The US naval landing craft, air cushion LCAC-008, cold weather tests

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RÉSUMÉ

En septembre 1987, l'engin de débarquement LCAC-008 à sustentation aérodynamique de l'U.S. Navy a terminé son programme d'évaluation climatique d'une durée de huit semaines, dans les installations d'essais McKinley de l'Eglin Air Force Base, en Floride. Dans la chambre d'essais, les températures ont varié entre 40 et –30°F (4 et –32°C), accompagnées de pluie, d'embruns, de vent et de neige.

L'engin LCAC est équipé en permanence d'appareils destinés à combattre le froid : circuit de réchauffage du combustible et de dégivrage des fenêtres et ensemble amovible pour le dégivrage des entrées de l'air d'alimentation et le dégivrage de la tuyère d'hélice. Le circuit de dégivrage du moteur principal présente la particularité de récupérer les gaz d'échappement de la turbine pour réchauffer les entrées de l'air.

À chacun des essais, plus de trois cents paramètres ont été enregistrés en temps réel. En outre, des essais pratiques ont permis d'évaluer les méthodes de dégivrage et de chargement/ déchargement, et aussi d'établir des procédures d'exploitation par temps froid.

Les résultats de tous ces essais climatiques sont présentés, de même qu'une évaluation sur le comportement des carburants, des huiles, des équipements et de la structure.

ABSTRACT

In September 1987, the U. S. Navy Landing Craft, Air Cushion LCAC-008, completed an eight week cold weather test and evaluation at the McKinley Climatic Laboratory located at Eglin Air Force Base, FL. Test temperatures in the chamber ranged from +40°F (4°C) to -30°F (-32°C) with simulated rain, spray, wind, and snow.

The LCAC is designed with permanently installed cold weather components, such as fuel heaters and window heaters, and a removable kit for gas turbine air inlet de-icing and propeller shroud de-icing. The LCAC main engine de-icing system is unique in that it uses reingested turbine exhaust to heat the air inlets.

Over three hundred real time test parameters were recorded during each test run. Practical experiments for ice removal methods, loading and unloading vehicles, and establishing cold weather operating procedures were also conducted.

The results of the performance of the craft in the cold/ arctic conditions will be presented together with the evaluation of fuels, oils, equipment operations, and structure.

INTRODUCTION

From July 20th to September 14, 1987, the Landing Craft, Air Cushion (LCAC) 008, underwent cold weather testing at the McKinley Climatic Laboratory, Eglin AFB, Florida (Figure 1) to demonstrate an LCAC's capability to operate in cold and arctic weather environments with simulated sea spray, rain, snow and wind. To operate in these environments the LCAC is constructed with cold weather enhancements for fuel, window, cabin and gas turbine blow-in door heating; and, when conditions require, removable cold weather kits are used for anti-ice protection of the main engine inlets, propeller shrouds, and the gas turbine powered auxiliary power units.

LCAC cold weather requirements are established by two environmental conditions: (a) cold weather for fuel systems is defined by temperatures below 48°F which, depending on the quality of the fuel, is the temperature that marine diesel fuel waxing will begin to occur, and (b) cold weather for gas turbine inlets is defined by temperatures at approximately 40°F and below. This is the temperature where inlet icing could occur downstream of the demister filters on the inlet guide vanes and in the bellmouth area of the gas turbines. At the gas turbine inlets, there can be an estimated static temperature drop of up to 8°F depending on the inlet area and mass flow velocity. With a relative humidity of 70% or greater, ice could form at the gas turbine inlets, break off and be ingested into the turbine compressor possibly causing blade damage. Of course, at 32°F and below, ice or snow blockage occurs on the inlet screens and filters from either sea spray, rain, or snow.

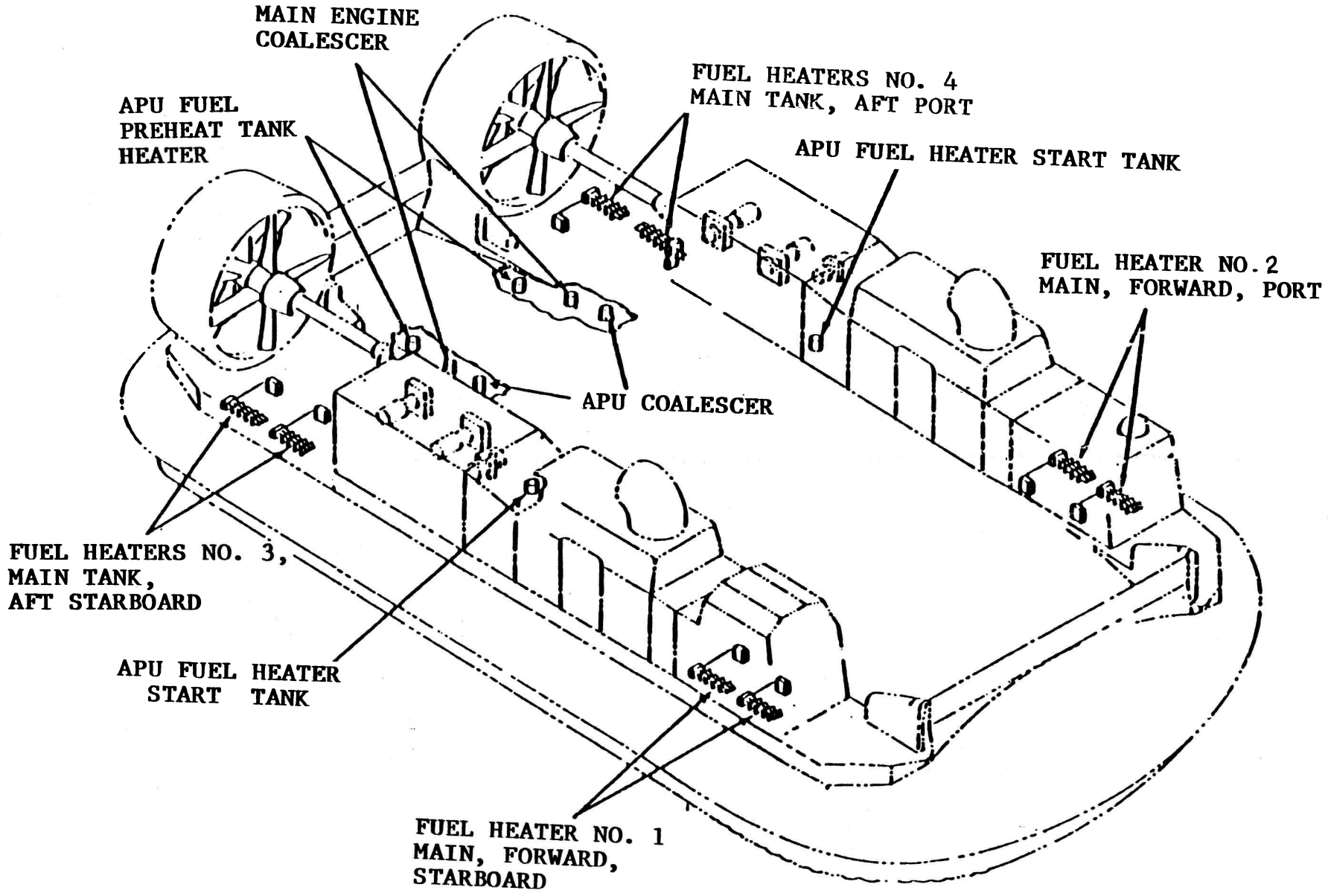
Craft cold weather capability was tested in two phases: (1) at temperatures from 40°F to 10°F in wet and dry conditions for contractual design evaluation, and (2) at temperatures from 10°F to -30°F in snow and dry conditions to simulate an arctic environment. In the development of the craft test plans,the cold weather experiences of other air cushion vehicles used in northern latitudes of Alaska and the Arctic were studied to incorporate the lessons learned for testing while the LCAC was in the cold weather chamber. Among other experiments tried, were ice accretion coatings on bulkhead and railing surfaces, cold weather support equipment such as portable hot air heaters, ice removal equipment, crew clothing, vehicle loading and unloading, and the evaluation of different fuels and oils. A general description and the principal characteristics of the LCAC are given in Appendix A.

COLD WEATHER EQUIPMENT

There are two types of cold weather equipment for the LCAC: either permanent that is installed during craft construction, or removable that is installed as a kit when temperatures are expected to reach 40°F and below. There are no arctic kits per se. Permanent equipment includes the electrically powered main fuel tank heaters, fuel coalescer heaters and the auxiliary power unit (APU) starting fuel heaters (Fig 2), the window heaters, main engine and APU blow-in door heaters, cold weather equipment remote controls and cabin heating. The removable kit(s) use removable ducts to supply: (a) APU bleed air to heat the propeller shroud, APU gas turbine inlet air, and hot air for a de-icing hose and nozzle assembly; and (b) the main engine exhaust gases to heat the main engine inlets.

As illustrated in Figure 3, bleed air is ducted to the base of the propeller shroud. The hot bleed air flows up and around both sides of the shroud, and out the top anti-icing vents. The purpose of heating the shroud is to prevent icing along the shroud inlet and in the plane of propeller rotation. Both port and starboard bleed air flows to the shrouds and APU inlets can be controlled at the craft engineer's cold weather control panel.

Unlike larger gas turbine installations that use self generated hot bleed air and/or electrical resistance heated inlets for anti-ice protection, the four main propulsion engines, Textron Lycoming TF40B(s), on the LCAC have to be heated with a portion of their exhaust waste heat gases. As illustrated Figure 4 and 5, hot exhaust gas is tapped off the engine exhaust stack with the manually adjusted flaps. The hot gas flow through the transverse tubes to the inlet is controlled by the craft engineer with two hydraulically activated butterfly valves to meet or limit inlet temperature requirements. There are certain main engine design factors that influenced the selection of this inlet heating method: (a) using its own bleed air, the available engine horsepower decreases and there is a severe increase in fuel



FUEL SYSTEM HEATERS

Figure 2

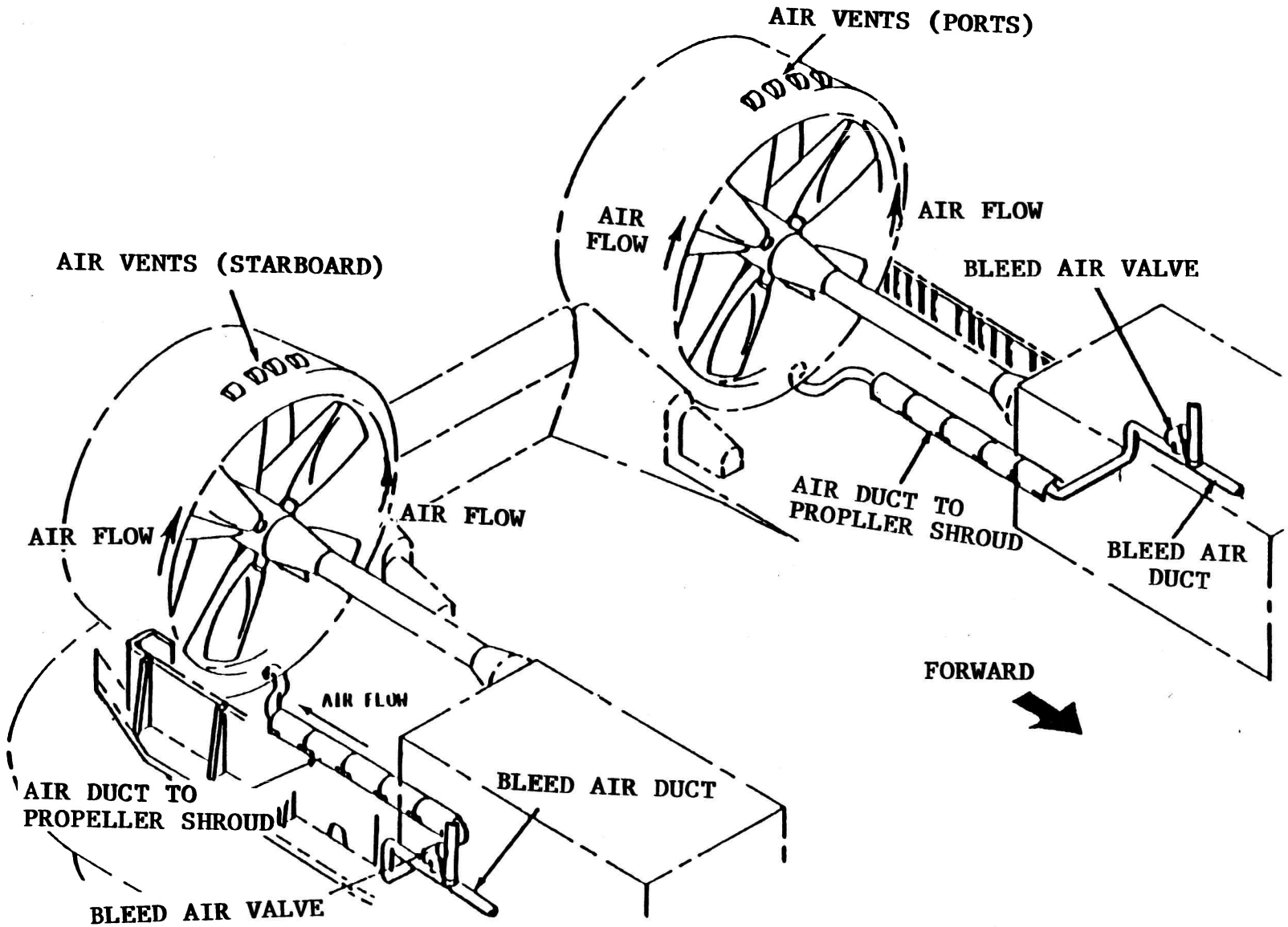
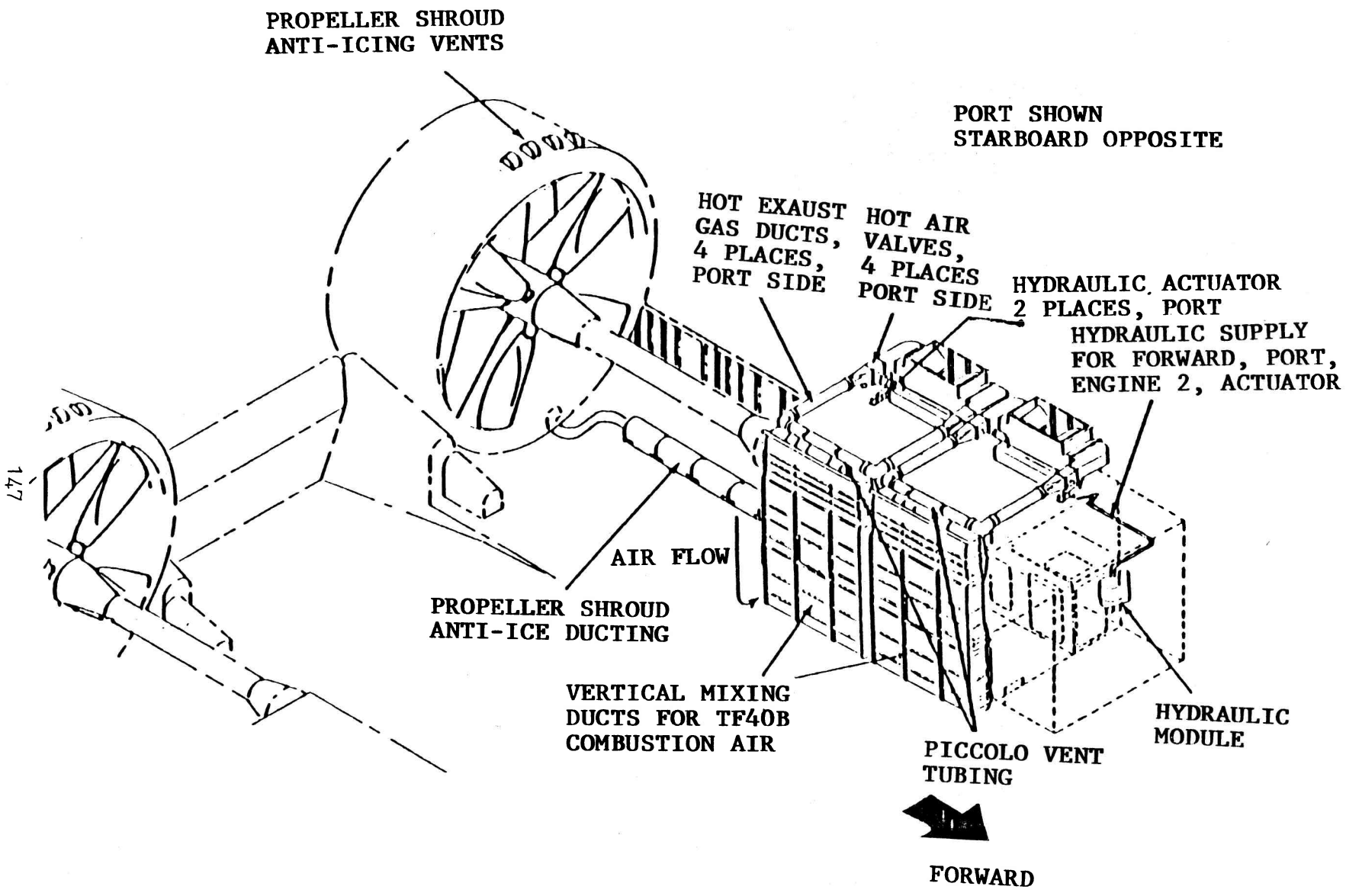
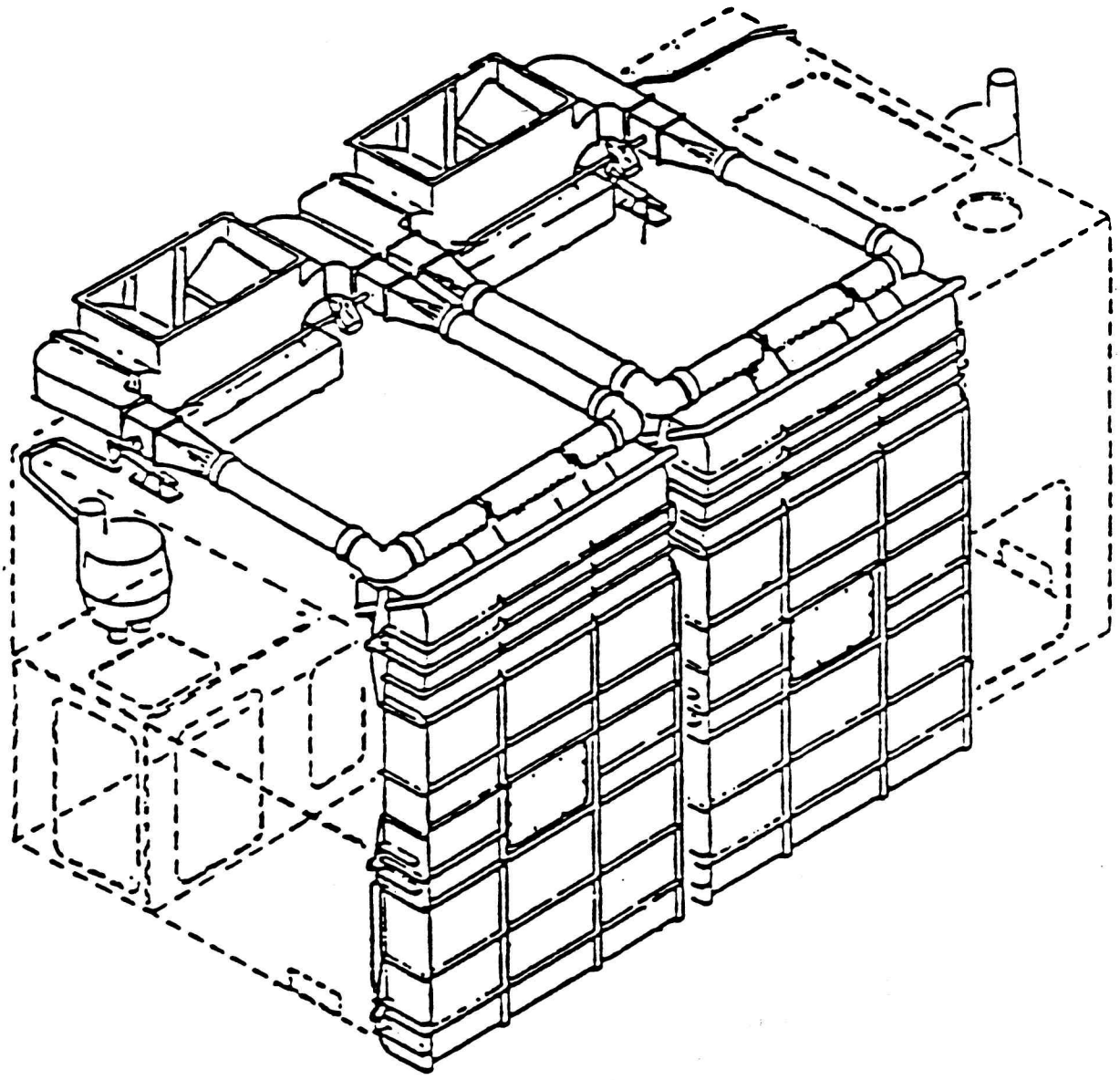

AIR VENTS (PORTS)
AIR FLOW
AIR FLOW
BLEED AIR VALVE
AIR VENTS (STARBOARD)
AIR DUCT TO
PROPLLER SHROUD
BLEED AIR
DUCT
FORWARD
AIR FLOW
AIR FLOW
AIR FLOW
AIR DUCT TO
PROPELLER SHROUD
BLEED AIR DUCT
BLEED AIR VALVE

Figure 3



TF40B Combustion Air Anti-Ice

Figure 4



Combustion Air Anti-Icing Group, Port

Figure 5

consumption; (b) the current TF40B engine bleed air regulation and bleed air manifold would have required major redesign; and (c) considering the engines power, there would not be sufficient bleed air from the engines at extremely low temperatures. Additionally, the APU cannot supply adequate bleed air to the main engines and simultaneously provide electrical power to resistance heaters combined with its requirement to supply hot bleed air to the propeller shroud and the normal cold weather electrical loads. The disadvantages of using exhaust gases for inlet heating are the ingestion of exhaust soot that can block inlet filters, and engine power loss created by the inlet and exhaust restrictions of the cold weather kit.

CRAFT TEST CONFIGURATION/OPERATION

In the cold weather chamber, the craft sat on its landing rails and was constrained from lateral movement by cables secured between the craft and chamber floor. About half of the skirt was removed to allow cushion air to escape and prevent lift. However, because of craft movement during initial power trials about seventy tons of dead weight was added, and air cushion lift vanes were preset to a 10^{o} opening. Although cushion air flow was restricted by the 10^{o} lift vane opening, it is felt that sufficient air flow to the cushion and APU combustion/main engine cooling air system was acquired to make an accurate technical assessment of the system designs.

Critical operating parameters were monitored with the craft's on board alarm and monitoring system (AMS) while other system measurements were recorded at remote test modules in the chamber. There were approximately three hundred test parameters measured and monitored including oil temperatures and pressures, air inlet and exhaust temperature and pressure measurements, fuel temperatures, vibration, etc., during the test.

Safety of personnel and equipment was of prime importance during the test. Craft was operated by a U. S. Navy crew. Prior to each test flight, test requirements, test procedures and craft equipment limits were thoroughly briefed with crew, test engineers, and test cell technicians. This method of operation proved quite beneficial in achieving all test objectives in the limited time schedule without damaging the craft.

TEST CONDITIONS

The conduct of the tests was done in the following phases: (1) the effects of dry cold temperature to $10^{o}F$, (2) cold temperatures to $10^{o}F$ with liquid water sprays of 1.5, 2.5, and 4 inches per hour, and (3) dry arctic temperatures and snow to $-30^{o}F$ to determine what effect, if any, the particular environmental condition had on craft systems. Table 1, 2 and 3 provides the matrix of test points for the test.

LCAC COLD WEATHER TEST MATRIX

Item/Event Description	Powered Systems Tests Temperature in Degrees Fahrenheit						
	40	25	10	0	-10	-20	-30
Auxillary Power Unit							
APU fuel heater	x	x	x	x	x	x	x
Battery start test			x				x
Start and run	x	x	x	x	x	x	x
Load carrying capability	x	x	x	x	x	x	x
Blow-in door strip heaters	x	x	x	x	x	x	x
Main fuel tank heaters	x	x	x	x	x	x	x
Main Engine/Propulsion							
Declutch engine	x	x	x	x	x	x	x
Start and run	x	x	x	x	x	x	x
Load carrying capability	x	x	x	x	x	x	x
Blow-in door strip heaters	x	x	x	x	x	x	x
Maneuvering Systems							
Prop pitch/hyd/oper	x	x	x	x	x	x	x
Bow thruster/hyd/oper	x	x	x	x	x	x	x
Rudder/hyd/oper	x	x	x	x	x	x	x

Table 1.

LCAC COLD WEATHER TEST MATRIX

Item/Event Description	Auxilliary Systems Tests Temperature in Degrees Fahrenheit						
	40	25	10	0	-10	-20	-30
Ancillary Systems							
Shaft Alignment			x				x
Lift Fan Bearings	x	x	x	x	x	x	x
Fwd ramp hyd system	x	x	x	x	x	x	x
Aft ramp hyd system	x	x	x	x	x	x	x
Cabin heater	x	x	x	x	x	x	x
Utility pump		x	x	x	x	x	x
Radar	x	x	x	x	x	x	x
Fire extinguish system	x	x	x	x	x	x	x
Smoke detection system	x	x	x	x	x	x	x
Fire detection system	x	x	x	x	x	x	x
Door/hatch mech oper			x				x
Condensation check		x	x				x
Fuel system integrity	x	x	x	x	x	x	x
Hydraulic system integrity	x	x	x	x	x	x	x
Anemometer	x	x	x	x	x	x	x
Deicing wand operation		x	x	x	x	x	x
CWK maintenance demo			x				x
Materials Systems							
Plating/structure		x	x	x	x	x	x
Welds		x	x	x	x	x	x
Fasteners		x	x	x	x	x	x
Skirts		x	x	x	x	x	x
LSD/LCAC Interface Systems							
Fuel hoses		x	x	x	x	x	x
Fresh water hoses		x	x	x	x	x	x
Salt water hoses		x	x	x	x	x	x
Fuel/Water fittings		x	x	x	x	x	x
Power cables/fittings		x	x	x	x	x	x

Table 2.

LCAC COLD WEATHER TEST MATRIX

Item/Event Description	Freezing Spray/Blowing Snow Test						
	Temperature in Deg. F.				Spray Rate		
	25	10	0	-10	Light 1.5"/hr	Med 2"/hr	Heavy 4"/hr
Freezing Spray Conditions							
Automatic Anti-icing Systems							
M.E. comb air anti-icers	x	x			x	x	x
APU comb air anti-icers	x	x			x	x	x
Prop shroud anti-icers	x	x			x	x	x
Windshield anti-icers	x	x			x	x	x

	Snow Rate	
	Med 1"/hr	Heavy 2"/hr
Blowing Snow Conditions		
Automatic Deicing Systems		
M.E. comb air anti-icers	x	x
APU comb air anti-icers	x	x
Prop shroud anti-icers	x	x
Windshield anti-icers	x	x

Table 3.

In dry cold conditions, the ability of the gas turbine engines to start; the times and capability to heat fuel; the change in clearances or lengths of lift fans and shafting, respectively; the oil heating rates of the transmission systems; the reaction of hydraulic control systems; and adequacy of gas turbine anti-ice systems were tested prior to adding the variables of either rain or snow.

In the rain and snow conditions, the primary goal of testing was to demonstrate the capability of the gas turbine anti-ice systems to keep their respective inlets open and free of ice/snow blockage, to keep the propeller shroud free of ice in the plane of propeller rotation, and assess the effect of ice on the externally exposed rotating machinery. Rain/spray was dispensed from an overhead rack covering the length of the craft, while snow and wind machines were used to create simulated snow fall conditions.

TEST RESULTS

Fuel Systems

The main purpose of heating fuel is to prevent flow blockage created when cold diesel fuel waxes in fuel lines and filters. The fuel heating system on LCAC uses DC or AC electrical power to preheat APU starting and operating fuel, and uses AC power to heat the four main fuel tanks and the two fuel coalescers. From an initial cold soak condition, the DC power is activated to heat the APU engine start fuel tanks. Once the fuel reaches a minimum 48^{o}F temperature, the APU is started and AC power system activated to begin heating both APU fuel system and main fuel tanks. The craft's AC fuel heating system can also be powered from an external power source which can be used when APU(s) are shut down.

A major problem was encountered in the early stages of the test; the APU fuel controls became internally iced and engine starts were difficult to achieve. This problem existed with both test fuels DFM and JP-5. Usually, the problem ceased when warm fuel reached the fuel control, but in colder conditions an external heat source would be required. A design change is in process to provide heat to the engine fuel control simultaneously with the APU fuel tank heaters.

With the exception of the fuel control icing and some mis-wired controllers, the fuel heating system worked exceptionally well. The time to heat measured quantities of fuel from a cold soak of 10^{o}F is given in Figure 6. Of interest to this test was the ability of the fuel tanks to retain heat. It took approximately 96 hours at a cold soak temperature of zero degrees to bring the fuel to a test temperature 10^{o}F from an 80^{o}F fuel load temperature. Fuel will be loaded in the support ship's well deck at about 80^{o}F, which will likely reduce the requirement for fuel heating when operating at sea with a support ship.

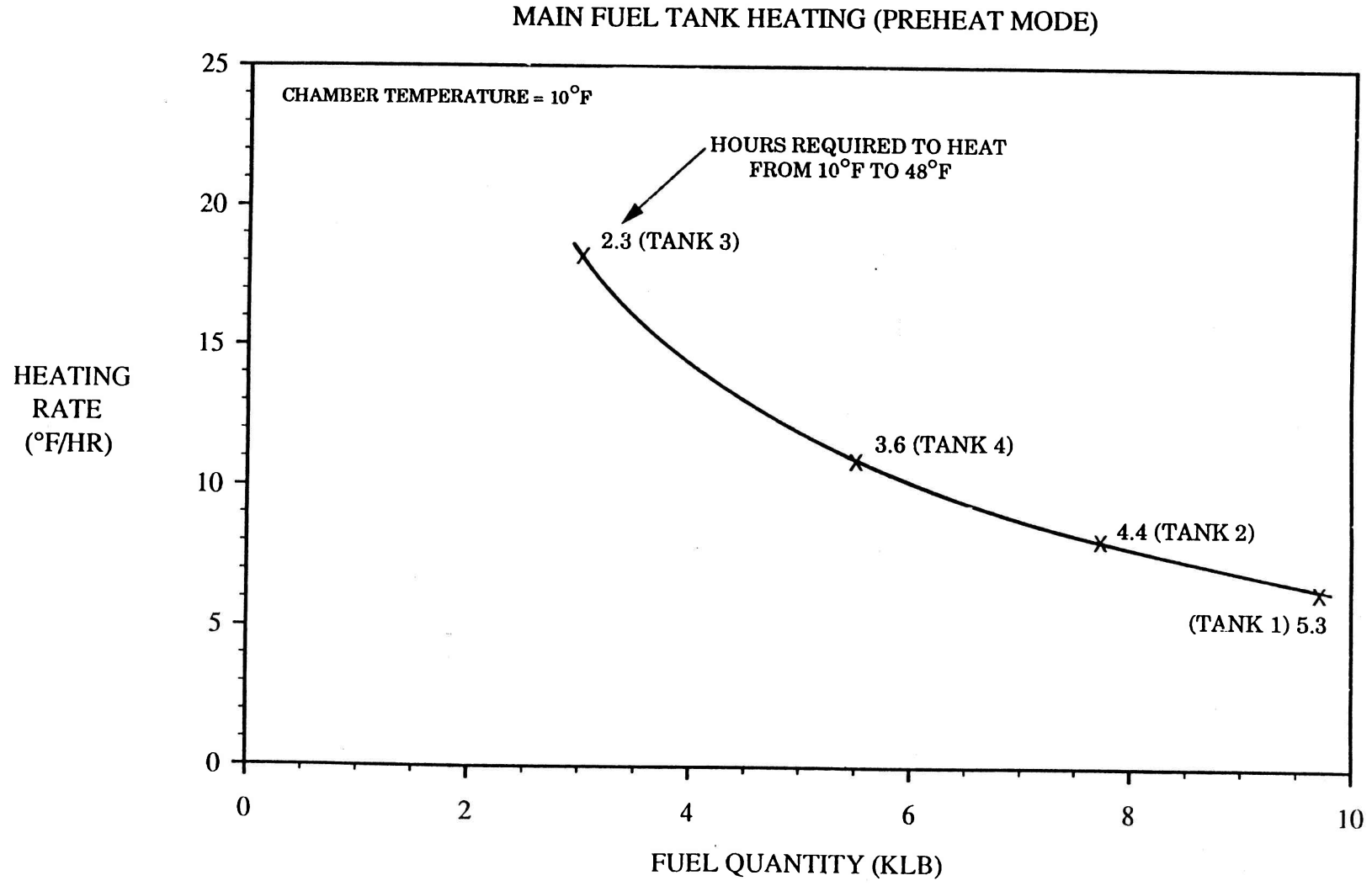

MAIN FUEL TANK HEATING (PREHEAT MODE)
CHAMBER TEMPERATURE = 10°F
HOURS REQUIRED TO HEAT
FROM 10°F TO 48°F
2.3 (TANK 3)
3.6 (TANK 4)
4.4 (TANK 2)
(TANK 1) 5.3
HEATING
RATE
(°F/HR)
25
20
15
10
5
0
0
2
4
6
8
10
FUEL QUANTITY (KLB)

Figure 6

The ability of the craft to operate on either diesel fuel marine (DFM) and JP-5 (an aviation fuel) was demonstrated through ambient temperatures of 40°F down to -30°F. There is no distinct operating advantage to either fuel, with the exception that JP-5 does not need heating until ambient temperatures go below -18°F. However, on some extremely cold occasions APU gas turbine engine flame-out can occur using DFM when, after a successful start and running for several minutes, a slug of cold/unheated fuel between the aft and forward APU start tanks enters engine combustor. This is not considered to be a design problem since the engine can be easily restarted.

MAIN ENGINE INLET ANTI-ICE SYSTEM

As previously described the main engine inlet air is pre-heated to prevent icing and snow blockage. The test evaluated the adequacy of the design to perform this function and to provide a basis for future fleet operating procedures. Also, significant unknown factors to be evaluated were what impact this system has on engine power performance, increases in exhaust gas temperatures (EGT) resulting from inlet flow loses and increases in engine back pressure, and inlet filter blockage from reingested exhaust soot.

From the test data, this cold weather kit can provide adequate heat to the inlet in the required temperature ranges of 40°F to -30°F if there is sufficient exhaust flow to the inlets. This flow is mainly a function of the engine power output. The most critical regions of operation are at idle speeds with either rain or snow at ambient temperature of 10°F and below. A slight improvement to the inlet temperature can be obtained by a wider opening of the diverter vanes in the exhaust. Figure 7 gives the average effects of diverter vane opening to inlet temperature change, as a function of TF40B gas generator speed (N1)/power output. Overall, the main engine heating system will function as required when the operator limits the engine's idle time in snow at extremely cold conditions. The long vertical duct provides an adequate flow mixture of air for an even temperature distribution along the inlet screen. Additionally, from the temperature data, the inlets will be fabricated completely of aluminum instead of stainless steel for a significant weight reduction of the cold weather kit.

Main engine performance changes were measured first as an average change in engine exhaust gas temperature (EGT). From a summary of EGT test data, the average corrected EGT between engines 2 and 4 increased approximately 10°F and 20°F, respectively. Exhaust gas temperature is a function of ambient inlet temperature and the load extracted by the power turbine. EGT is used for monitoring engine performance and also as a temperature limit control to prevent high pressure turbine damage. From the test data it appears that the average EGT increase from the cold weather kit will not impact engine performance or be a limit to the power output of the engine.

AVERAGE TF40B INLET TEMPERATURE CHANGE
VS. DIVERTER VANE SETTING

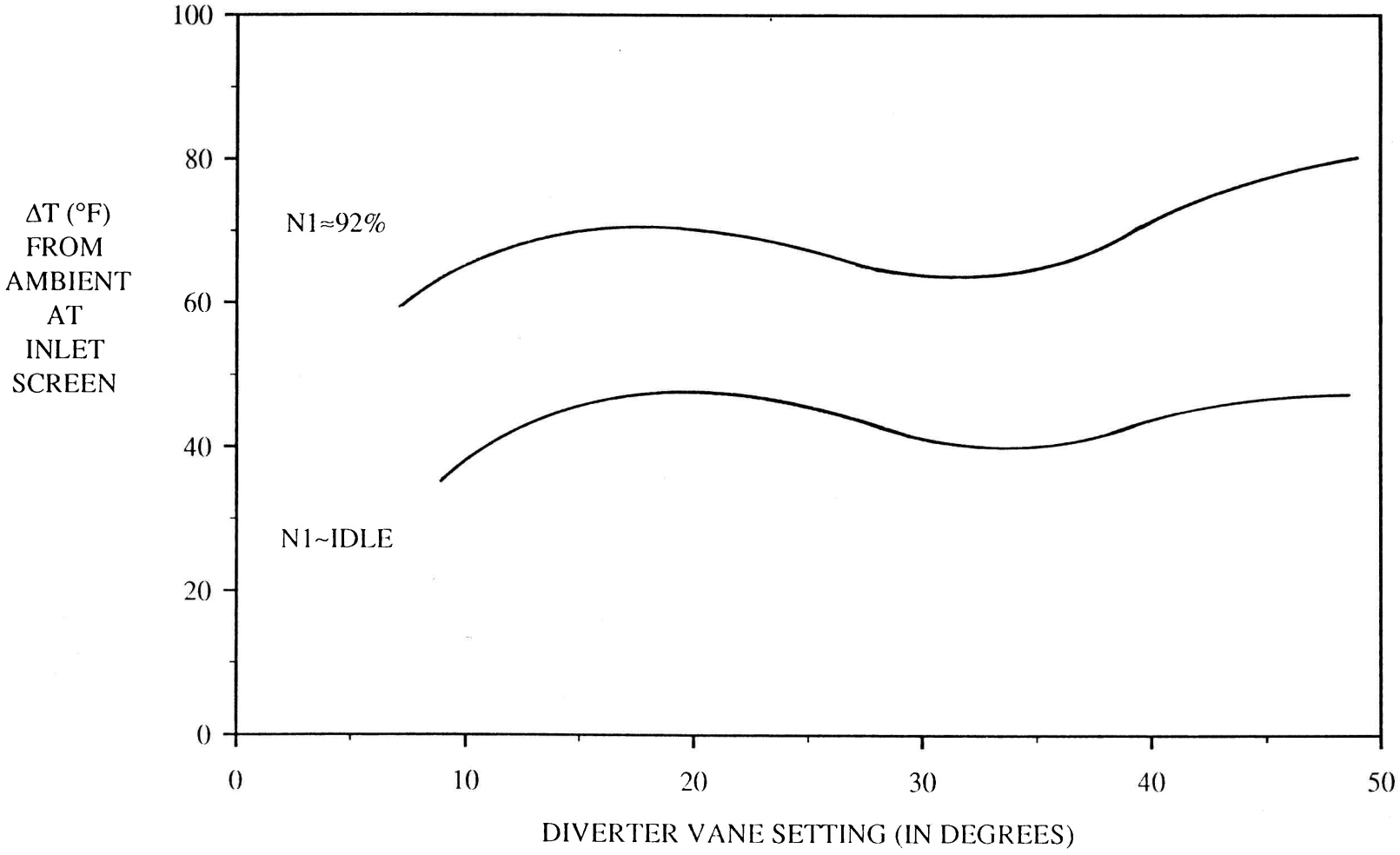


Figure 7

The pressure drop of air flowing through an inlet together with exhaust back pressure also has an impact on the performance of the gas turbines. These two parameters are significantly changed by the addition of the cold weather kits. The inlet air flow velocity increases as it passes through the smaller heating inlet duct causing a loss of inlet head, whereas, the exhaust back pressure increases from the restriction of the cold weather exhaust ducts. Both the inlet loss and the increased back pressure can cause an increase in EGT, engine power loss, and an increase in fuel consumption. Figure 8 illustrates typical changes in percent of TF40B engine power from inlet and exhaust pressure losses. The actual inlet pressure losses for the LCAC engines as a function of N1 (gas generator) speed are illustrated in Figure 9. Figure 10 shows the effects of the diverter vane position in the exhaust stack. The tests showed an increase of inlet losses and back pressure that equates to an approximate power loss of 2% at a corrected inlet temperature of 80°F.

There was no significant degradation noted with the inlet filters from reingested exhaust gas soot during the test. Whether this finding is accurate, further fleet operations with the cold weather kits will have to be monitored.

Prior to testing in the cold chamber, operations at an ambient temperature of 90°F with cold weather inlet ducts installed were conducted on shore and at sea. The purpose was to determine the effect on inlet temperatures since the air intake is in close proximity to the exhaust. There is also possibility of operating above 40°F ambient temperatures with the cold weather kits installed. These tests showed that the maximum inlet temperature reached was 125°F. This is 15°F below the 140°F maximum allowable. However, there has been one case reported when an LCAC experienced excessively high inlet temperatures in a ships well deck. Further well deck testing is planned in the near future.

APU ANTI-ICE SYSTEM

The Auxiliary Power Unit (APU) combustion air anti-ice system was tested for its capability to anti-ice or to prevent icing of the last stage APU inlet air filter. As shown in Figure 11, there is a hot bleed air dispensing tube (i.e., piccolo tube) in each APU compartment. This anti-ice system was designed to be operated when the craft was off-cushion. The air flow can enter either through the louvered door at frame 15 and through the APU blow-in doors into the APU compartment, or through the main engine cooling air fire doors (see Figure 12). For on-cushion operations the air flow comes from the lift fans through the cooling air filters into the APU compartment.

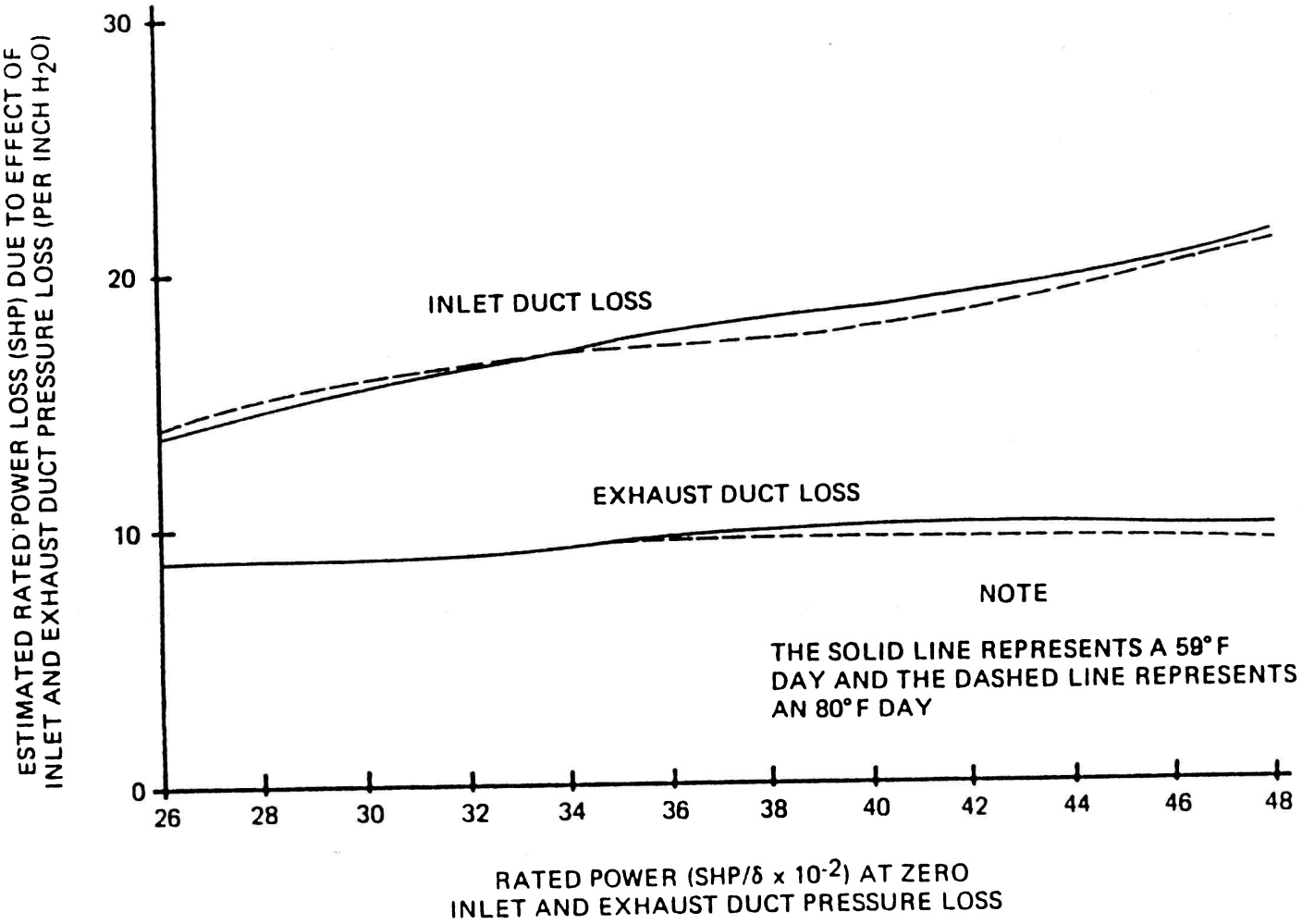


Figure 8. Estimated Effect of Inlet and Exhaust Duct Pressure Losses at Rated Powers (At Optimum Power Speed)

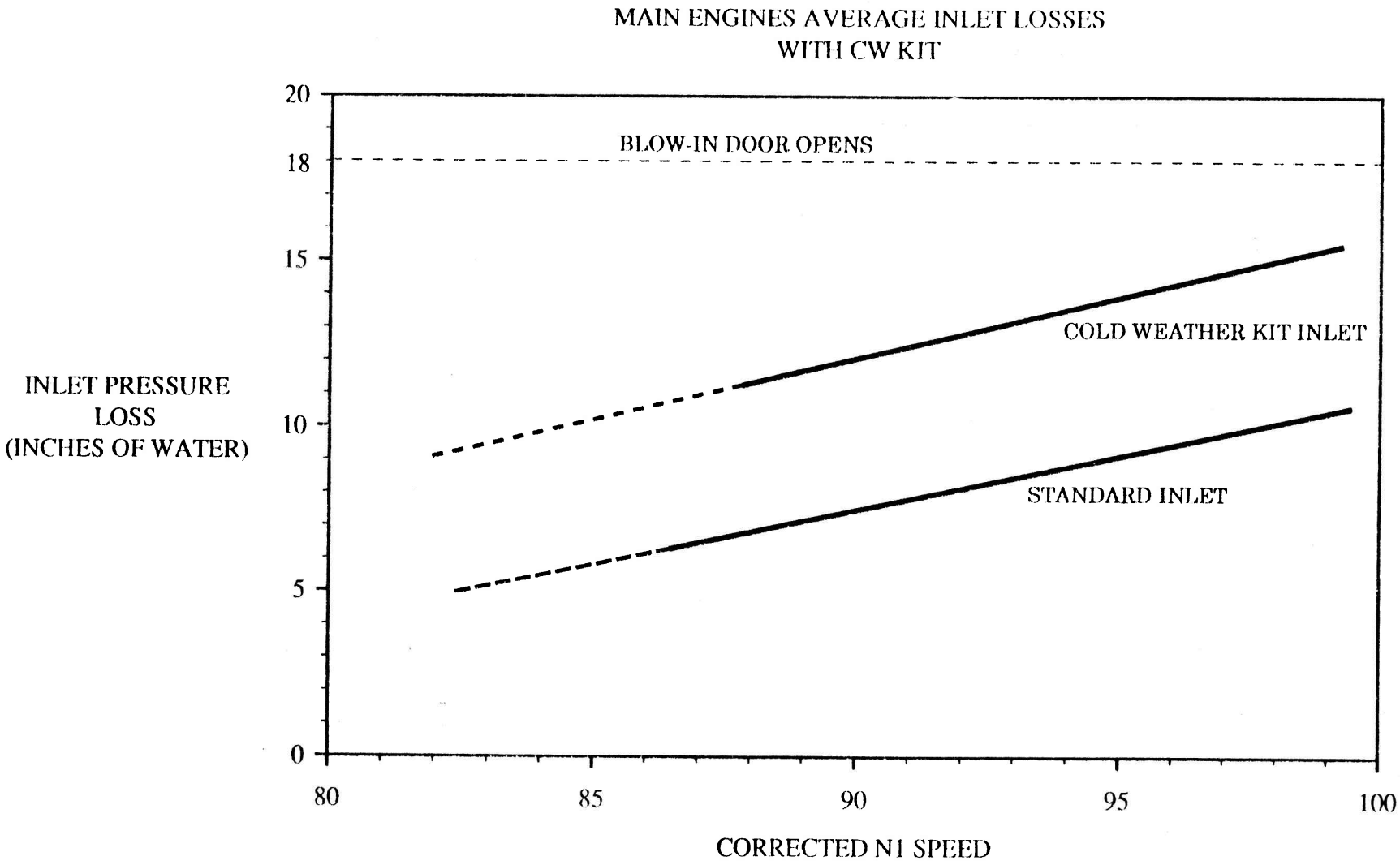

MAIN ENGINES AVERAGE INLET LOSSES
WITH CW KIT
INLET PRESSURE
LOSS
(INCHES OF WATER)
20
18
15
10
5
0
BLOW-IN DOOR OPENS
COLD WEATHER KIT INLET
STANDARD INLET
80
85
90
95
100
CORRECTED N1 SPEED

Figure 9

MAIN ENGINE EXHAUST BACK PRESSURE

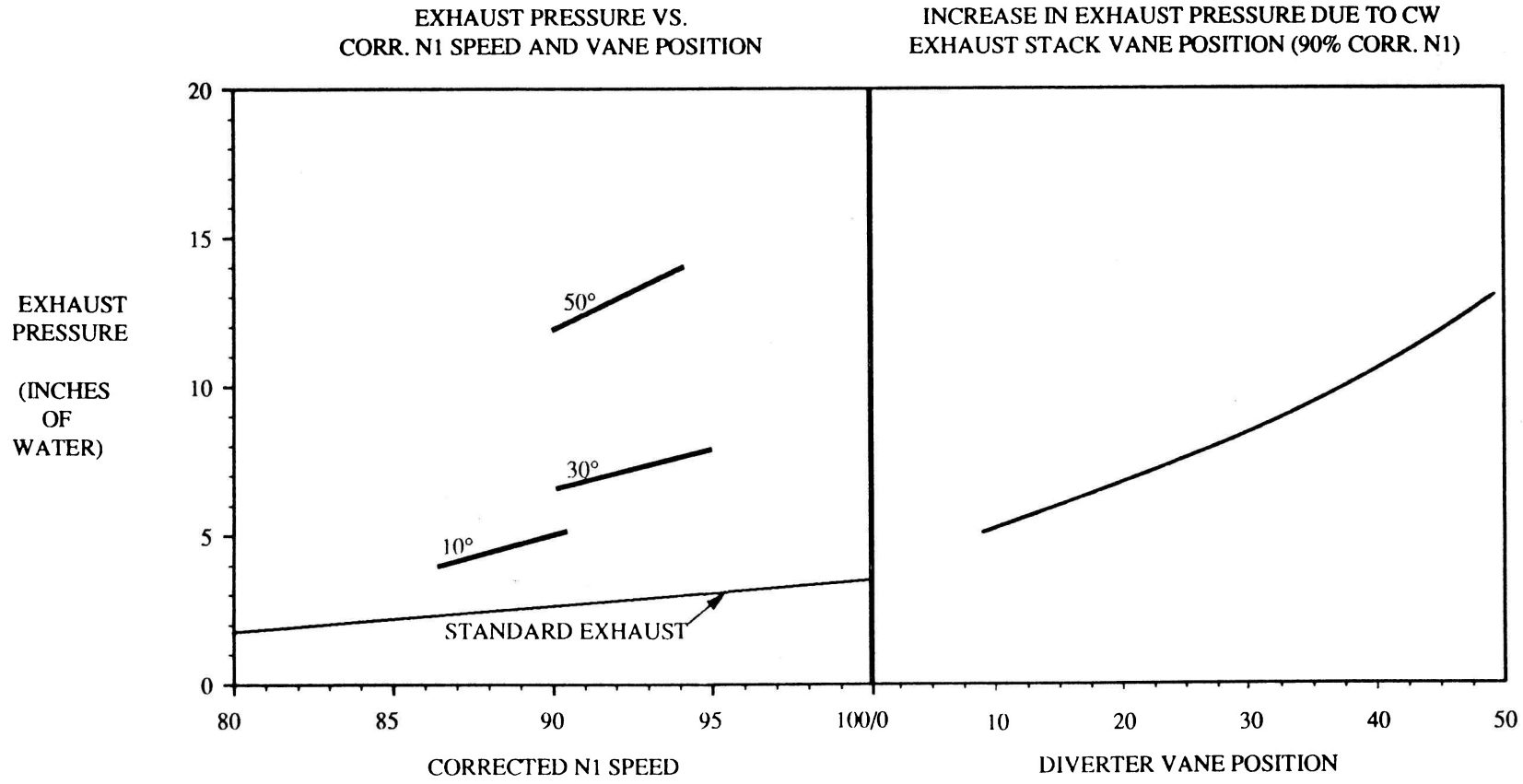


Figure 10

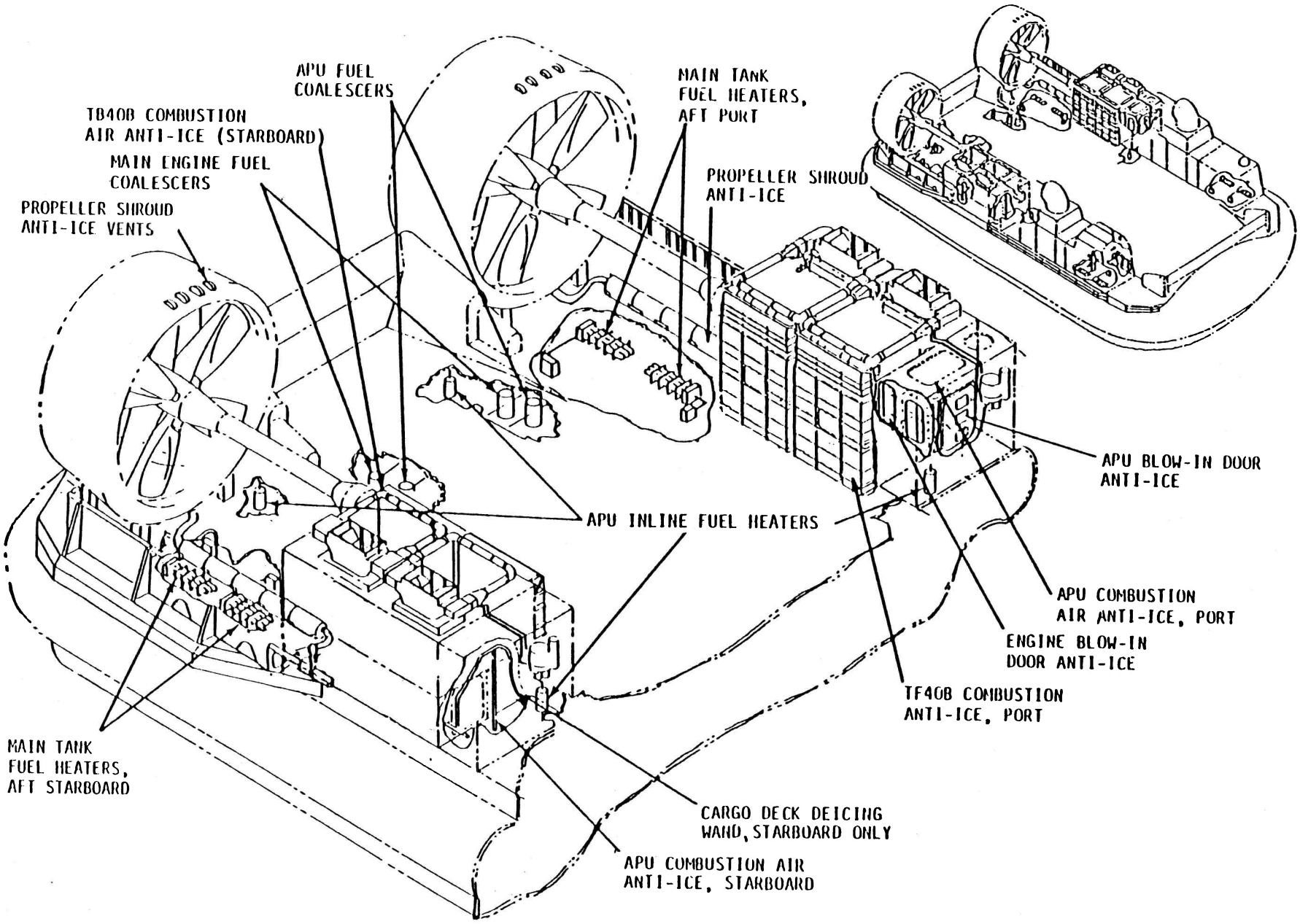
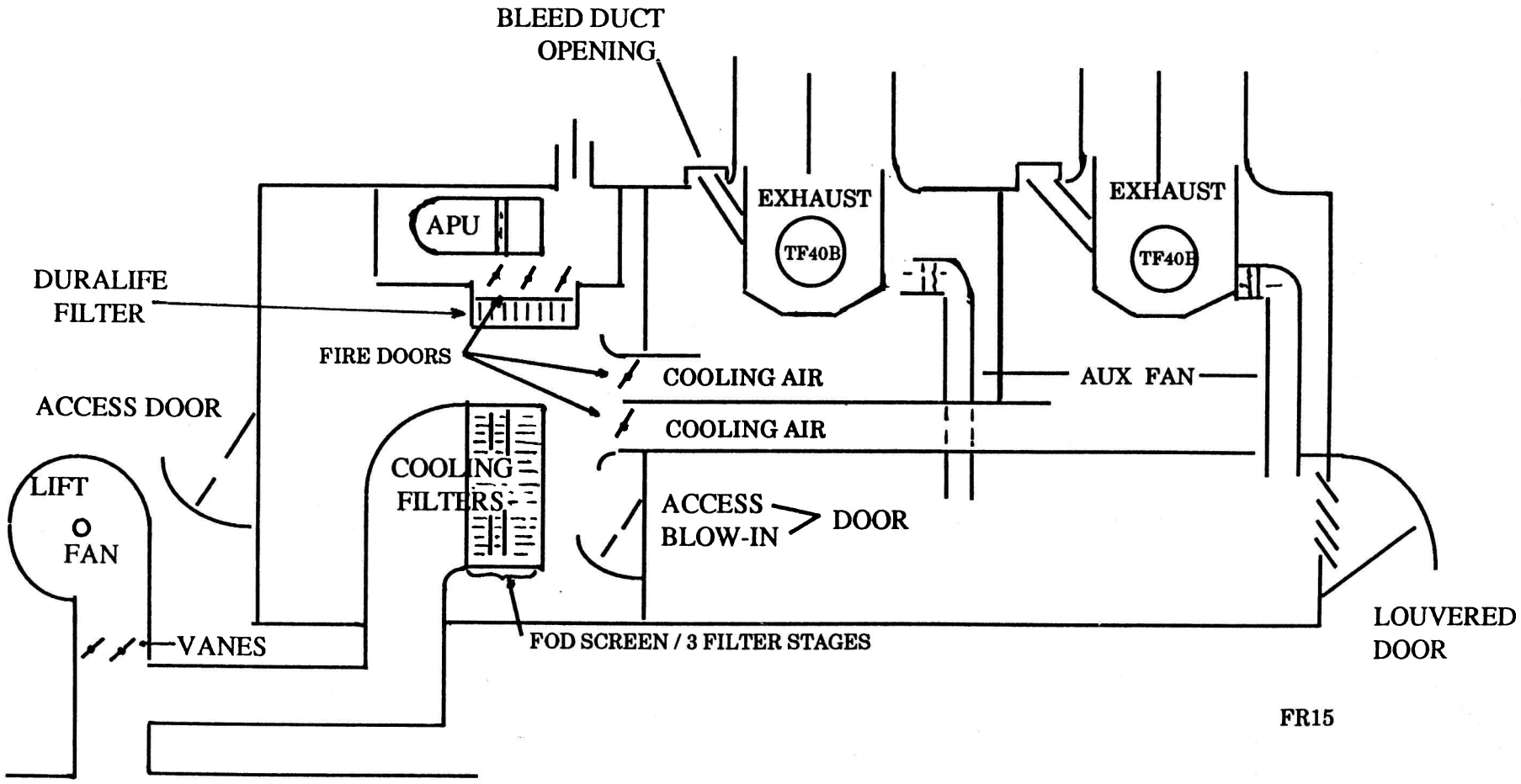

APU FUEL
COALESCERS
MAIN TANK
FUEL HEATERS,
AFT PORT
TB40B COMBUSTION
AIR ANTI-ICE (STARBOARD)
MAIN ENGINE FUEL
COALESCERS
PROPELLER SHROUD
ANTI-ICE
PROPELLER SHROUD
ANTI-ICE VENTS
APU BLOW-IN DOOR
ANTI-ICE
APU INLINE FUEL HEATERS
APU COMBUSTION
AIR ANTI-ICE, PORT
ENGINE BLOW-IN
DOOR ANTI-ICE
TF40B COMBUSTION
ANTI-ICE, PORT
MAIN TANK
FUEL HEATERS,
AFT STARBOARD
CARGO DECK DEICING
WAND, STARBOARD ONLY
APU COMBUSTION AIR
ANTI-ICE, STARBOARD

Figure 11



APU - COOLING AIR SYSTEM

Figure 12

Operating on-cushion this compartment is pressurized by lift fan pressure that provides cooling air flow to main engines and combustion air to the APU. Before the cold weather test, it was assumed for on-cushion operation that the work of the lift fans would raise the ambient air temperatures about 25 degrees. During the test it was found that the temperature rose as a function of the lift fan speed with the most increase when the fan speed went above 85%, but at lower temperatures the fans could not provide sufficient rise in ambient temperature to prevent possible icing in the MEP, hook vane filters, or leaf screens of the cooling filters system, especially when there is snow ingestion by the lift fans. Figure 13 shows the rise in temperature of cushion air as a function of fanspeed (N2).

After going to the off-cushion mode, when the APU bleed anti-ice method would be normally used, test data indicated that there was sufficient residual heat from the main engine modules to adequately heat APU combustion air coming through the main engine cooling air fire doors.

Since the lift fan speed is dependent on the craft loading/ lift requirements and ambient temperature, there is no certainty that the cooling filters will remain free of ice for low load and low temperature on-cushion operations because of the lower rise in temperature from the lift fans. After rain testing ice was found on the walls in the air tunnel leading to the filters. However, in snow testing, the snow did accumulate on the upstream side of the cooling filters. From these findings it was determined that a redesign the APU anti-ice system to dispense hot air into the upstream side of the cooling filters is necessary.

Shroud anti-ice test in snow also revealed that bleed air was not required to heat the shroud because a cold dry snow does not adhere to the shroud surfaces. This finding confirms that there will be more than adequate anti-ice bleed air available to keep the cooling filters free of snow blockage.

LUBRICATION AND HYDRAULIC OILS

Drawing on the experience of the JEFF A (an LCAC prototype) hovercraft operations in Alaska and the suggestion of equipment manufacturers, two types of lubricating/hydraulic oil were tested. MIL-L-23699 oil, which is the standard U. S. Navy shipboard lubrication/hydraulic oil, was recommended for ambient temperatures between +10°F and 100°F. MIL-L-7808 oil, which is a low viscosity aviation oil, was recommended for temperatures from +10°F to -30°F. All seals and materials in the transmission and hydraulic systems are, by design, compatible to both oils. Because there are distinct differences in the lubricity and the viscosity of the

AVERAGE TEMPERATURE RISE FROM LIFT FANS
VS FAN SPEED AT VARIOUS SPEEDS AND CONDITIONS

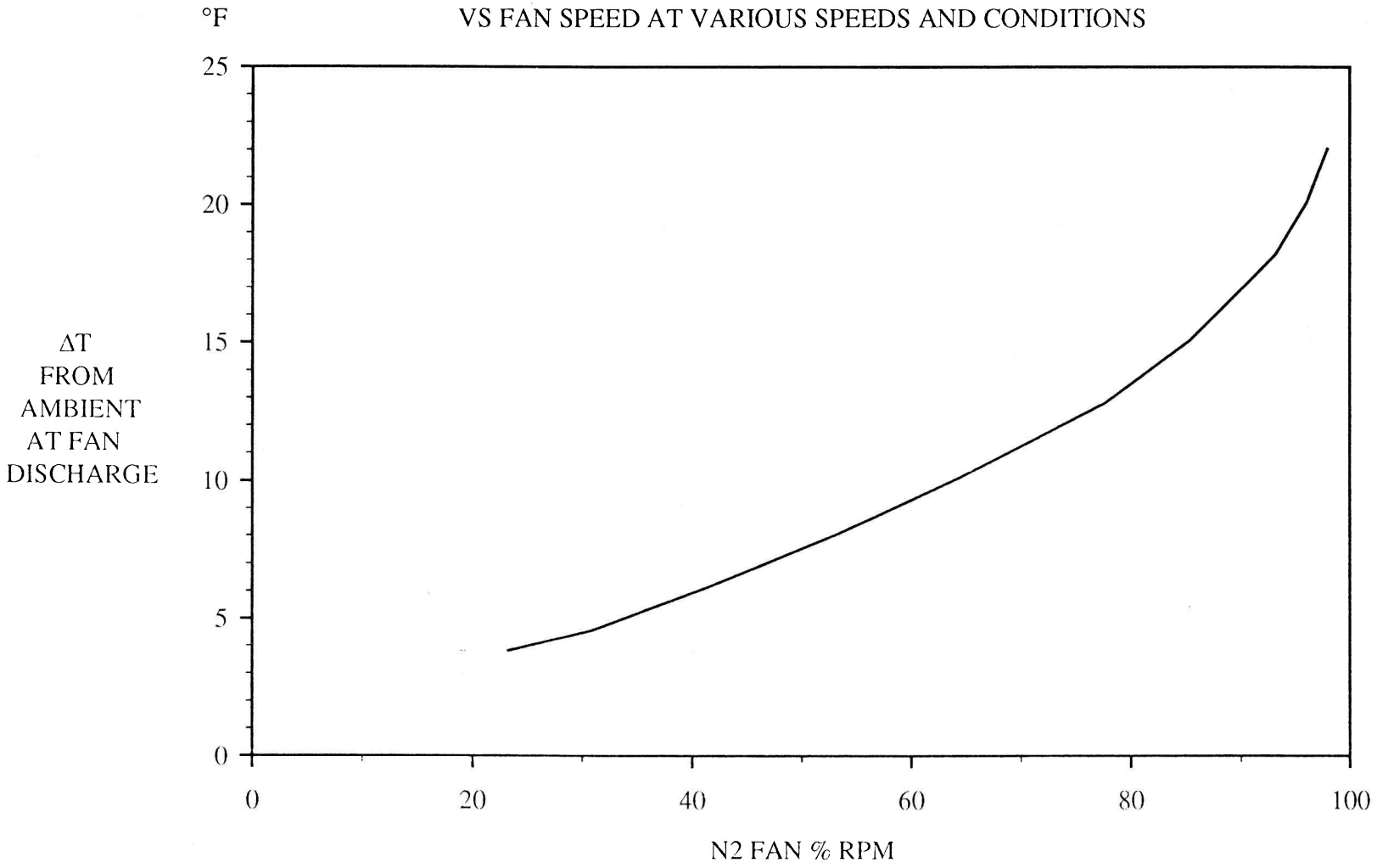


Figure 13

oils at different operating temperatures, the test plan was to evaluate the effects of temperature change on equipment control and the time required to reach recommended oil temperatures for full torque and load application. This section on the lubrication/ hydraulic oils will be broken down into the effect on specific mechanical systems.

GAS TURBINE ENGINES

The LCAC uses four Textron Lycoming TF40B gas turbine engines for main propulsion and lift, and two Turbomach T62 gas turbine engines for auxiliary electrical power and bleed air requirements. Both engines were operated down to -30°F with MIL-L-23699 and down to -15°F with MIL-L-7808.

Because the TF40B engine oil transducers only monitor the oil temperature at +32°F and above, the TF40B engines would be run at idle and no load until oil temperatures reached the +32°F threshold. The average time was less than five minutes to warm up engines from the coldest temperatures (with both type oils). Engine oil pressures for MIL- L-23699 oil averaged 15 psig higher than the lower viscosity oil, MIL-L-7808, Figure 14.

At the very low temperatures, the engine oil pressure with MIL-L-23699 oil approached and sometimes exceeded 90 psig. At 100 psig the oil pressure transducer goes off scale and will trigger an engine shutdown for a "low lube" indication on the AMS panel. There were a few instances when high oil pressure readings would fluctuate and engine would automatically shutdown. Also noted in cold temperatures were unsteady idle speeds that can be attributed to the cold oil, since the fuel metering valves are controlled hydraulically with engine lubricating oil. Therefore, for operations below 10°F the addition of oil heaters has been proposed.

The APU oil pressures also averaged about 15 psig higher for MIL-L-23699 oil, but the average warm-up times to reach 32°F were almost double the time of the TF40B(s). However, the APU gas turbines have been designed to start and operate at an ambient temperature of -60°F, and unlike the TF40B, the engine fuel control is not hydraulically controlled. This design capability allows the APU to accept electrical load and provide bleed air within a short time after start.

TRANSMISSION SYSTEMS

The LCAC transmission systems consist of two right angle engine gearboxes with overrunning sprag clutches, a forward offset gearbox, an aft offset gearbox and a disconnect clutch on each side of the craft, Figure 15. Each of the four transmission systems, that consist of an offset gearbox and an engine gearbox, has its own separate lubrication system and oil cooler.

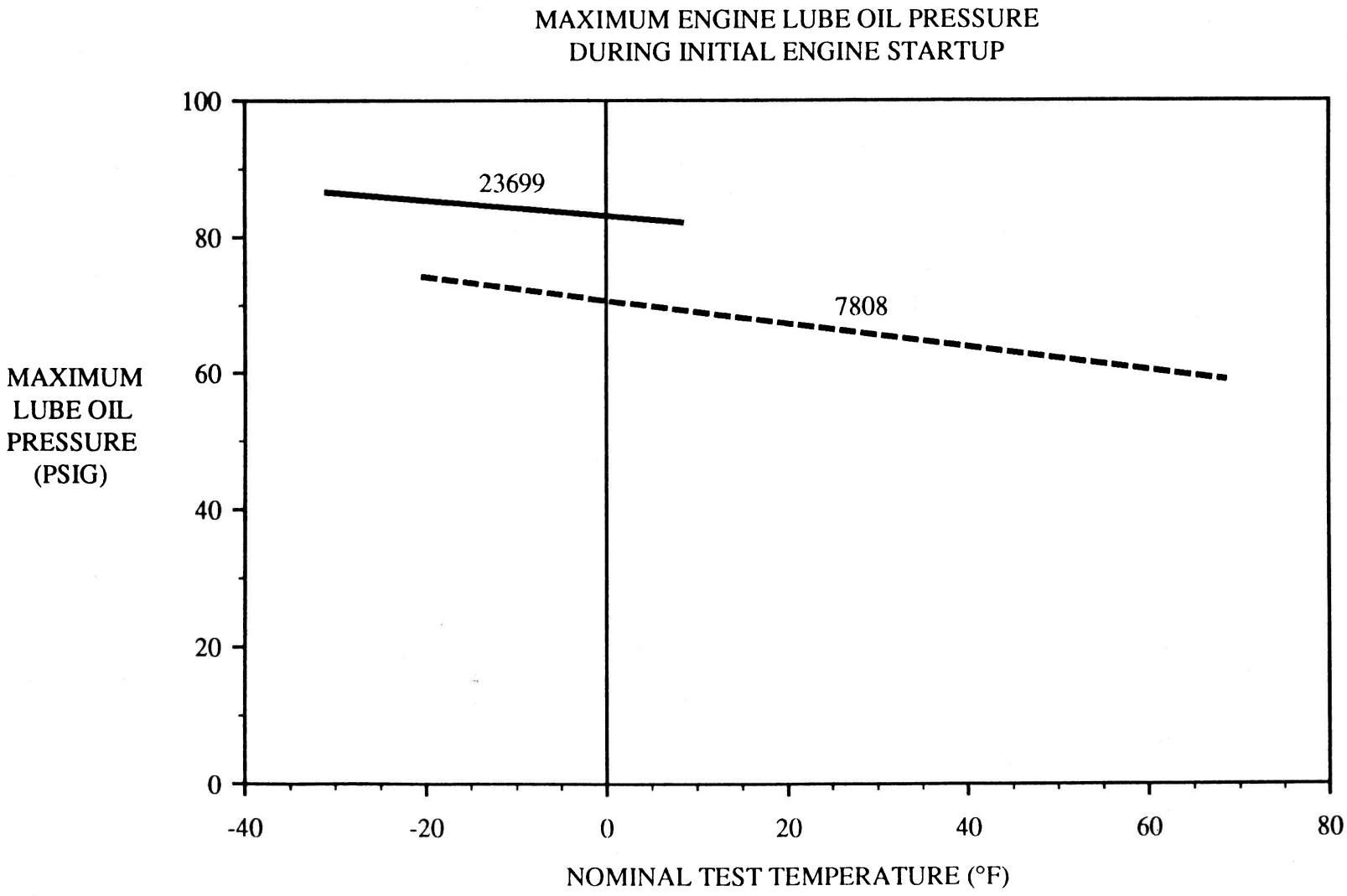
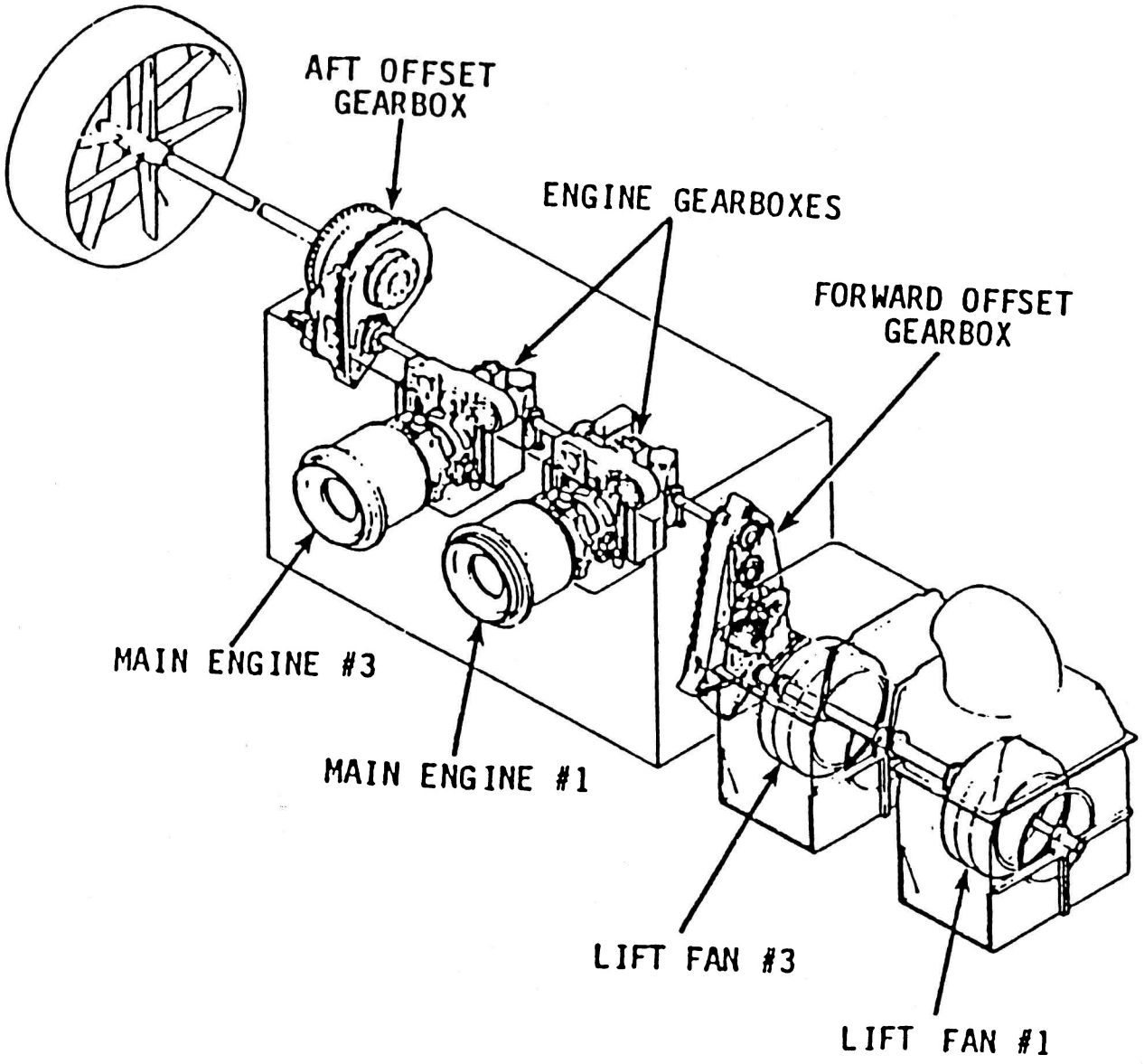

MAXIMUM ENGINE LUBE OIL PRESSURE
DURING INITIAL ENGINE STARTUP
MAXIMUM LUBE OIL PRESSURE (PSIG)
100
80
60
40
20
0
23699
7808
-40
-20
0
20
40
60
80
NOMINAL TEST TEMPERATURE (°F)

Figure 14



LCAC Transmission System - Starboard

Figure 15

Pretest limits were established by the shipbuilder and the gear manufacturer. These limits were (1) MIL-L-23699 had to be warmed at idle to +32°F before increasing power, (2) MIL-L-7808 had to be warmed to -6°F before applying load, and (3) because of MIL-L-7808 lower viscosity, its temperature would not be allowed to exceed 130°F. The reason for switching oils at temperatures below +10°F was again at the recommendation of the manufacturer to assure proper lubrication of the sprag clutches. A cumbersome start procedure for warming the individual engine gearboxes with MIL-L-23699 oil at 10°F was also recommended, but the Navy elected to risk initiating a simultaneous main engine start procedure for port and starboard engines. This procedure was also employed using MIL-L-23699 down to -30°F, allowing a full range without changing oils. In the final analysis, this innovative start procedure was one of the reasons for cancelling the requirement for switching to MIL-L-7808 in the transmissions.

As shown in Figure 16, the times for achieving required lubrication oil temperatures were short. This figure is for MIL-L-23699. Times and temperature for MIL-L-7808 follow the same pattern. Switching to MIL-L-7808 led to further complications with the oil cooler because of the 130° temperature limit. The oil coolers could not maintain MIL-L-7808 below 130° in ambient temperatures at and below 10°F during high power runs.

PROPELLER LUBRICATION

The propeller hub has it's own separate lubrication system. During the test the oil temperatures for both test oils averaged only slightly above ambient temperatures. There were no low lubrication oil pressure alarms reported throughout the test.

HYDRAULIC CONTROL SYSTEMS

The three control systems that can use either MIL-L-23699 oil or MIL-L-7808 oil are the propeller pitch control, the rudder control actuators, and the bow thruster controls. During the test all three systems' rates of motion were essentially constant at fluid temperatures down to 50-60°F. At temperatures below this temperature range, the rate of movement decreased. Figure 17 provides a summary plot of the control system rate with MIL-L-23699 oil in the hydraulic systems. This plot shows the effect of temperature on the change in rate of movement, the bow thruster being the most severely affected.

The hydraulic oil was changed to MIL-L-7808 but insufficient data was obtained to do a comparative plot. However, comparing viscosity data and limited test data, MIL-L-7808 would likely have the same reduced rates beginning at about a 35°F ambient temperature.

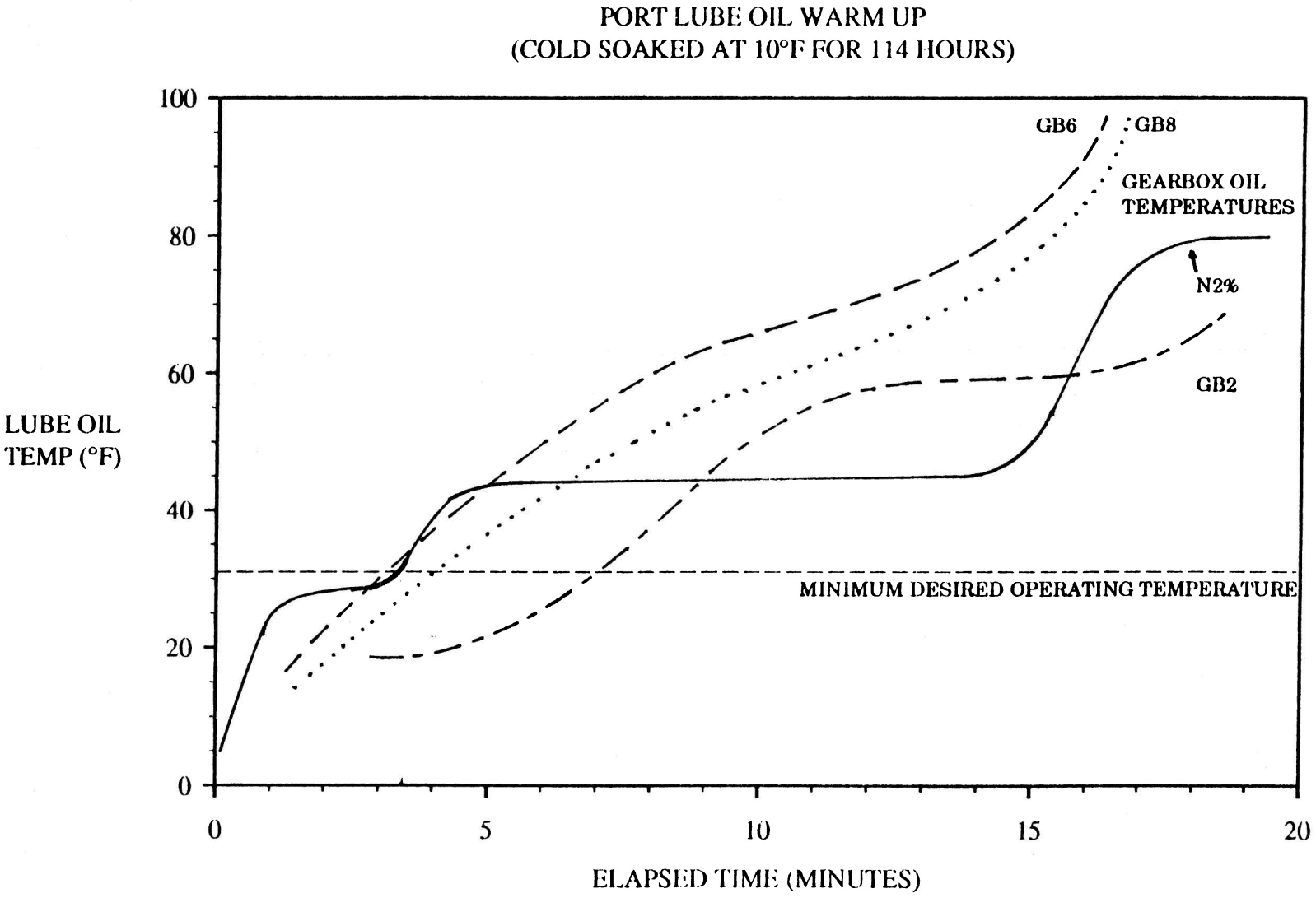

PORT LUBE OIL WARM UP
(COLD SOAKED AT 10°F FOR 114 HOURS)
LUBE OIL TEMP (°F)
100
80
60
40
20
0
0
5
10
15
20
ELAPSED TIME (MINUTES)
GB6
GB8
GEARBOX OIL TEMPERATURES
N2%
GB2
MINIMUM DESIRED OPERATING TEMPERATURE

Figure 16

SUMMARY OF COLD WEATHER EFFECT ON LCAC CONTROL SYSTEM RATES
WITH 23699 OIL IN THE SYSTEMS

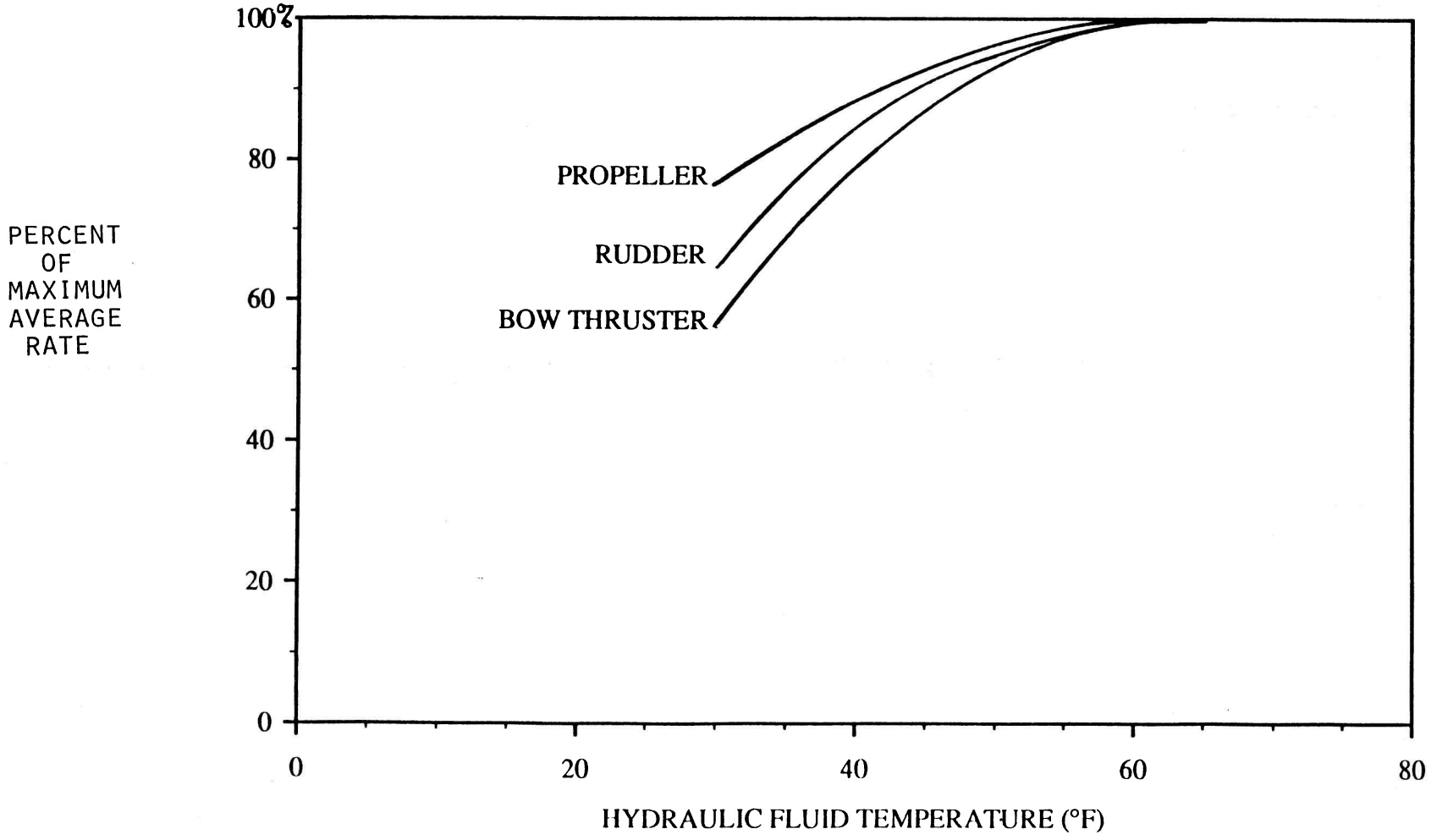


Figure 17

Because the hydraulic control system is exposed externally to the elements and only a small amount of work is being done with the fluid, the temperature increases only a maximum of 30°F above ambient.

From data we have concluded that MIL-L-7808 oil would be best suited for both arctic temperatures and warmer ambient temperatures for the hydraulic controls. To enhance the hydraulic system controls in colder weather, lube oil heaters are being proposed as a design improvement.

EFFECTS OF ICING AND SNOW

Icing effects were created by dispensing water spray from overhead racks that covered the entire length and width of the craft. Simulated snow conditions were created with snow machines similar to units used on ski slopes. The rate of spray ranged from 1.5 inches spray per hour (1.7 gm/m3) liquid water content (LWC) to 4 inches per hour (3.96 gm/m3 LWC). The latter rate is an extremely heavy flow. The snow rates were one inch (light) to two inches (heavy) per hour.

In addition to testing the craft's cold weather anti-icing equipment, effects of icing on the hull, skirts, lift fans, exposed drive shafts, propellers, bow thrusted and bow and stern ramps were evaluated. Practical exercises using ice removal equipment and vehicle loading were also tried.

PROPELLER SHROUD, PROPELLER AND LIFT FANS

The propeller shroud's leading edge and plane of propeller rotation is protected from icing by heating with hot bleed air flow from the APU. The hot air enters at the base of the shroud and out the vent ports at the top. The approximate area heated is about 1.5 feet back from the leading edge. When operated in all spray conditions and test temperatures, the propeller shroud was kept free of ice in the heated areas. However, the shroud area aft of the leading edge, the struts and the rudders, accumulated heavy icing. Also, icing occured in front of the shroud on the FOD screen railings. There is a danger of ice breaking loose in these areas and being ingested in the propeller. After a mission it is advisable to clear any ice in this area.

In snowing conditions, it was not necessary to use the shroud anti-ice feature because the snow does not adhere to the shroud surfaces. This finding will allow more bleed air use for the improved APU anti-ice design.

Ice accumulation from spray can occur on the propeller and the propeller spinner. This can set up an unsymmetrical imbalance of the propeller that can be felt by the crew as craft vibration. This imbalance can be corrected by changing the prop blade angle

(pitch change) momentarily which sheds the remaining ice. Similarly, the shedding of ice accumulation from the lift fans will sometimes create a vibration imbalance. In this case a momentary cycling of shaft speed (N2) by the crew will correct the imbalance.

STRUCTURAL ICING

In freezing rain the unheated areas of the craft become encrusted with a layer of ice. This icing will increase craft weight and may inhibit the craft's performance. Although several ice phobic coatings showed some potential from this test, there is no practical way to avoid surface icing. The probability of actually experiencing this amount of icing is, however, small.

Among the observations about icing on the LCAC were: (1) the engine modules stayed warm and free of ice, (2) the ice phobic coatings only worked on vertical surfaces, (3) the bow thrusters can become frozen in place in periods of inactivity, (4) the craft windshield de-ice system provides adequate heating, (5) the best method used for ice removal was a steam lance operated from a portable steam generator, (6) there can be significant ice accumulation on fan FOD screens, which may produce significant air flow blockage in heavy rain. De-icing the FOD screens is required.

COLD WEATHER ELECTRICAL POWER REQUIREMENTS

The LCAC electrical power requirements are close to design predictions and well within the on board generators' capacity. Normal operating power requirements, including the cold weather kit system, can be supplied by a single APU. An exception to this is pre-mission heating of the main fuel tanks. A single APU cannot provide sufficient power to heat all four main fuel tanks simultaneously, along with other system requirements, such as cabin heating.

CABIN HEATERS

The cabin heaters supply adequate heat to maintain both cabins' temperatures at 68°F or above the crafts' lower design ambient air temperature of 10°F. However, the rate at which the cabin warms up is slow. It takes approximately 6-1/2 hours to achieve this temperature.

A temperature of 68°F may be maintained in the port cabin at temperatures down to approximately -20°F but it would take a long time to achieve this temperature without auxiliary heating.

The starboard cabin has a much higher heat loss factor, probably due to its larger size and extensive windshield area, and requires additional heater capacity for arctic temperatures.

MATERIALS (SKIRT SYSTEMS)

The skirt system materials remained sufficiently flexible to allow raising and lowering of the ramps without damage to the skirts at temperature down to -30°F. No skirt system damage was noted throughout, or following, the cold weather tests.

BATTERIES

The LCAC lead acid batteries demonstrated satisfactory performance at ambient temperatures down to -30°F. Since completion of the cold weather tests, the battery has continued to charge normally and operate satisfactorily.

VIBRATION ANALYSIS

Vibrations were monitored on the aft offset gearbox, engine fuel control, and lift fan bearings which exceeded the test limit of 1.0 inches per second (IPS) for short periods. The maximum level recorded was 1.5 IPS. These vibrations were caused by unsymmetrical ice/snow accumulations on the propellers, fans, or fan shafts. The crew could feel the vibration well before it reached the limit level. Cycling the propeller pitch ±5 to 10 degrees from the operating setting would generally shed the ice/snow accumulation on the propeller blades. Buildups on the fan rotors and/or shafts were generally shed after relatively short periods of time without any crew action, or by cycling shaft speed N2 slightly.

The engine gearboxes exhibited vibrations greater than 1.0 IPS, at bevel gear mesh frequency, which persisted for periods up to 10 minutes. Previous experience has shown that these vibrations occurred occasionally on other engine gearboxes at amplitudes as high as 2.5 IPS. These vibrations are not considered cold weather related and do not appear to indicate a significant problem since the high time engine gearbox has over 1000 hours of operation with no vibration related failure.

There were no vibrations which prevented the machinery systems from operating as required to accomplish the test objectives in freezing rain and snow environments and ambient temperatures down to -30°F.

CONCLUSION

This cold weather test demonstrated that the LCAC can operate and function in cold environments down to +10°F with its' permanently installed cold weather components and the removable cold weather kits. However, there were problems found that will require the shipbuilder to make design improvements and corrections to meet the 10°F operating specification. Operating the craft to arctic temperatures of -30°F, also revealed a need for enhancements and changes that will improve craft responsiveness at these extremely cold temperatures. Even the design of the removable cold weather kits has been re-evaluated to improve accessibility to the machinery compartments, to reduce the number of removable components, and to facilitate ease of installation.

The following significant changes and observations have resulted from this test:

- Auxiliary Power Unit (APU)
  - -- Improve APU starting capability in cold weather with a fuel control heater.
  - -- Add a DC power thermostatic control in APU fuel pre-heater.
  - -- Preheat fuel lines between start tanks and engine.
  - -- Redesign APU anti-ice system to preheat compartment cushion air flow for snowing conditions.
- Lubrication/Hydraulic Systems
  - -- MIL-L-23699 oil shall be used in main engines, APU(s), and all transmissions for the full range of LCAC operating temperatures.
  - -- MIL-L-7808 oil shall be recommended for use in all hydraulic systems for the full range of LCAC operating temperatures.
  - -- For an arctic environment capability, oil pre-heaters shall be used to heat oil sumps of the main engines, transmissions, propeller hub, and hydraulic control systems.
- Either DFM or JP5 fuels can be used down to -30°F.
- Lead acid batteries can be used down to -30°F.

- Make improvements to portable cold weather equipment
  - -- To reduce installation complexities and logistics, make the shroud anti-ice kit a permanent craft installation.
  - -- Redesign the exhaust stack for use in both normal and cold weather applications.
  - -- Fabricate main engine inlet ducts of aluminum to save weight.
  - -- Improve engine accessibility with cold weather inlet kits using quick disconnect latches.
  - -- Delete the bleed air anti-ice wand assembly (lacks sufficient hot air flow to melt ice on shackles).
- Add heating capability to all rear windows of command module.
- Increase heating capacity for arctic temperatures in the command and port modules.
- For arctic weather operations, LCAC units must have de-icing and equipment warming heaters.
  - -- Portable hot air blowers that can use DFM or JP5 fuel.
  - -- Portable steam generator for de-icing with a steam lance.
- Craft Operating Procedures Revisions
  - -- Cold weather pre-flight checks.
  - -- Main engine and APU light-off procedures.
  - -- Warm-up times.
  - -- Cold weather running parameters.
  - -- Cold weather related equipment trouble-shooting procedures.

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[1] TF40B Technical Manual, S92334-ES-MMA-030, 1 April 1985

[2] Marine Gas Turbines, John B, Woodward, 1975
John Wiley & Sons, Inc.

[3] NAVSEA Technical Manual, S9510-AW-MMA-010, Cold Weather Kit Manual

ACKNOWLEDGEMENT

The LCAC 008 cold weather test and its' successful completion is the result of the dedicated teamwork of all the test team members, who spent many hours in the daily test preparation, test conduction and data analysis. The test plan development and conduct of the test by Naval Coastal Systems Center, the test analysis and engineering support of Textron Marine Systems, and the operation and the technical advice of the LCAC crew and staff of Assault Craft Unit Four is gratefully acknowledged.

APPENDIX A

LANDING CRAFT, AIR CUSHION

General Description

The Landing Craft, Air Cushion (LCAC) is a high speed amphibious landing craft capable of carrying a 60-ton payload. LCAC is capable of traveling over land and water, and will operate from well deck equipped amphibious ships of the LSD 41, LSD 36, LPD, LHA and LHD Classes. The LCAC is the production follow-on to the Advanced Development JEFF Craft, which were built and tested by the Navy under the Amphibious Assault Landing Craft (AALC) Program.

Mission

The primary mission for the LCAC is amphibious warfare. The role of the LCAC in this mission is to transport from ship-to-shore and over the beach, weapon systems, equipment, cargo, and personnel organic to the elements of a Marine Air/Ground Task Force. In a typical mission, the craft will embark equipment, troops, and/or supplies; launch from amphibious ships; transit at high speed to the beach under assault; transit the surf zone and beach; proceed inland to a suitable offload site; offload rapidly; and return to the amphibious ships for reload and follow-on sorties.

Principal Characteristics

Length	
Hull (Less Cushion)	81'0"
On Cushion	87'11"
Beam	
Hull (Less Cushion)	46'9"
On Cushion	47'0"
Height	
Off Cushion	19'2"
On Cushion	23'6"
Cargo Deck Dimensions	67'0"x27'0"
Weight	
Normal Payload	338,250 lb
Maximum Overload	368,250 lb
Operational Capabilities	
Speed, Sea State 2	>40 Knots
Speed, Sea State 3	>30 Knots
Range (Nominal)	200 n mi

APPENDIX A (Cont'd)

Crew/Personnel		
Operating Crew		5 Members
Starboard Cabin Seating,	Upper	Operator, Craft Engineer, Navigator, Group Commander
	Lower	Eight Troops
Port Cabin Seating	Upper	Deck Hand/Engineer
	Lower	Sixteen Troops and Load Master
Structure		
Construction		All Welded Hull - Riveted Rudders and Propeller Shrouds
Skirt		Bag and Finger with Stability Trunks
Propulsion System		
Engines		Four Avco-Lycoming TF40B Gas Turbines Each Rated at 3955 SHP Max Continuous
Transmission Gearboxes		Four Engine Gearboxes, Two Forward Offset Fan Drive Gearboxes, Two Aft Offset Propeller Drive Gearboxes
Variable Pitch Propellers		Two Four-Bladed 11.75 ft Diameter Reversible
Centrifugal Lift Fans		Four 63-in Diameter Double-Entry Double Discharge
Control System		Fly-by-Wire, Bow Thrusters, Rudders and Differential Pitch Prop.
Electrical System		
Type		28 vdc and 120/208 vac 400-Hz, 3 phase
Generators		Two 120/208 vac, 60 KW, Turbomach T-62 APU Gas Turbine Driven
Batteries		24 vdc, Lead Acid Type
External Power		115/200 vac 400 Hz 3-phase, 120 vac, 60-Hz, single-phase
Fuel		
Capacity-Forward Tanks (Total)		20,446 lb DFM (19,720 lb JP5)
Capacity-After Tanks (Total)		22,560 lb DFM (21,760 lb JP5)
Types (2)		DFM (MIL-F-16884) JP5 (MIL-T-5624)