m	metal-temperature increase to emergency power, K
T_{wt}	blade relative total temperature, K
W	weight of flywheel rim, kg
W_f	fuel flow, kg/hr
ω	angular velocity, rad/s
ω_1	initial flywheel speed, rad/s
ω_2	final flywheel speed, rad/s
σ_1	allowable turbine-blade-root stress at the highest rating design point, n/m^2
σ_2	allowable blade-root stress at emergency power, n/m^2
θ	absolute temperature divided by standard temperature, T/T_o

3.0 GOALS

Since no requirement currently exists for HOEI operation, the following goal has been established in this report: "Provide adequate emergency power to hover OEI for a sufficient time to achieve minimum-power forward-flight speed and continue on to a safe landing area at normal rated power at the required altitude-temperature combination."

3.1 Adequate Emergency Power

Adequate emergency power is defined as the capability of sustaining one engine failure while the helicopter is in a critical slingload hover mode (HOGE), maintaining emergency power long enough to accelerate in forward flight to minimum-power speed, and continue at normal rated power to a safe landing area. Emergency power must be more than twice the normal hover power required, and must also include the following factor which adds to the magnitude of emergency power: effect of ground vortex on rotor power required as the helicopter moves from hover toward minimum-power forward-flight speed or when helicopter is hovering in equivalent winds (ref. 3). The actual helicopter configuration will determine the delta horsepower increase required to overcome this ground vortex.

Preliminary tests have shown that a slingloaded helicopter will accelerate from hover to minimum-power speed (60 knots) by using a nosedown attitude of 5 to 10 degrees from trim with some gain in altitude. For illustration purposes, a 6-degree nosedown attitude would require approximately 10 percent additional power for acceleration.

3.2 Time Required for Emergency Power

The time required for accelerating a slingloaded helicopter from hover through transition to minimum-power forward-flight speed was estimated between 15 to 20 seconds for any size of helicopter. Fifteen seconds should therefore be considered the absolute minimum time for full emergency power to be available. Since the FAA currently recognizes a 2-1/2 minute time duration for emergency-power OEI for helicopter takeoffs and/or landings, we have used 2-1/2 minutes as the time-duration goal for full emergency power in order to be compatible with FAA requirements.

3.3 Altitude-Temperature Required for HOEI

The altitude-temperature combination which should be specified for the HOEI requirement should be studied to determine the optimum cost-effective combination for the commercial-helicopter market in the U.S. For this study, we have used sea-level, static, 308K (95°F).

4.0 POTENTIAL CONFIGURATIONS FOR EMERGENCY-POWER HOVER OEI

For this report, the CH-47C Chinook helicopter with twin T55-L-11C engines was used for estimating the potential benefits of engine emergency power, since this helicopter represents current technology and performance of the helicopter and engine is known. Engine emergency power, discussed in paragraph 4.1 below, has been calculated for a time duration of 2-1/2 minutes to conform to current FAA regulations for emergency power.

The two other forms of emergency power, rocket turbine and flywheel, depend upon stored energy and are not effective from a weight standpoint for time durations longer than 15 seconds. These two emergency-power methods have been calculated for a projected twin-engine, single-rotor, 50-passenger helicopter of 17 237 kilograms (38,000 pounds) gross weight, which requires about 23 percent less hover power than the current Chinook helicopter.

4.1 Engine Emergency Power

4.1.1 Engine overspeed and overtemperature (dry augmentation). – Boeing Vertol performed an analytical study (ref. 2) of five selected current helicopter engines to assess the potential power increases and to estimate the emergency-power capability of each model for 2-1/2, 10, and 30 minutes by overspeed and overtemperature. The study was based upon the assumption that the limiting factor in an engine is the first-stage-turbine rotor-blade stress-rupture life in the environment of higher rotative speeds and higher turbine-blade-metal temperatures corresponding to emergency power. The calculations used average blade-metal temperatures and material properties typical of the nickel-steel blade alloys. The time duration for the emergency-power capability was derived by dividing the calculated blade stress-rupture life by 2.5, a factor which introduces conservatism into the permissible length of time the emergency capability could be used. This reflects the usual engine-specification test requirement to demonstrate the higher power capability for a substantially longer time duration during the engine development program. Emergency-power estimates were made at sea-level, static, 308K (95°F) ambient-temperature conditions. (Refer to Appendix A for details of analysis.)

The results of the Boeing Vertol stu are summarized in Table 4-1 together with data provided by the engine manufacturers. The basis of the estimated emergency-power capability was first-stage turbine-blade stress-rupture life using average blade-metal temperature and material properties typical of the nickel-steel blade alloys. In the table N_g is expressed as a percentage of the design rpm, ΔSHP is the percentage increase in emergency power above the 30-minute rating, and the time duration is the length of time that emergency power can be used safely.

TABLE 4–1. BOEING VERTOL AND ENGINE MANUFACTURER ESTIMATES OF EMERGENCY POWER FOR FIVE SELECTED ENGINES

Engine	Performance Parameters at 30-Minute Power Rating		Increased Emergency-Power Capability Above 30-Minute Power Rating Boeing Vertol Estimate: 2-1/2-Minute Capability			10-Minute Capability			30-Minute Capability			Increased Emergency-Power Capability Engine Manufacturers Estimate	
	TIT (K)	N_g (%)	TIT (K)	N_g (%)	ΔSHP (%)	TIT (K)	N_g (%)	ΔSHP (%)	TIT (K)	N_g (%)	ΔSHP (%)	ΔSHP (%)	Time (min)
A	1211	100.9	1437	107.2	56	1398	106.3	48	1329	104.5	33	21	2-1/2
												14	30
B		100.9		106.3	40		105.5	33		103.7	20		
C	1347	100.9	1558	106.2	49	1525	105.6	43	1469	104.0	33		
D	1266	98.2	1525	106.3	65	1492	105.6	57	1436	103.4	44	49	2-1/2
												43	30
E	1397	100.2	1643	106.1	53	1607	105.4	46	1537	104.3	31	29	

NOTE: Sea level, 308K (95°F) ambient temperature

Engine D in the above table is the T55-L-11C engine, and our calculations indicate the following emergency-power capability:

Time (min)	ΔSHP (%)	Emergency Power at SL/308K kw (shp)	Percent Increase N_g	TIT
2-1/2	65	3544 (4,752)	8.1	20.5
10	57	3372 (4,522)	7.4	17.9
30	44	3092 (4,147)	5.2	13.5

The 30-minute power rating of this engine at sea level is 2148 kw (2,880 shp).

The very high levels of emergency-power operation may result in some distress to hot-section components such as nozzles and blades, and a hot-section inspection will be required following its use. However, the emergency power is very rarely required in normal operations.

It should be noted that other factors could limit emergency-power capability. For instance, blade creep could limit speed and temperatures; or the capability of static parts in the hot section of the engine, both combustor and turbine, could be a significant factor in emergency-power life, especially for sizable increases over known test levels. The effect of resultant circumferential and radial combustor temperature profiles on liners, nozzles, and shrouds must be demonstrated, since peak temperatures are difficult to forecast in advance. The engine manufacturer must also employ a degree of conservatism in defining emergency time limits, in order to preserve a small increment of calculated blade life. Figure 4-1 illustrates how the fuel control limits the engine power output depending upon the ambient temperature. The solid line shows that either referred gas-generator speed ($N_g/\sqrt{\theta}$), fuel flow (W_f), TIT, or N_g could be the limiting parameter. In order to achieve emergency-power levels, these parameters would have to be exceeded and fuel-control modifications would be required.

The CH-47C helicopter at 19 958 kg (44,000 lb) GW requires approximately 4377 kw (5,870 shp) to hover out of ground effect at sea level, 308K ambient conditions. From the foregoing tabulation, the best 2-1/2-minute emergency power with dry augmentation which could be expected from the engine is 3544 kw (4,752 shp). Therefore, additional augmentation is required to achieve HOEI.

4.1.2 Water-alcohol inlet injection (wet augmentation). – In order to achieve the HOEI goal, additional augmentation is required, and wet augmentation using a water-alcohol mixture will provide additional emergency power by increasing the mass flow without further increasing the engine speed (N_g) or the turbine-inlet temperature (TIT).

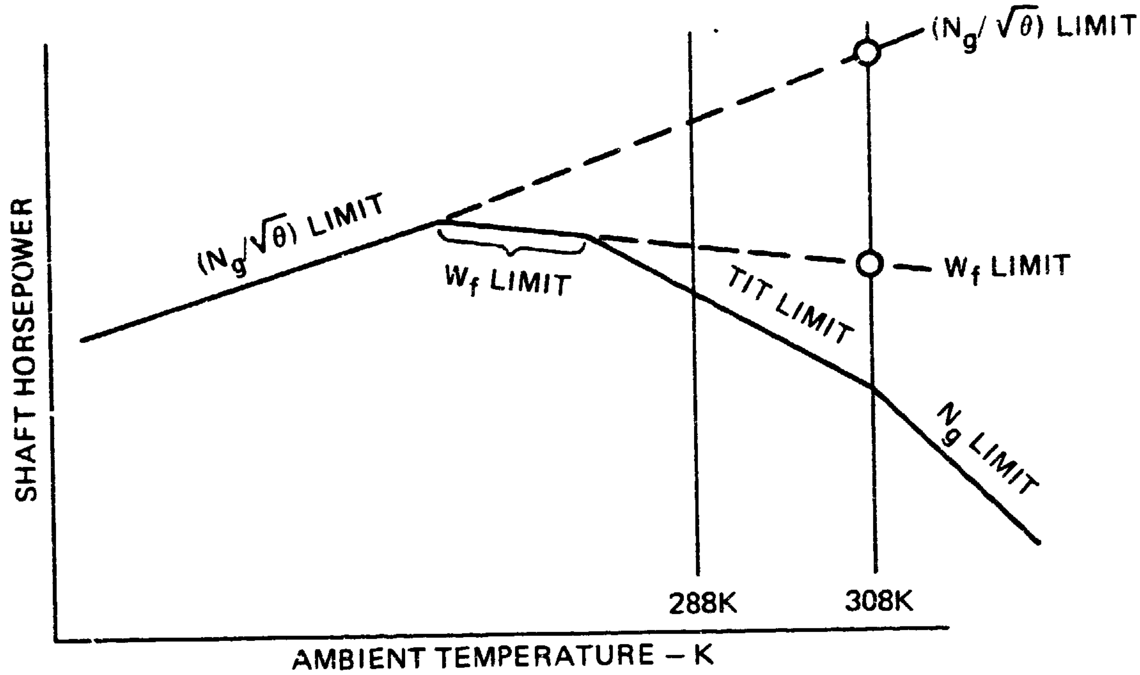

Figure 4–1. Engine power-limit parameters

Wet augmentation was selected by General Electric as an optimum method for obtaining additional emergency power or for improved altitude hot-day engine performance, after a comprehensive analysis was made of many possible methods for increased engine performance (ref. 4). Refer to Appendix B for a description of the wet augmentation system.

Some major advantages to the water-alcohol injection system are listed below:

- System provides high levels of power augmentation (up to 1.47 with a water-alcohol/airflow ratio of 0.0313).
- System weight is one of the lowest studied.
- Effects on unaugmented engine are negligible.
- Development risk is low.
- System is simple and easy to maintain.
- No hazards involved in handling.
- Minimum response time obtained by maintaining a filled spray manifold at all times.

Some minor problems associated with this system are as follows:

- Uneven water-alcohol spray can cause inlet distortion problems. Proper design of spray manifold can overcome this problem.
- Compressor must be designed to provide sufficient compressor-blade clearance to prevent tip rub when water evaporation cools and shrinks the compressor casing. Proper clearance would minimize the effect on compressor efficiency.
- Relatively clean water-alcohol fluid is required. Distilled water is preferred. Fluid-system supply is a small problem because the system is used very rarely.
- Fuel-control modifications are required to accommodate the high augmentation ratios.

4.1.3 Combined wet and dry augmentation. – By combining the wet and dry augmentation capability of the engine, we exceed the augmentation ratio required for HOEI for the current Chinook helicopter. The following tabulation shows that the ultimate T55-L-11C engine emergency-power capability exceeds the hover power required:

Augmentation ratio	= 1.65 (dry) x 1.47 (wet)	=	2.4255 (combined)
Emergency power available for 2-1/2 minutes at sea level, 308K (95°F)	= 2148 x 2.4255	=	5210 kw (6,985 shp)
HOGE power required at sea level, 308K, 19 958 kg GW		=	4377 kw (5,870 shp)

The above tabulation shows that the required combined engine-augmentation ratio is 4377/2148 = 2.04, while the calculated ultimate engine-augmentation-ratio capability is 2.43. Figure 4-2 shows the margin of power available versus power required for HOEI.

The engine manufacturer agrees that combining the wet and dry augmentation method is a viable concept. An emergency-power capability which more than doubles the 30-minute power rating for HOEI operations can be realized, thereby eliminating the need for a third engine. The result should prove to be a cost-effective solution for providing emergency power.

This combined emergency-power capability calculated for a current production engine should also be available on projected future rubberized engines. Based on Chinook field experience for over 10 years covering more than 2 million engine flight hours in the continental USA and in Southeast Asia, the occurrence of power losses averages one in 4,400 engine flight hours (excluding battle damage); and if precautionary landings are excluded from the statistics, power losses averaged one in 15,000 engine flight hours. This very infrequent requirement for emergency power suggests that using ultimate power levels which may damage hot-section engine components could still be cost-effective. Following the use of emergency power for 2-1/2 minutes, the engine would have the capability of continuing operation at a normal power rating for a limited period to allow for continued flight to a safe landing area.

The dry augmentation ratio used in the foregoing sections was based on sea level, 308K ambient conditions since the ratio of power required to power available is higher than at sea-level, standard-temperature conditions. The following example illustrates this fact:

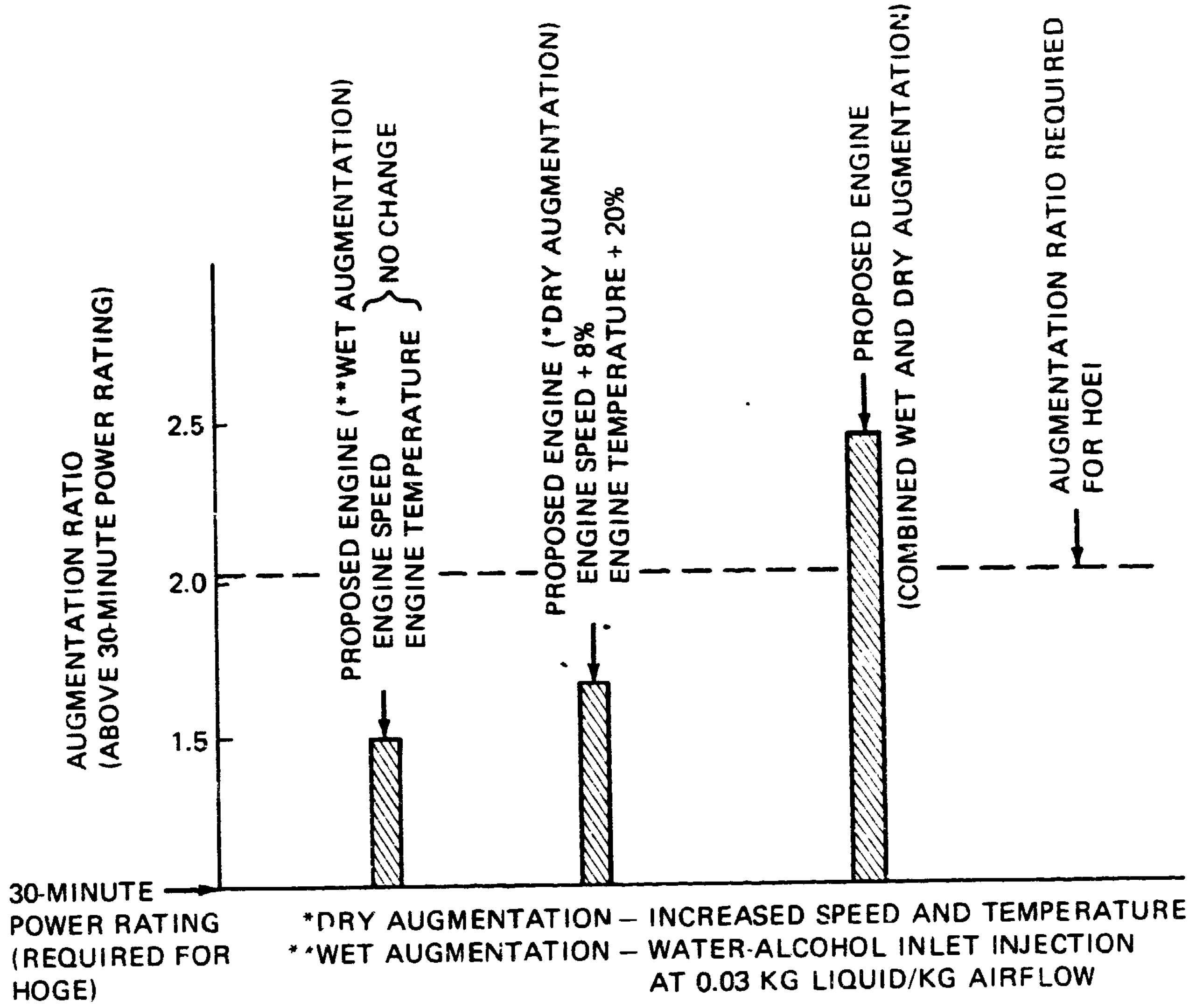

Figure 4–2. Turboshaft-engine emergency-power capability for 2-½ minutes

CH-47C Helicopter at 19 958 kg (44,000 lb) GW

	SL, 288K (59°F)	SL, 308K (95°F)
Power required to HOGE	4293 kw	4377 kw
Power/engine available at 30-minute rating	2535 kw	2148 kw
HOEI power augmentation required	$\frac{4293}{2535} = 1.69$	$\frac{4377}{2148} = 2.04$

The estimated weight penalty for a water-alcohol system for the T55-L-11C engine for 2-1/2 minutes of operation is 106.7 kg (235 lb).

This concept for emergency power also is compatible with the regenerative engine, since the regenerator can be bypassed during HOEI operation.

In our judgment, this concept of using the ultimate emergency-power capability of an engine with a minimum weight penalty represents the most effective method of meeting the HOEI requirement.

The research and development effort required for this approach is outlined in Section 5.0, and the cost and schedule estimates are given in Section 8.0.

4.2 Rocket-Turbine Emergency Power

The rocket-turbine standby engine is a hot-gas turbine system which can be powered by FAA-approved solid-propellant rocket engines. Mechanical power is transmitted from the turbine through a gear train and overrunning clutch directly into the helicopter drive system (ref. 5).

One solid-propellant power source is an adaptation of the Aerojet Model 15NS-250 aircraft rocket engine. This rocket unit is safe to handle, easy to replace, and has achieved a good history of increased payload and safety on many fixed-wing aircraft.

Using a projected twin-engine, single-rotor, 50-passenger helicopter of 17237 kg (38,000 lb) GW, the hover power required for a sea-level, 308K day is 3378 kw (4,530 shp). The delta power required for HOEI is 1689 kw (2,265 shp). For this delta power, Aerojet estimates that a standby engine with five 15NS-250 rocket units would provide the required emergency power for 15 seconds. The estimated weight of such a unit is 145 kg (320 lb). This weight penalty is reasonable, and this type of emergency power appears to warrant further investigation. A schematic of such an engine is shown in Figure 4-3.

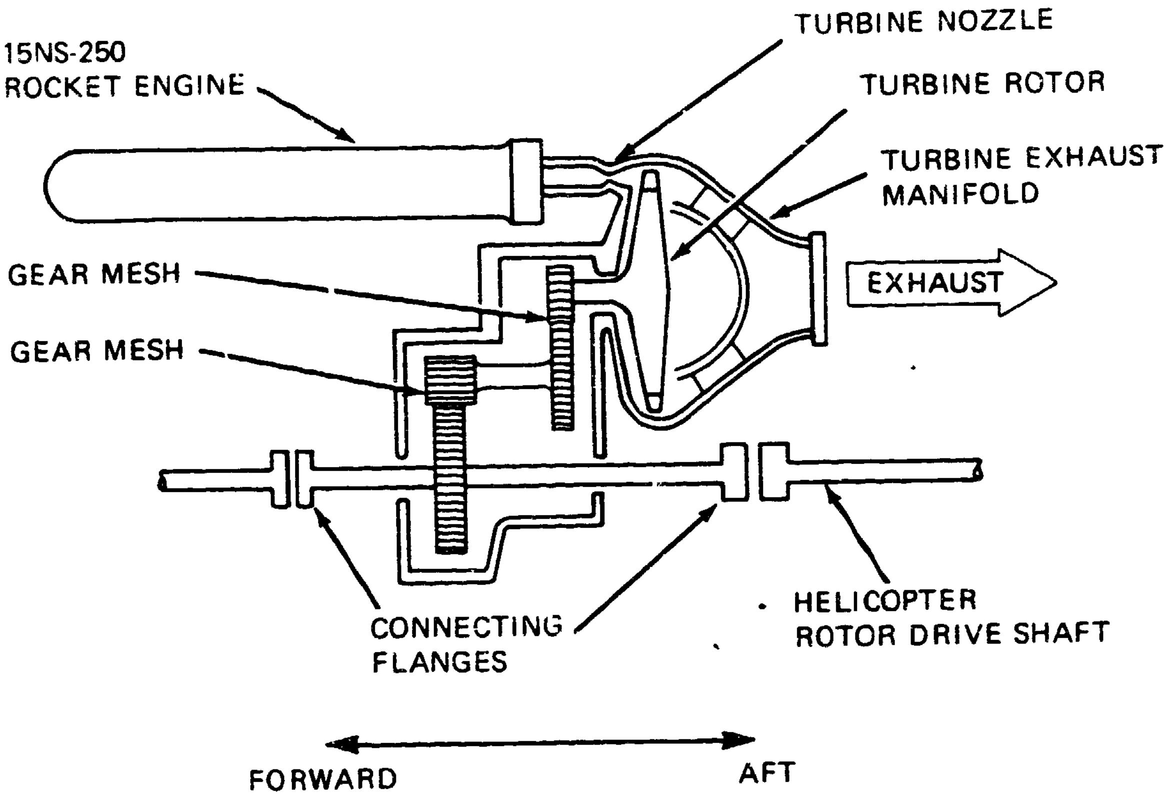

Figure 4–3. Schematic of helicopter standby engine

4.3 Flywheel-Energy Emergency Power

Flywheel energy for emergency power could provide a means for meeting the HOEI requirement, but the time duration could not exceed the minimum required time of 15 seconds. Requirements for the application of flywheel energy to helicopters involve the following factors:

- Dual-flywheel design with transmission to provide for counterrotation. Gyroscopic forces from a single flywheel would adversely affect helicopter control.
- High-speed drive to obtain the highest possible storage energy per pound of weight.
- High-energy-density flywheel design to limit the weight of the system.
- Duration of usage for emergency power must be short (15 seconds or less) to limit weight.

4.3.1 Dual-flywheel design. – As stated in the requirements, a high-speed counter-rotating flywheel drive is required. Figure 4-4 shows the trend of flywheel weight with speed versus duration of operation. These trends are based on flywheel rim weights only and with a radius of gyration, K = 40.64 cm (16 inches). The rim kinetic energy available is calculated for a maximum allowable speed decrease of 10 percent. A sample calculation of flywheel rim weight is provided in Appendix C.

Table 4-2 shows the effect of time duration for emergency power. Flywheel speed is 40,000 rpm.

TABLE 4–2. SUMMARY OF FLYWHEEL RIM WEIGHTS FOR VARIOUS EMERGENCY-POWER TIME DURATIONS

Duration Minutes or	Seconds	Rim Weight kg (lb)	% of Gross Weight
2.5	150	920.4 (2,029)	5.3
1.0	60	368.2 (811.7)	2.1
0.5	30	184.1 (405.8)	1.1
0.25	15	92.0 (202.9)	0.53

Although these flywheel rim weights appear reasonable for the shorter time durations, the added weight required for the flywheel hubs, bearings, and transmissions to drive the counterrotating flywheels will make the total weight penalty more than double these calculated weights. Further study should include the possibility of allowing a total speed decrease up to 20 percent.

Flywheel-energy density is defined in units of watt-hours/kilogram. Current maraging-steel flywheels have been designed and tested with energy densities as high as 55.1 watt-hours/kg

(25 watt-hours/pound), and higher values are possible as the usable stress levels of high-strength steels and other materials continue to increase (ref. 6). The energy density of the sample flywheel in Appendix C is 77.2 watt-hours/kg (35 watt-hours/pound), which represents a high level by today's technology. This energy density would decrease with the actual design when the weights of the hub, bearings, gears, and shafts are added to the rim weight of the flywheel. However, additional analyses and feasibility studies are required to determine the operational suitability to helicopters for this approach.

4.3.2 Flywheel energy at rotor-blade tips. – The use of weights at the rotor-blade tips was also investigated; however, because of the relatively slow rotor rotational speed, the tip weights required for the shortest time duration (15 seconds) amounted to approximately half of the gross weight of the helicopter without considering the added structural weight required to retain these tip weights. This approach does not appear to be feasible for even the shortest durations of emergency power.

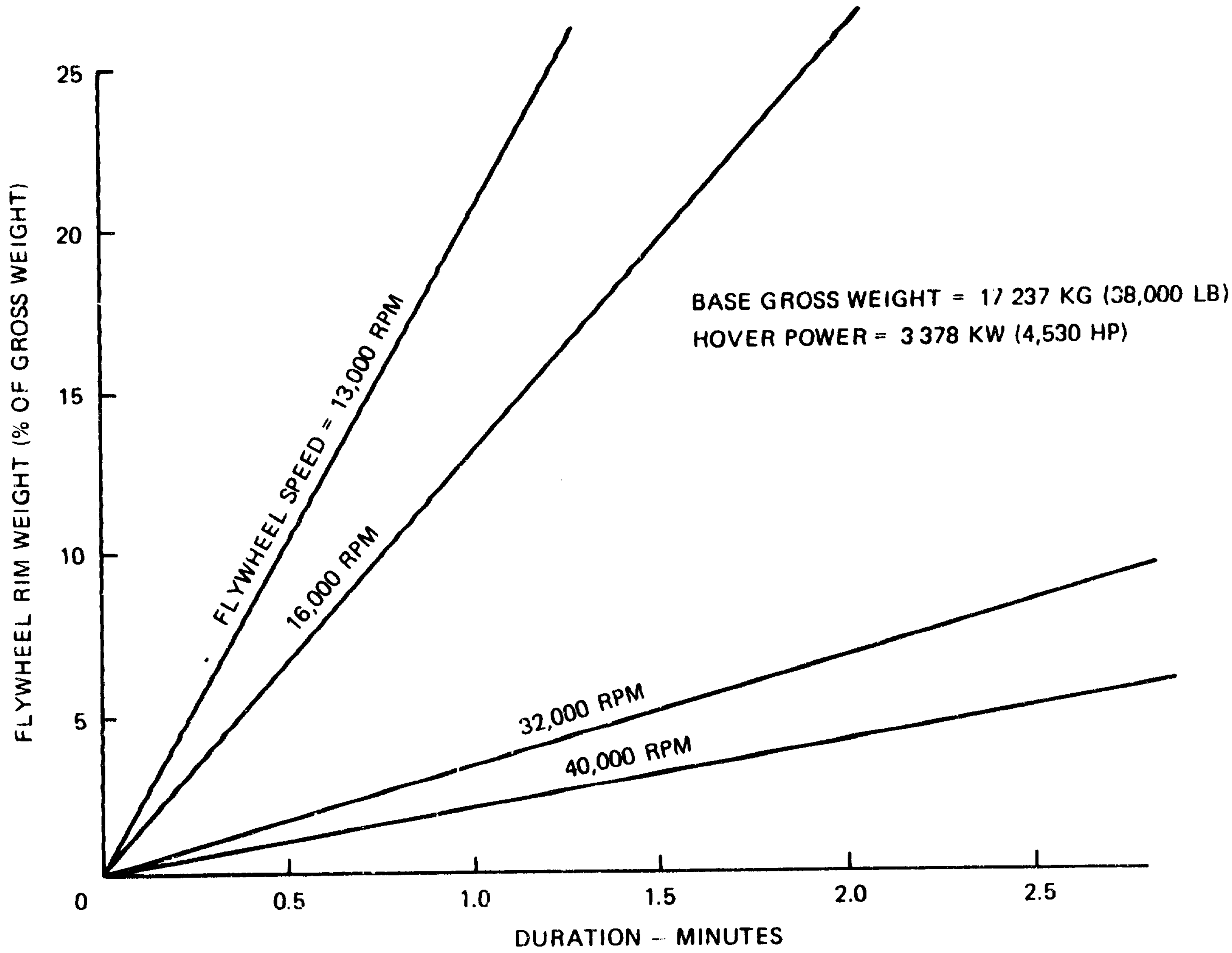

Figure 4 4. Flywheel rim weight versus duration of application

5.0 RESEARCH AND DEMONSTRATION REQUIREMENTS

5.1 Engine-Augmentation Development Required for Emergency-Power HOEI

5.1.1 Engine overtemperature and overspeed system (dry engine augmentation). -- This method of engine augmentation increases engine power by increasing both the turbine-inlet temperature and gas-generator speed to the engine's limit for safe operation. The engine development required is outlined below:

- Combustor Temperature Profiles: The effects of increased fuel flow required for augmentation must be determined for the combustor so that temperature peaks can be minimized.

- Blade Creep: The effects of high-temperature and high-speed operation for short periods must be determined.

- Fuel Control: Modifications required to accommodate the augmentation system must be determined.

- Engine Testing: Emergency-power output must be determined by test for various augmentation levels and time durations.

5.1.2 Water-alcohol inlet-injection system (wet augmentation). – This method of engine augmentation increases engine mass flow and reduces compressor work by complete evaporation within the compressor, while maintaining the same engine speed and temperature. The system consists of a water-alcohol storage tank, a tank-pressurization valve, a water-injection manifold with nozzles evenly distributed around the compressor inlet, a manifold control valve, and other valves, lines, and fittings required to complete the system.

The system development required is listed below:

- Inlet Spray Pattern: Uneven water spray can cause inlet temperature-distortion problems. Thus tests on spray patterns must be conducted.

- Compressor-Case Clearance: Shrinkage of compressor case caused by evaporation of water-alcohol within compressor must be determined to eliminate possibility of tip rubs.

- Fuel Control: Modifications required to accommodate the augmentation system must be determined.

- Engine Testing: Emergency-power augmentation must be determined by test for different liquid-air inlet-injection ratios. Effect of augmentation power on engine must be determined for various time durations from 1/4 to 2-1/2 minutes.

5.1.3 Combined wet and dry augmentation systems. – The combination of the wet and dry augmentation systems is considered to be the optimum method for obtaining emergency power for HOEI. In order to demonstrate its feasibility for commercial helicopter application, the selected engine model should be tested as follows:

- Demonstrate the emergency-power capability for time durations from 1/4 to 2-1/2 minutes.
- Run a demonstration test on an engine with hot-section components which have previously passed a 150-hour qualification test. This simulates an engine with high service time.
  - Demonstration test should include actual operation at emergency-power levels for a time duration of 2.5 times the emergency-power time duration, followed by a run at normal rated power for 30 minutes.
  - Inspect hot-section components following demonstration test to determine what the future inspection requirements will be following the usage of emergency power.

5.1.4 Helicopter development to accommodate double power for HOEI. – In order to accommodate the emergency-power capability from either engine in a twin-engine helicopter, each engine transmission, drive shaft, and combining transmission will have to accept the double power rating.

The following development will have to be conducted on the helicopter:

- Drive System: The effect of double power loads on the transmissions and drive systems will have to be analyzed and tested.
- Engine Control System: The optimum control system for using emergency power in the helicopter will have to be developed for the selected emergency-power system.

5.2 Rocket-Turbine Development

The rocket-turbine emergency-power concept involves the design of a complete standby engine powered by an approved solid-propellant rocket engine plus a turbine rotor, reduction geartrain, and overrunning clutch. The power is transmitted directly to the rotor drive system through a flanged connection. The standby engine is normally stationary until emergency power is required.

Power is then transmitted into the rotor system through the automatic engagement of the overrunning clutch. A design-feasibility study of this concept should be conducted before proceeding with hardware development of the components of the system listed below:

- Rocket-turbine engine
- Gear-reduction unit

- Overrunning-clutch unit
- Control system

5.3 Flywheel-Energy Development

Flywheel energy for helicopters requires exceptional design to provide high energy-storage capacity for minimum weight. These conflicting design requirements will necessitate trade studies for each of the three main components of the system: the dual flywheel (counterrotating), the high-speed gear drive, and the control system for using the flywheel energy. Each of these three system components will have to be individually analyzed for optimum design to determine whether the flywheel-energy principle is feasible for emergency power in airborne helicopters.

6.0 IMPACT OF INTERACTIONS

The effect of incorporating emergency power for HOEI upon other systems of the helicopter is discussed below for each of the three emergency-power concepts.

6.1 Impact on Helicopter Systems

The concept which provides engine emergency power by wet and dry augmentation has the following impact on other systems:

- Drive System: Double power loads on the transmissions and drive shafts will have to be analyzed and tested. Based upon current drive-system experience, this effect upon weight should be minimal.
- Engine Control System: An emergency-power engine control system activated by the pilot will have to be developed for the helicopter.
- Other Systems: Other helicopter systems should be unaffected by emergency power.

The rocket-turbine emergency-power concept results in the following interactions:

- Drive System: The input of emergency power into the drive system of the helicopter will require a redesign to accommodate the added power. The weight increase should be nominal.
- Emergency-Power Control System: The emergency-power system activated by the pilot will have to be developed for the helicopter.
- Other Systems: Other helicopter systems should be unaffected by emergency power.

The use of flywheel energy for emergency power would affect the drive system and may require a special control system for engaging and disengaging the flywheel drive. Acceleration and deceleration of the rotor system would be directly affected; however, the counterrotating flywheel will eliminate adverse helicopter control response.

6.2 Comparisons with Three-Engine Helicopter

The following chart lists the interaction effect of the three proposed methods of obtaining emergency power on helicopter operations compared to a three-engine helicopter.

	Emergency Power Provided by:		
	Engine Augmentation	Rocket	Flywheel
• Energy use reduced	Yes	Yes	Yes
• Engine noise reduced	Yes	Yes	Yes
• Drive system loads and maintenance reduced	Yes	Yes	Yes
• Safety improved	No	No	No
• Reliability improved	No	No	No
• Interior noise reduced	Yes	Yes	Yes
• Airframe design simplified and drag reduced	Yes	Yes	Yes
• Empty weight reduced	Yes	Yes	Yes

7.0 APPLICABILITY TO SIZE OF HELICOPTER

All of the methods for obtaining emergency power for HOEI which are recommended for action in the research and development requirements summary sheet are applicable to any size of helicopter.

8.0 COSTS AND SCHEDULES FOR PROGRAMS

The estimated planning costs and times for each of the programs discussed in Section 5.0 are given in the following tabulation. These estimates cover the nonrecurring costs of designing, fabricating, and testing of the complete systems through a demonstration test which verifies the system performance. FAA certification is not included.

RESEARCH AND DEVELOPMENT PLANNING COST
ESTIMATES FOR EMERGENCY POWER FOR HOEI

Emergency-Power System	Estimated $ Million	Estimated Time (months)
• Engine Emergency Power by Wet and Dry Augmentation	3.0	18
– Associated Helicopter Development	2.5	24
• Rocket-Turbine Emergency Power	0.75	18
– Associated Helicopter Development	2.5	24
• Flywheel-Energy Emergency Power	2.0	24
– Associated Helicopter Development	5.0	30

9.0 CONCLUSIONS AND RECOMMENDATIONS

The comparison of a three-engine helicopter with HOEI capability and a two-engine helicopter without HOEI capability in a previous NASA study (CR-144953, ref. 1) showed that the three-engine helicopter was penalized by an 11-percent increase in gross weight and a 32-percent increase in fuel consumption for equivalent missions. The current study indicates the feasibility of meeting the HOEI requirement with a two-engine helicopter by providing engine augmentation for emergency power which can more than double the 30-minute power rating. It is concluded that attention must be concentrated on adequate emergency power for HOEI in order to minimize the gross-weight and fuel-consumption penalties and approach the safety of a three-engine configuration.

The methods for obtaining adequate emergency power which were identified in this report have been compared in terms of technological risk, energy-storage capability, weight, development cost and direct operating cost, and complexity. These comparisons indicate that the following concepts warrant further research and development effort:

- Engine Emergency Power by providing more than double the 30-minute power rating of the engine with wet and dry augmentation.

- Rocket-Turbine Emergency Power by using FAA-approved solid-propellant rockets turning a turbine geared into the helicopter drive system.

- Flywheel-Energy Emergency Power by using dual counterrotating high-speed flywheels to eliminate adverse effects on helicopter control and minimize weight.

In order to comply with FAA requirements, full FAA certification for 2-1/2-minute emergency power for Category A will require a daily preflight check on each engine to demonstrate that emergency power is available if needed during subsequent flight operations. The daily check will reduce the amount of dry augmentation which can be tolerated without the possibility of damaging hot-section components. This constraint suggests other design approaches to achieve the additional augmentation needed for the HOEI requirements, including the following:

- Variable turbine-cooling airflow to provide proper cooling at peak powers and minimize performance penalties at low power.

- Variable turbine geometry to maximize peak power and reduce fuel consumption at partial power.

- Variable turbine geometry combined with wet augmentation.

- Oversized APU available for in-flight operation to provide needed boost power.

Results of this study on emergency power for HOEI have indicated areas where industry, FAA, and NASA should be concentrating their efforts in order to provide technological benefits which should improve the cost-effectiveness of commercial helicopter operations significantly. The areas recommended for action on emergency power are listed in Table 9-1. The associated development costs and schedules for these programs are estimated in Section 8.0.

TABLE 9–1. SUMMARY OF RECOMMENDED RESEARCH AND DEMONSTRATION REQUIREMENTS FOR HOEI EMERGENCY POWER FOR HELICOPTERS

Item No.	Item	Recommendation for Action	Priority	Payoff
1	Water-Alcohol Inlet-Injection System (Wet Augmentation)	Yes	High	High
2	Engine Overtemperature and Overspeed (Dry Augmentation)	Yes	High	High
3	Combined Wet and Dry Augmentation	Yes	High	High
4	Helicopter Development to Accommodate Double Power for HOEI	Yes	High	High
5	Rocket-Turbine Study	Yes	High	High
6	Flywheel-Energy Study	Yes	Medium	Medium
7	Study of Partial Engine Oversizing With Wet Augmentation Only	Yes	High	High
8	Write Complete Propulsion-System Requirement Specification	Yes	High	High
9	Study Variable-Area Turbines	Yes	High	High

In order to achieve a system meeting the HOEI requirement for FAA certification, a complete propulsion-system requirements specification is needed. This specification should be prepared and include the following requirements as a minimum:

1. 2-1/2-minute emergency power for HOEI (= twin-engine helicopter power required to HOGE at design gross weight, zero wind, sea level, 308K).

2. Engine must have a minimum fuel consumption at 25 percent of emergency power, above.

3. Engine response time from 50 percent to 100 percent emergency power must not exceed 2 seconds.

4. Emergency-power system must be automatic and require no pilot action.

5. Emergency-power system must be minimum weight (design goal is 20 percent of engine weight as a maximum).

6. Emergency-power capability must be checked on a daily preflight basis or equivalent.

10.0 REFERENCES

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APPENDIX A

ANALYSIS OF ENGINE OVERSPEED AND OVERTEMPERATURE (DRY AUGMENTATION)

This appendix outlines the analytical steps to calculate the emergency-power capability of an engine achieved by overspeed and overtemperature.

a. Turbine-Blade Life at Highest Rating

One of the necessary assumptions for the calculations was to define turbine-blade life at the highest engine rating in order to determine the blade design-point stress level, this blade life or time at the highest rating to be consistent with the selected engine design life of 5,000 hours. Turbine-blade life was assumed to be 1,000 hours at the highest rating, whether maximum power or military (intermediate) 30-minute power rating. Some engine power-use profiles suggest that 20 percent of the time at highest rating, or 1,000 hours of the 5,000-hour engine design life, is a reasonable estimate.

If 500-hour turbine-blade life at the highest engine rating were to be assumed, turbine blades could be designed to higher stress levels, but it would follow that the possible increases in turbine temperature and rotative speed to emergency levels would be reduced. However, the result is only a 14K (25^{o}F) difference in the possible turbine-inlet temperature for emergency power.

b. Material Stress-Rupture Properties

Figure A-1 pictures the master stress-rupture properties curve for conventional nickel-based blade alloy used in most of the calculations, although there were some advanced-technology engines which needed improved material properties.

A straight-line approximation of the materials properties curve in Figure A-1 has been developed, resulting in the equation,

$$\sigma_2 - \sigma_1 = 54360\,[T_{m_{DP}}\,(3.0 - \log_{10} t_2) - 20\Delta T_M] \qquad (1)$$

where

σ_1 = allowable turbine-blade-root stress at the highest rating design point, n/m^2

σ_2 = allowable blade-root stress at emergency power, n/m^2

$T_{m_{DP}}$ = blade-metal temperature at the design point, K

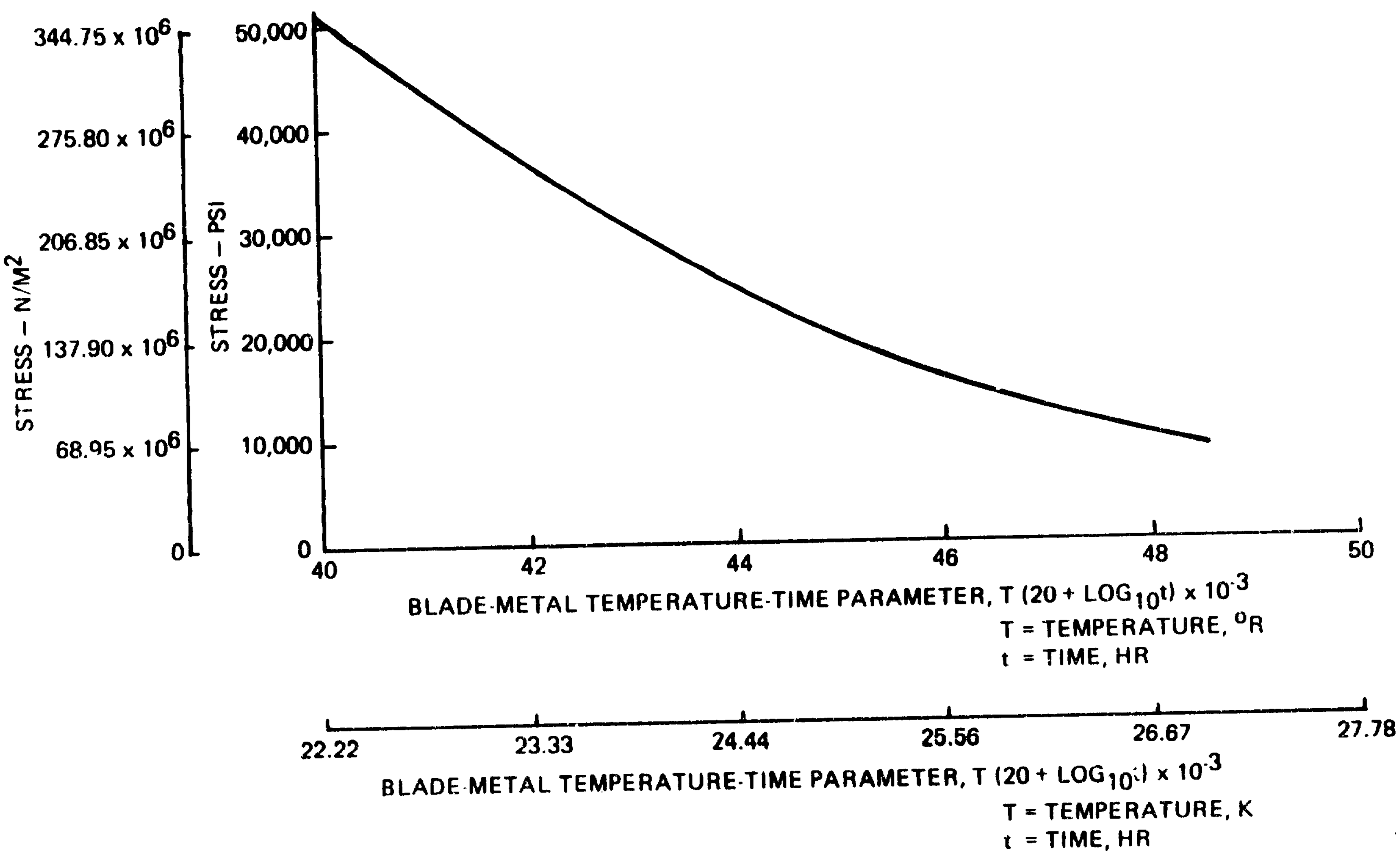

Figure A-1. Master stress-rupture curve

ΔT_m = metal-temperature increase to emergency power, K

t_2 = time duration at emergency-power level, hour

c. Turbine-Blade Temperature

The calculation of emergency power was based upon first-stage turbine-blade life. A 50-percent reaction-stage design-point was assumed, such that the relative total temperature at the first blade was the average of the first-stage inlet and exit total temperatures. For uncooled-turbine rotor blades, metal temperature was assumed to be equal to the relative total temperature. For convection-cooled-turbine rotor blades, a cooling effectivity of 0.30 was selected.

$$\text{Cooling effectivity} = 0.30 = \frac{T_{wt} - T_m}{T_{wt} - T_c} \tag{2}$$

T_{wt} = blade relative total temperature, K

T_m = blade-metal temperature, K

T_c = cooling-air temperature (compressor-exit temperature, T_3), K

At the design-point rating, then, the blade-metal temperature for a cooled blade,

$$T_{m_{DP}} = 0.7 \times T_{wt} + 0.3 \times T_3. \tag{3}$$

d. Blade-Root Stress

The higher gas-generator-turbine rotative speed (N_g) corresponding to the emergency-power level results in higher blade stresses in proportion to the square of the speed change. Turbine-blade-root stress,

$$\sigma = F \times \frac{\rho}{g_o} \times l \times \left(\frac{2\pi}{60}\right)^2 \times N_g^2 \times r = K_1 N_g^2. \tag{4}$$

The constant K_1 is a function of blade material and geometry: area taper ratio, F: material density, ρ; radial length, l; and mean radius, r. Consequently, the increased stress corresponding to the higher turbine speed associated with emergency power, σ_2, is provided by the following equation:

$$\sigma_2 - \sigma_1 = K_1 \left(N_g^2 - N_{g_{DP}}^2\right). \tag{5}$$

e. Generalized Engine-Performance Trends

General trends of engine-performance parameters were used in the calculations: gas-generator speed, N_g; shaft horsepower, shp; and turbine-inlet temperature, TIT. The parametric relationships are plotted in Figures A-2 and A-3, in which the standard θ and δ values are used to generate corrected performance parameters.

In Figure A-2 corrected gas-generator speed is plotted as a function of the corrected TIT, both parameters normalized by dividing by values at the sea-level, 288K (59°F) rating condition (*). Corrected shaft horsepower is plotted as a function of corrected TIT in Figure A-3, again with both parameters normalized by the values at sea-level, 288K rating condition(*).

f. Emergency-Power Estimate

The emergency-power calculation is outlined in the following steps. Initially, design-point values of certain parameters are determined corresponding to the highest rating, whether maximum power or military (intermediate) 30-minute power rating, 308K (95°F) ambient temperature. The relative total temperature at the first-turbine blade is calculated as the average of the first-stage-inlet total temperature (TIT_{DP}) and stage-exit total temperature. At the design point:

$$T_{m_{DP}} = 0.70 \times T_{w_t} + 0.30 \times T_3 \tag{3}$$

Blade life at $T_{m_{DP}}$,

$$t_1 = 1000 \text{ hours}$$

Allowable blade stress (Figure A-1),

$$\sigma_1 = f\left\{T_{m_{DP}}(C_1 + \log_{10} t_1) \times 10^{-3}\right\}$$

$$K_1 = \frac{\sigma_1}{N^2_{g_{DP}}} \tag{4}$$

In the calculation of emergency power, a value of turbine-inlet temperature (TIT) is selected and the temperature increase above the design point is calculated:

$$\Delta T = TIT - TIT_{DP}$$

$$\text{Then } N_g = f\left\{\frac{TIT/\theta}{TIT^*}\right\}, \text{ Figure A-2}$$

$$shp = f\left\{\frac{TIT/\theta}{TIT^*}\right\}, \text{ Figure A-3}$$

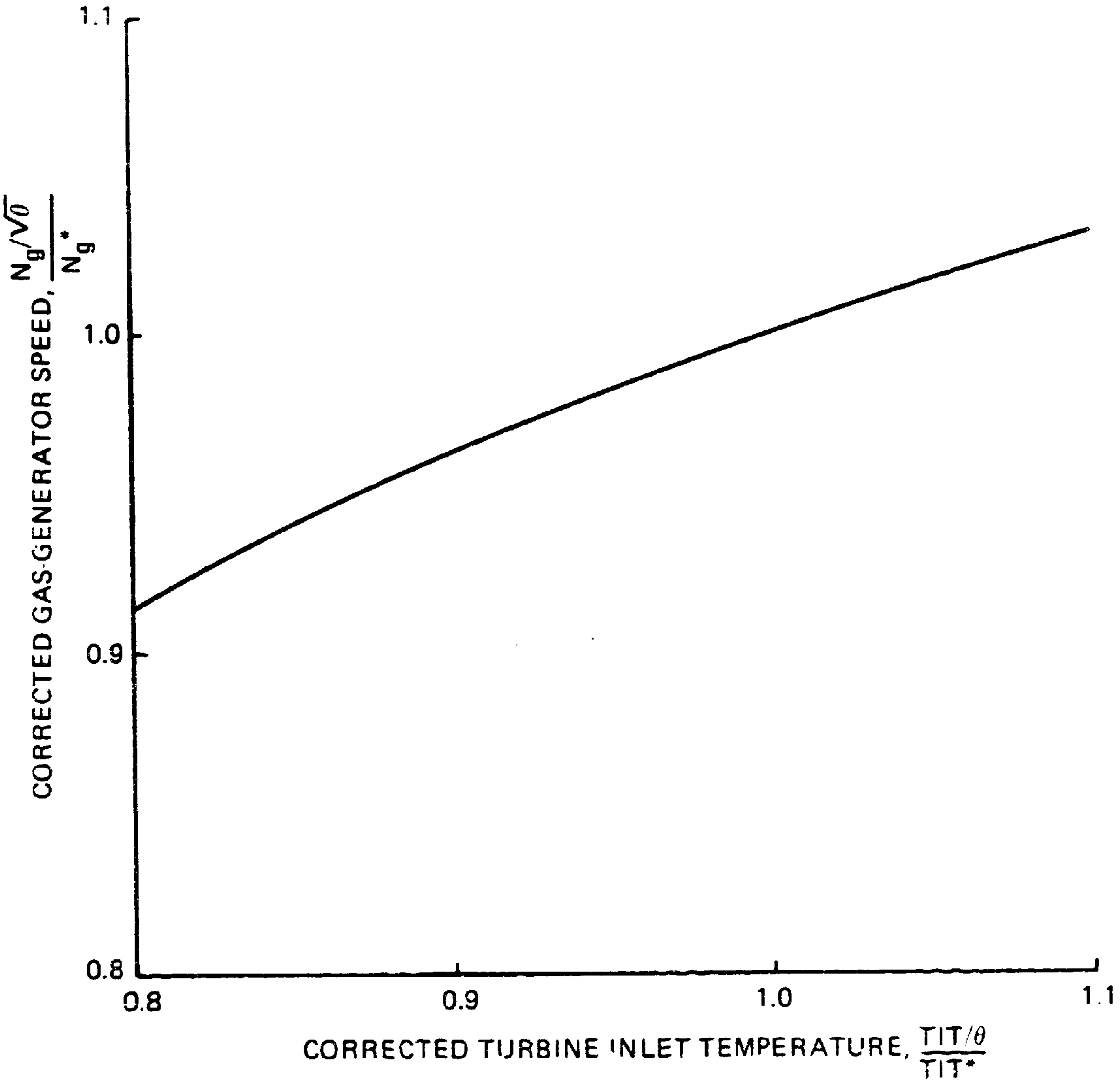

Figure A–2. Corrected gas-generator speed

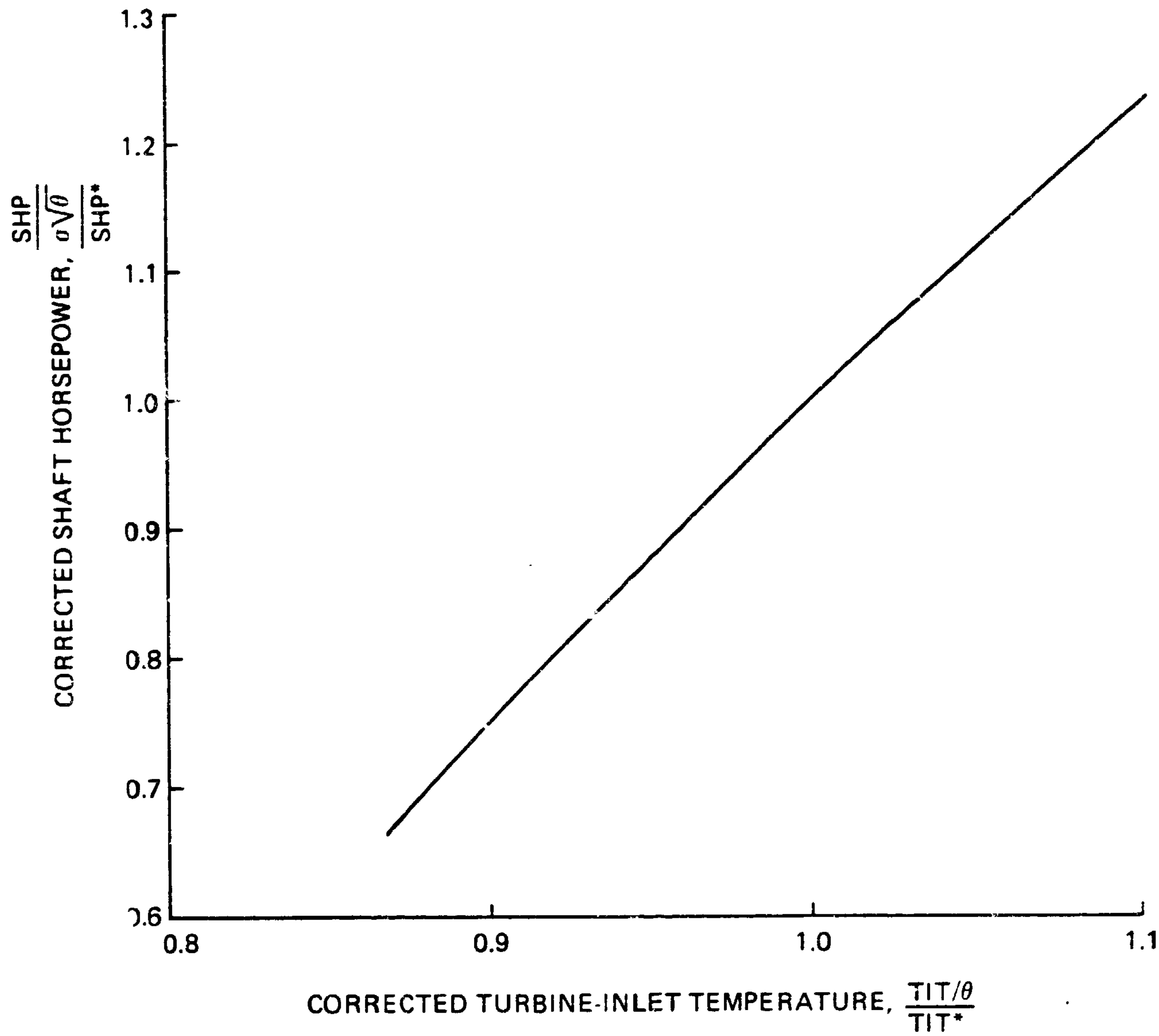

Figure A–3. Corrected shaft horsepower

The increase in blade stress,

$$\sigma_2 - \sigma_1 = K_1 \left(N_g^2 - N_{g_{DP}}^2\right)$$

The allowable increase in blade stress (related to blade stress-rupture life),

$$\sigma_2 - \sigma_1 = 54\,360\,[T_{m_{DP}} (3.0\text{-}\log_{10} t_2) - 20 \times \Delta T] \quad (1)$$

Emergency-power capability represented by shp should be available for t_2 hours. However, conservatism is introduced by dividing t_2 by 2.5 to determine the duration of time that should be specified for the contingency-power capability.

The ΔT value used in the above calculation is the difference in turbine-inlet temperatures, from highest rating to emergency power. Actually, the corresponding increment in blade-metal temperature should be used, but that value is not readily calculable. The procedure as used should provide a conservative estimate of emergency power as a result.

APPENDIX B

DESCRIPTION OF WATER-ALCOHOL INLET-INJECTION SYSTEM (WET AUGMENTATION)

The water-alcohol inlet-injection system has the highest overall reliability, is simple in design, contains a minimum of additional components, and places no additional maintenance requirements on the engine after use in an emergency situation. Emergency power with this augmentation system is a proven method suitable for long-term standby storage without loss of performance potential. The logistics of resupply of the water required are small, and the weight penalty of this system is small.

Augmentation ratios obtainable from injection of water or water-alcohol mixtures into the compressor inlet vary directly with water/air ratio and the type of engine to which it is applied (see Figure B-1). The addition of water or water-alcohol to the engine inlet is measured as a ratio of the weight of the liquid to the weight of the engine airflow. Water-alcohol has been selected as the mixture to use for wet augmentation because it permits the spray manifold to be filled with mixture under all ambient-temperature conditions. A minimum response time for emergency power is achieved by maintaining a filled spray manifold at all times. At a water/air ratio of 0.025, the augmentation ratio obtained for a nonregenerative engine is 47 percent. A mixture of 35-percent alcohol and 65-percent water would give the same augmentation except the liquid-air ratio would be 1.25 times higher due to the lower latent heat of vaporization for the water-alcohol mixture. However, the heating value of the alcohol would decrease the amount of additional main fuel required to the degree to which the alcohol burned.

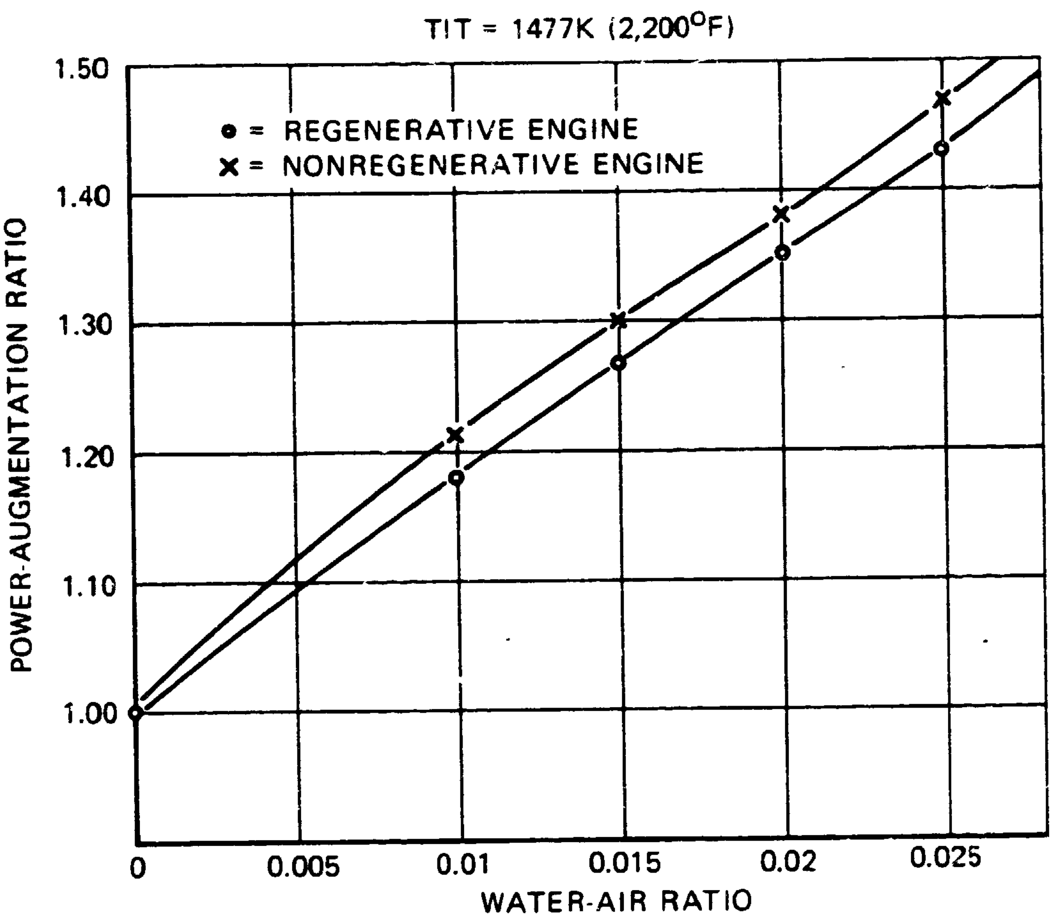

Figure B–1. The effect of compressor-inlet water injection on power-augmentation ratio, 1829 meters (6,000 feet) static, T ambient = 308K (95°F)

APPENDIX C

EXAMPLE CALCULATION OF FLYWHEEL WEIGHT

In order to investigate quantitatively the effect of applying flywheel energy to a helicopter for emergency power, a single-rotor helicopter with a 17 237-kg (38,000-lb) GW was assumed having the following design parameters:

Hover power required	= 3378 kw (4,530 shp)
Number of blades, b	= 4
Tipspeed	= 193.5m/s (635 ft/sec)
Rotor radius	= 9.14m (30.0 ft)
Rotor speed	= 200 rpm

The kinetic energy available from the rim of a flywheel having a radius of gyration of 40. 6 cm (16 in.), rotating at 40,000 rpm with an allowable speed decrease of 10 percent, is:

$$KE = 1/2\,W\left(\frac{K}{100}\right)^2 [\omega_1{}^2 - \omega_2{}^2]$$

W = weight of flywheel rim, kg

K = radius of gyration of rim mass, cm

ω_1 = initial flywheel speed, radians/second

ω_2 = final flywheel speed, radians/second

$$KE = 1/2\,W\,(0.406)^2 \left[\left(\frac{\pi \times 40{,}000}{30}\right)^2 - \left(\frac{\pi \times 36{,}000}{30}\right)^2\right]$$

$$KE = 274{,}760\,W \text{ (joules)}$$

The flywheel energy required for one minute for emergency power HOEI =

$$\frac{\text{Total Engine Power Required to HOGE}}{2} \times 1{,}000$$

$$\text{KE required for 1 minute} = \frac{3{,}378}{2} \times 1{,}000 \times 60 = 101.34 \times 10^6 \text{ joules/minute}$$

For emergency-power duration of 1 minute,

$$KE_{available} = KE_{required}$$

$$274{,}760\ W = 101.34 \times 10^{6}$$

$$W = 368.8\ kg$$

Percent of helicopter GW = 2.1%

Note: Further study should consider a total speed drop of 20 percent including the energy in the main-rotor system.

END

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