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DESIGN CRITERIA FOR APPLICATION OF MEMBRANE NITROGEN
INERTING SYSTEMS TO ARMY AIRCRAFT FUEL TANKS

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Prepared for
APPLIED TECHNOLOGY LABORATORY
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Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

The feasibility study contained in this report clearly establishes the sensitivity of design parameters and aircraft penalties associated with the application of membrane nitrogen inerting systems for the ullage protection of Army aircraft. Sufficient information is presented to permit valid vulnerability trade-off analyses which compare this technique with other ullage protection concepts. In general, this concept offers several advantages over reticulated foam for ullage protection. It is believed that further optimization of the preliminary designs and improvements in overall membrane separation technology could significantly reduce the aircraft application penalties over those cited in this report.

Mr. Charles M. Pedriani, Safety and Survivability Technical Area, Military Operations Technology Division, served as the Project Engineer for this effort.

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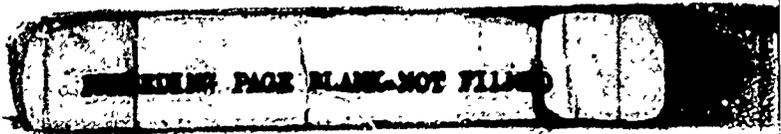
vulnerability of this volume to explosion and fire hazards associated with the presence of an ignition source from hostile gunfire. Unlike some other fuel tank inerting systems, the inert gas generating system requires no regular resupply of expendables and does not add to the fuel tanks any materials that displace or retain fuel. Feasibility studies of system designs and aircraft penalties were evaluated for U.S. Army AH-1G, AAH, UH-1H, UTTAS, CH-47C, and OV-10 aircraft. Preliminary designs were prepared for systems for the following aircraft: AH-1G, CH-47C, and OV-10 (drop tanks only). The design of a flightworthy system was completed for the AH-1G Cobra helicopter. A breadboard test system to generate up to 0.25 lb/min of inert gas at oxygen concentrations of 8 to 12 percent by volume was designed, fabricated, and tested during the program. When supplied with pressurized air, this unit, which was delivered to the Eustis Directorate of USAAMRDL by the contractor, is suitable for use with ground-test facilities including the UH-1B located at the Eustis Directorate test range.

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SECTION 1

INTRODUCTION

This report discusses the work performed to establish design criteria for application of the AIResearch hollow-fiber permeable membrane to nitrogen inerting systems for Army aircraft fuel tank ullage.

The purpose of such systems is to render the fuel tank ullage immune to ignition from combat threats by providing a source of low oxygen content gas with which to purge the ullage. Testing has shown that if ullage oxygen concentrations are below 9 percent by volume, combustion reaction overpressures will not be hazardous.

A permeable membrane system will separate the more permeable constituents of air (including oxygen) from the less permeable gases (primarily nitrogen), resulting in an oxygen-rich discharge that can be vented overboard, and an essentially inert gas (primarily nitrogen) that can be used to protect the fuel tank ullage from fire.

The work was performed in three tasks as specified by the contract statement of work and as summarized below.

Task I, Concept Evaluation and Overall Design Feasibility

Determination--This task consisted of the following two subtasks:

- (1) Analysis: estimation of size and weight of membrane inerting systems that would reduce oxygen concentration to 9 percent (or less) by volume in ullage of various aircraft during specified maneuvers; investigation of effects on system weight of increasing oxygen concentration to 12 percent by volume and of using an air source other than bleed air to drive systems.
- (2) Preliminary Design: preliminary design of membrane inerting systems that would reduce oxygen concentration in fuel tank ullage to 9 percent (or less) by volume, throughout specified mission profiles for three different aircraft.

Task II, Detailed Design of Ground- and Flight-Test Inerting Systems--This task involved two subtasks:

- (1) Detailed design of a breadboard membrane inerting system adaptable for use on a ground-test UH-1B helicopter, suitable for testing. The system was to provide a minimum of 0.25 lb/min inert gas flow and to allow inert gas oxygen concentration to be varied between 8 and 12 percent by volume while operating from a pressurized air source of 100 psia or less.

- (2) Detailed design of a flightworthy membrane inerting system for the AH-1G helicopter and provision of installed system specifications.

Task III, Fabrication--This task was to fabricate, test, and deliver to the Government one ground-test membrane inerting system designed under Subtask II(1).

The following sections discuss the work performed during each program task.

SECTION 2

TASK 1, CONCEPT EVALUATION AND OVERALL DESIGN FEASIBILITY DETERMINATION

SUBTASK 1(1), ANALYSIS

Inert Gas Flow Requirements

The establishment of an optimum fuel tank inerting system based on the AiResearch hollow-fiber permeable membrane inert gas generation system technology is dependent both on the helicopter mission scenario and on the helicopter subsystem design parameters, interface characteristics, and arrangement.

Inert gas generator (IGG) fuel tank inerting system designs are strongly influenced by flow capacity; therefore, it is of critical importance to establish the flow requirements. The rate of inert gas flow required from the inerting system at any instant is dependent on the sum of three separate requirements: (1) the replacement of consumed fuel with inert gas, (2) the ullage repressurization resulting from descents; and (3) additional flows for fuel scrubbing, degassing, or sweeping oxygen that evolves from the fuel into the ullage. The maximum flow requirement is established by the design condition resulting in a peak in this summation. In simple terms, this may be written as:

$$\dot{M}_{TOTAL} = \dot{M}_{FUEL} + \dot{M}_{PRESSURE} + \dot{M}_{SWEEP} \quad (1)$$

The two components of Equation (1) relating to changes in ullage volume and pressure requirements may be expressed in terms of the flight profile, the gas composition, and an assumed constant gas supply temperature. If the ideal gas law is used, this results in the summation equation below:

$$\dot{M}_{TOTAL} = \left(\frac{P}{RT}\right) \dot{V} + \left(\frac{V}{RT}\right) \dot{P} + \dot{M}_{SWEEP} \quad (2)$$

where P = fuel ullage pressure

R = mixed gas constant

T = assumed inert gas supply temperature

\dot{V} = fuel consumption rate (volumetric)

\dot{P} = rate of ullage pressure change

(Fuel consumption is taken as positive \dot{V} ; ullage pressure increase is taken as positive \dot{P}).

To establish the design flow rate, as well as to evaluate the mathematics of Equation (2), the helicopter mission scenario must be considered. Unlike transport, fighter, or bomber aircraft, the role of the military helicopter generally involves low-altitude operations. Descents during exposure to ignition sources (usually small arms fire) are of short duration but nevertheless result in flow rates that predominate in the mathematical evaluation of the flow requirements from Equation (2). Therefore, a necessary complementary task in a helicopter study is to perform a survivability and vulnerability analysis to determine whether these short descent bursts of gas flow justify the substantial increase in system size and weight necessary to maintain oxygen concentration at or below a given limit for inerting during short transient phases of flight profiles.

The flow rate due to fuel consumption is a function of engine power settings; this may be high during ascent and cruise, but is seldom high during rapid descent. The ullage repressurization flow only occurs during descent; this term has a negative value during ascent and may actually offset (or completely obliterate, depending on ullage volume) the fuel displacement requirement. The sweep or scrubbing flow is required to prevent the buildup of oxygen in the fuel ullage from the evolution of gases dissolved in the fuel. In general, the release of dissolved gas is by slow diffusion toward equilibrium oxygen concentrations. The buildup of excessive oxygen concentrations in the ullage may be prevented by the establishment of minimum sweep flow requirements. During ascent, the dissolved gas pressure could exceed the established ullage pressure by a sufficient amount to cause a rapid release of the dissolved gas, although this is largely dependent upon fuel tank design, agitation, fuel-dissolved gas conditions, etc. The scenario of a helicopter mission and the survivability/vulnerability requirements generally preclude the concern for rapid evolution of gases during critical ignition exposure.

Inert Gas Generator (IGG) System Description

The separation of mixed gases into enriched streams involves the use of a polymeric membrane surface in the form of a collection of extremely small-diameter, filament-like hollow fibers. The walls of the hollow fibers are the membrane surfaces. A gas mixture under pressure is introduced into one end of the membrane fiber bundle and flows through the hollow fibers. Due to differing membrane permeability rates of the various gases in the mixture, the high-pressure gas becomes depleted of the components of higher permeability; those permeant gases filter through the hollow-fiber membrane walls. The gas flowing through the hollow fibers thus becomes enriched in low-permeability gases.

Figure 1 shows the major IGG system elements. In this example, pressurized air is supplied to the IGG system; air is primarily a binary mixture of oxygen and nitrogen in which the oxygen concentration is approximately 21 percent and oxygen is the more permeable gas. The IGG system removes most of the oxygen and produces primarily nitrogen, an inert gas. Pressurized air first is filtered to remove particulate

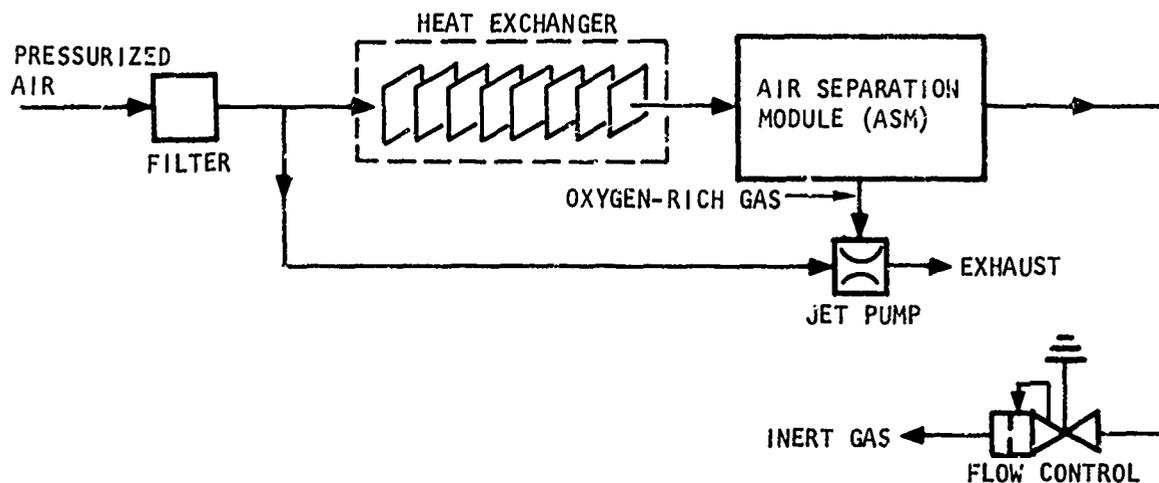


Figure 1. IGG System Schematic Diagram

contamination and to avoid fouling downstream components. Before entering the air separation module (ASM) the air is conditioned to reduce its temperature to near ambient sink temperature in a heat exchanger. Cooling air is usually derived from available fan-driven air or environmental control unit (ECU) air in helicopter operation; ram air may be used for fixed-wing aircraft. As the pressurized air flows through the ASM, oxygen permeates through the walls of the hollow-fiber membrane, leaving the nitrogen-rich, essentially inert gas. The inert gas leaving the ASM is delivered to the protected volumes by means of a flow control valve that may be of the fixed-flow or pressure-demand type, or may incorporate both functions. Filtered bleed airflow to a jet pump is used to exhaust the permeant (oxygen-rich) gas overboard and to reduce the exhaust back pressure of the ASM for improved performance. In addition, ambient airflow over the shell side of the fibers can be provided to maintain a reduced, near-constant shell-side oxygen concentration. The addition of this ram airflow is called "wash".

Design Inputs

In this subtask, estimates of physical size and weight of hollow-fiber permeable membrane IGG fuel tank inerting systems were established for the various Army aircraft mission profiles listed in Table 1. Airflows required for the systems and their inert gas output requirements were defined for several typical missions associated with each aircraft application studied during this subtask. To provide the best available estimates for subsequent Army determination of system application feasibility, maximum use was made of data developed during other recent studies of hollow-fiber membrane applications. In addition, modeling techniques developed at AIResearch--such as digital computer programs to assist in the design and to simulate IGG performance--were employed.

TABLE 1.
SUMMARY OF RESULTS
TASK 1(1), ANALYSIS

Mission Mode	Propulsion System		Descent Rate	Inert Gas Flow, lb/min	Bleed Flow, lb/min		Estimated System Weight, lb			
	Aircraft	Type			Power Setting	Fuel Tank Condition	9% O ₂ or 12% O ₂	12% O ₂	9% O ₂	12% O ₂
Attack	AH-1G	T53-L-13	30 percent normal	1/3 full (140-gal ullage)	6,000 fpm from 5,000 ft	0.310	1.74	1.18	50	36
	Generic AH	T700-GE-700	30 percent normal	1/3 full (200-gal ullage)	6,000 fpm from 5,000 ft	0.437	2.60	1.74	80	52
Troop Insertion	UH-1H	T53-L-13	flight idle	1/2 full (110-gal ullage)	3,000 fpm from 5,000 ft	0.124	1.21	0.73	92	52
	Generic UTTAS	T700-GE-700	flight idle	1/2 full (170-gal ullage)	3,000 fpm from 5,000 ft	0.187	1.54	0.96	84	52
Let-down (mission completion)	CH-47C	T55-L-11	flight idle*	1/2 full (600-gal ullage)	3,000 fpm from 5,000 ft	0.655	3.32	2.29	75	65
	UH-1H	T53-L-13	40 percent normal	20 min remaining (200-gal ullage)	1,000 fpm from 5,000 ft	0.082	0.42	0.29	20	17
Nap-of-the-earth	Generic UTTAS	T700-GE-700	40 percent normal	20 min remaining (300-gal ullage)	1,000 fpm from 5,000 ft	0.116	0.56	0.44	28	22
	CH-47C	T55-L-11	40 percent normal	20 min remaining (1100-gal ullage)	1,000 fpm from 5,000 ft	0.416	2.17	1.49	53	37
Nap-of-the-earth	AH-1G	T53-L-13	100 percent normal	1/3 full (140-gal ullage)	--	0.0186	0.08	0.053	10	9
	Generic AH	T700-GE-700	100 percent normal	1/3 full (200-gal ullage)	--	0.014	0.07	0.048	11	10

*For CH-47C troop insertion mission mode, a boost compressor is required to obtain twice the engine bleed pressure.

In all cases, actual conditions at the various potential design points, including fuel tank volume and ullage, available pneumatic pressure for the current propulsion engine settings, and descent ratings associated with the mission profiles, were considered in the design evaluation.

Also evaluated were the effects on the systems of varying the oxygen content of the inert gas leaving the IGG system between 12 percent and 9 percent (by volume). In addition, the net effects of using alternate air pressure sources were evaluated. On the basis of this analysis, the optimum configurations for each helicopter and mission profile were derived. Results of the analysis are summarized in Table 1 and Figure 2.

Fuel Tank Inerting System Configurations Evaluated

Using the engine bleed air extraction penalty factors given in Table 2, the following system configurations were evaluated from the standpoint of engine bleed flow and systems weight requirements. Results of the system configuration evaluations are presented in Figures 3 through 12.

- (a) No jet pump (NJP), no wash (NW), 9 and 12 percent oxygen
- (b) No jet pump, 23 percent wash (W), 9 and 12 percent oxygen
- (c) Jet pump (JP), no wash, 9 and 12 percent oxygen
- (d) Jet pump, 23 percent wash, 9 and 12 percent oxygen
- (e) Jet pump, no wash, engine bleed pressure booster (PB), 9 and 12 percent oxygen

Recommended Fuel Tank Inerting System Configurations

For the AH-1G, UH-1H, generic AAH, and generic UTTAS, the recommended system consists of a jet pump with no wash. The use of wash flow would result in a reduction in weight, but the large increase in engine bleed flow cannot be tolerated and, in some instances, the required oxygen concentration cannot be achieved. Doubling the engine bleed pressure would reduce ASM weight and bleed flow, but the added complexity of a compressor and controls is not considered justified.

The system recommended for the CH-47C consists of a jet pump, no wash, and a boost compressor. During flight idle operation, engine bleed pressure is low, and the use of a boost compressor to increase IGG inlet pressure will allow a significant reduction in ASM weight. The 9-percent (by volume) oxygen concentration in the outlet gas cannot be achieved with wash flow.

The inert gas flow required is a function of the rate of change in fuel tank ullage volume and pressure. For the mission profiles listed in Table 1, the rate of change in ullage pressure during descent is the

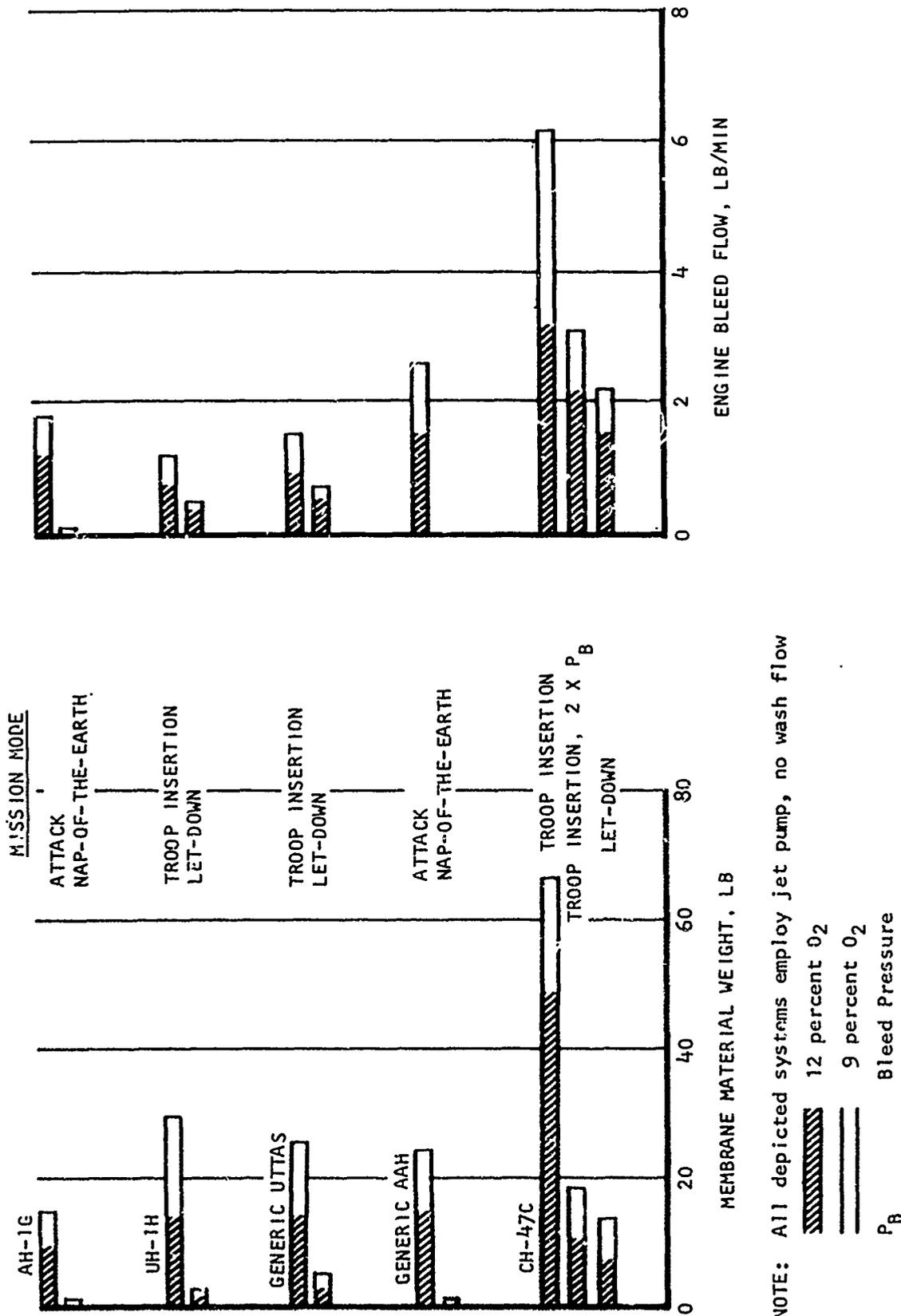


Figure 2. Summary of Requirements for Selected Systems

TABLE 2.
ENGINE BLEED AIR EXTRACTION
PENALTY FACTORS

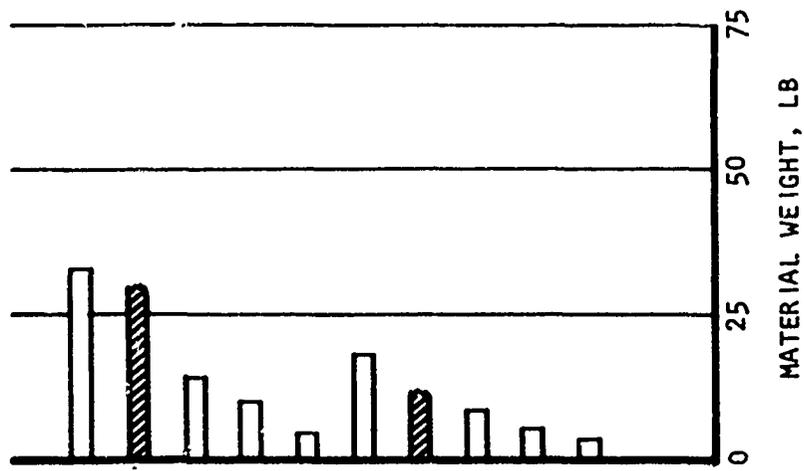
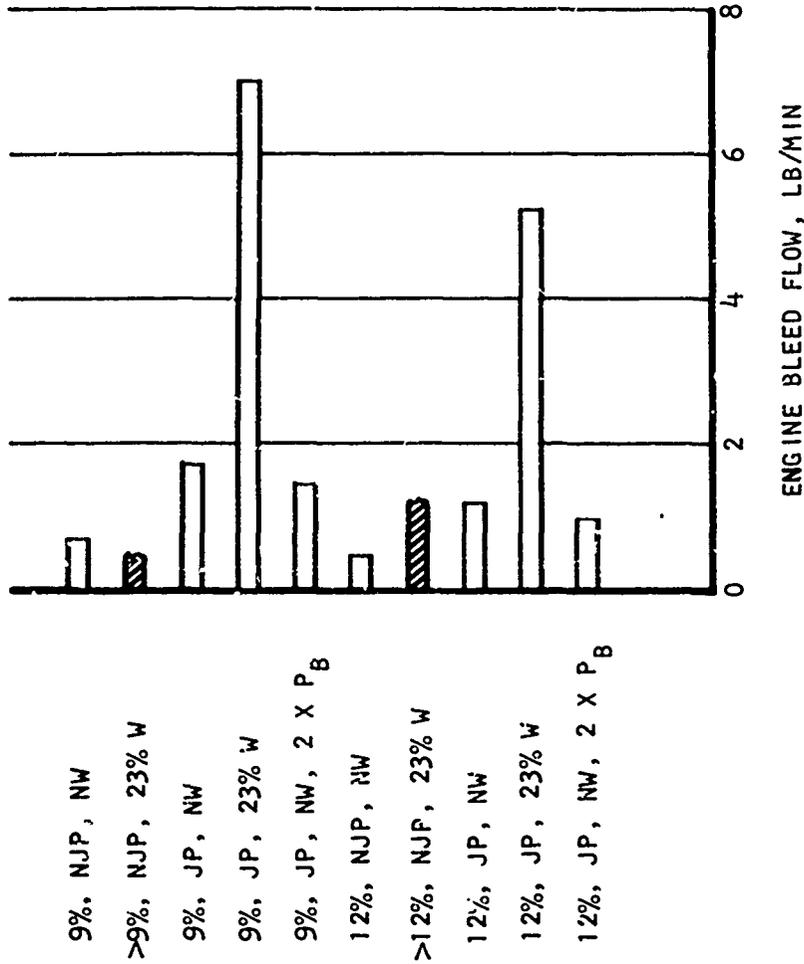
<u>Penalty</u>	<u>Factor</u>	<u>Units</u>
Turbine inlet temperature rise	7.900	$\frac{^{\circ}\text{F}}{\text{lb/min (bleed air)}}$
Power loss due to bleed airflow	6.050	$\frac{\text{hp}}{\text{lb/min (bleed air)}}$
Lift loss due to power loss	5.290	$\frac{\text{lb (lift)}}{\text{hp (extracted)}}$
Lift loss due to bleed airflow	32.00	$\frac{\text{lb (lift)}}{\text{lb/min (bleed air)}}$
Fuel loss due to bleed airflow	2.450	$\frac{\text{lb/hr (fuel)}}{\text{lb/min (bleed air)}}$
Fuel loss due to power loss	0.400	$\frac{\text{lb/hr (fuel)}}{\text{hp (extracted)}}$
Fuel loss due to weight gain	0.077	$\frac{\text{lb/hr (fuel)}}{\text{lb (installed weight)}}$

deciding factor in establishing the inert gas flow requirement, and hence the size and weight of the system. The rate of change in ullage volume due to fuel flow requires significantly less inert gas flow, as shown for the nap-of-the-earth missions.

Penalty Evaluations

Penalty evaluations were made for the AH-1G, CH-47C, and OV-10 (drop tanks only). The evaluations were based on (1) the mission profiles and system configurations, (2) the bleed airflow and system weight requirements of Table 1, and (3) the bleed air extraction penalty factors of Table 2.

System sizing was most affected by the descent portion of the flight profile. To be compatible with in-service experience, the preliminary designs selected for the AH-1G and CH-47C were based on a descent rate of 3000 fpm. The penalty evaluations resulting from system sizing are presented in Table 3, which shows that the bleed extractions and resulting penalties for the systems are not excessive for the missions analyzed; however, system weight can be reduced significantly if the oxygen



▨ CANNOT ACHIEVE REQUIRED O₂ CONCENTRATION

Figure 3. AH-1G, T53-L-13 Engine, 30-Percent Normal Power, Attack, 6000-fpm Descent, 140-gal Ullage, 500 ft, 75°F Day

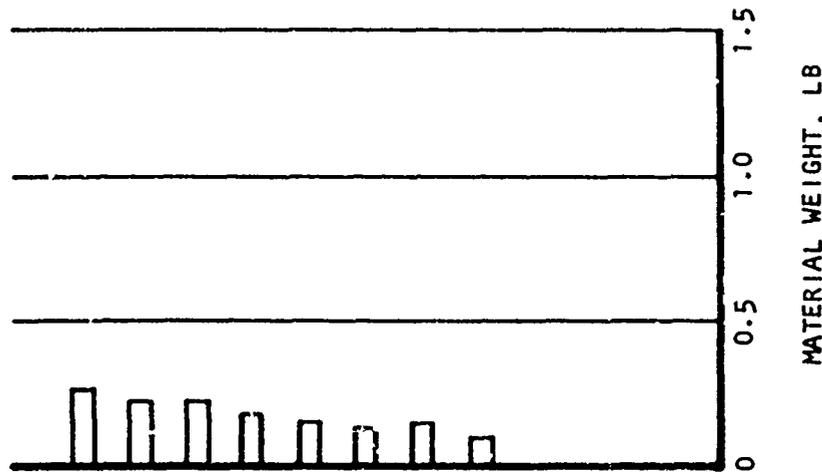
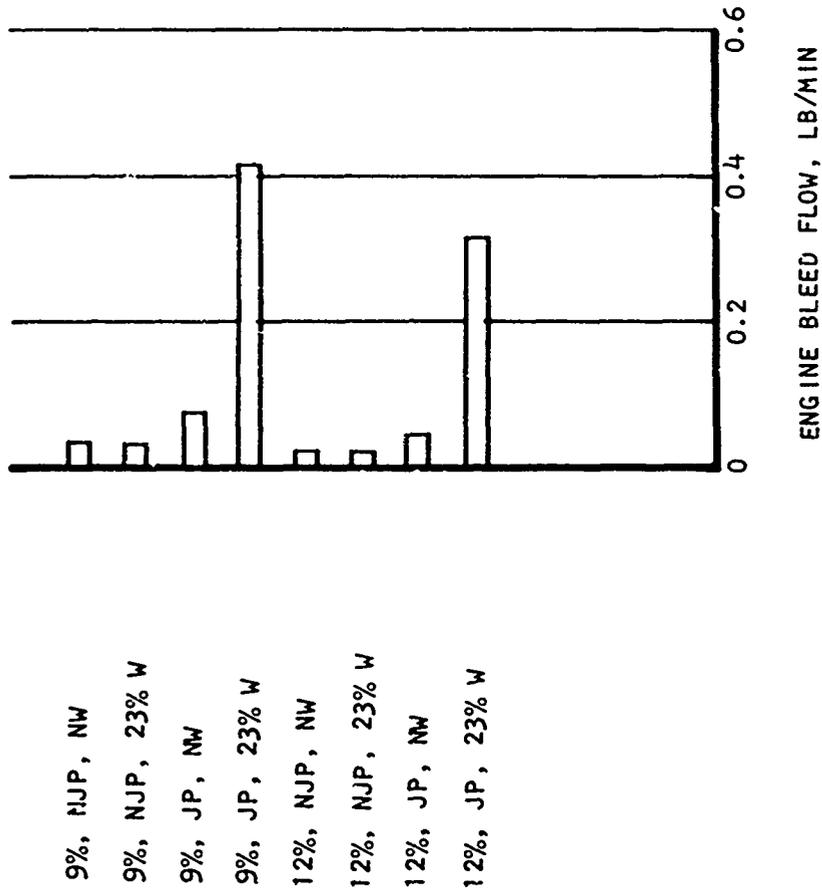


Figure 4. AH-1G, T53-L-13 Engine, Normal Rated Power, Nap-of-the-Earth, 140-gal Ullage, 500 ft, 75°F Day

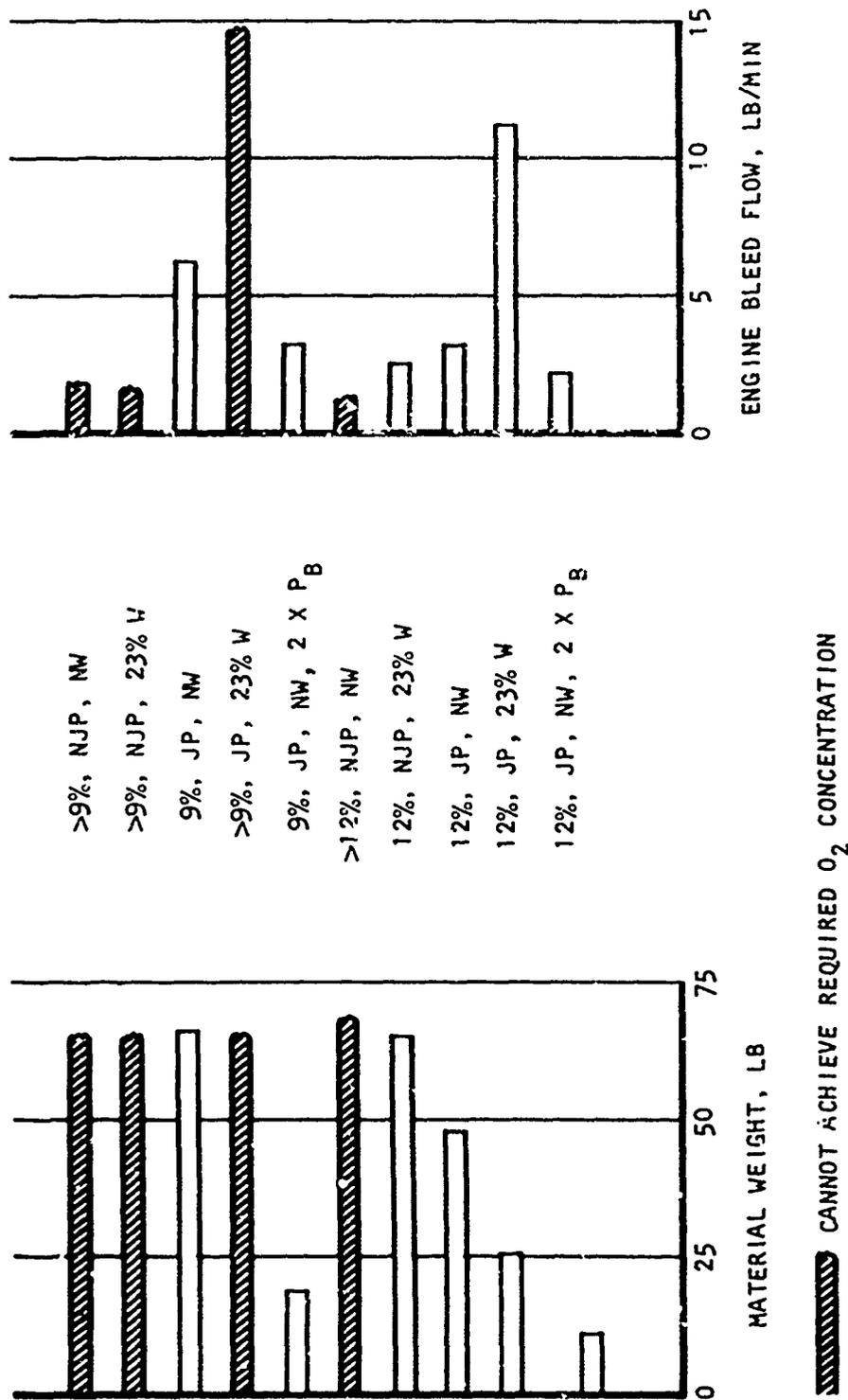


Figure 5. CH-47C, T55-L-11A Engine, Flight Idle, Troop Insertion, 3000-fpm Descent, 600-gal Jilage, 500 ft, 75°F

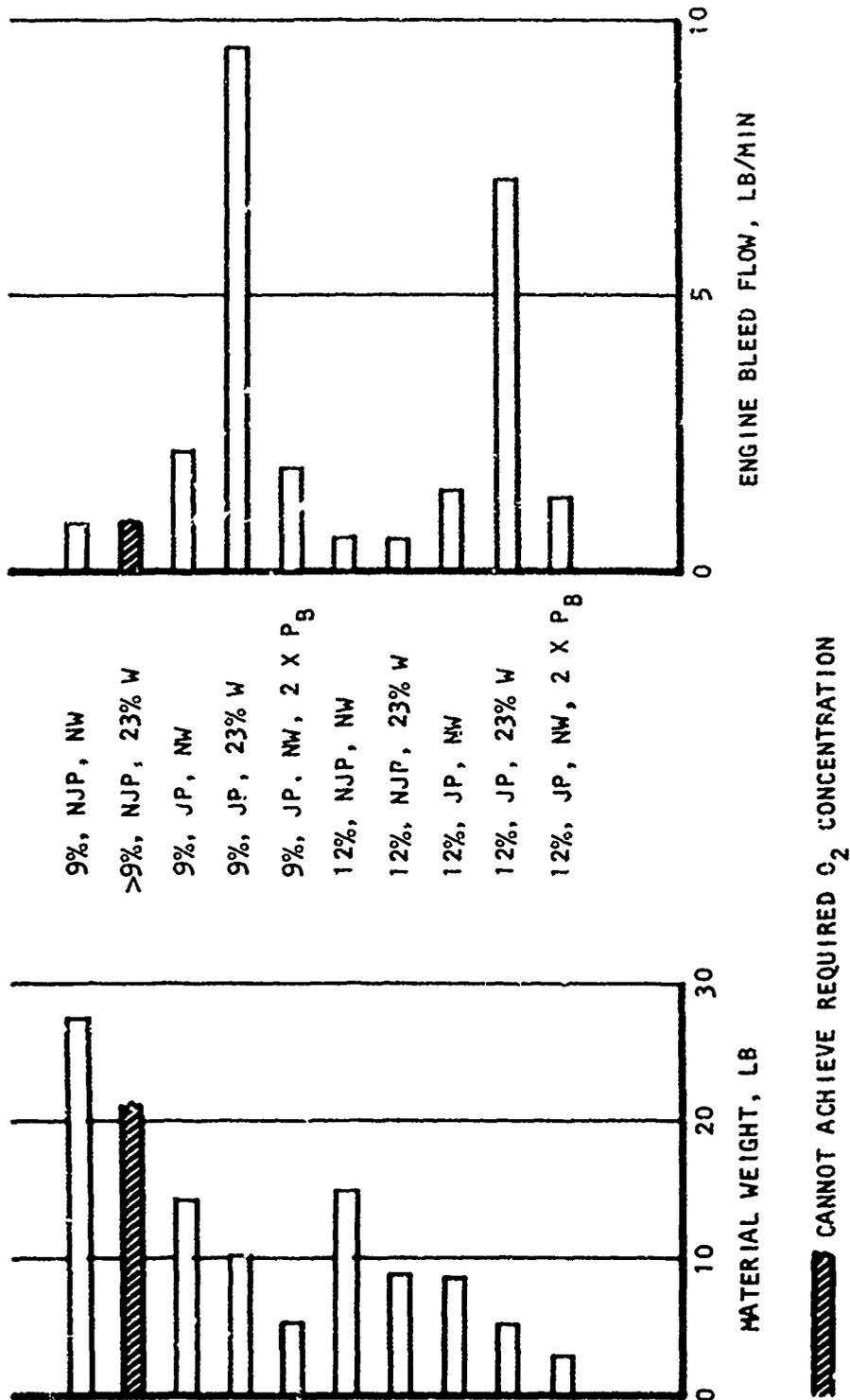


Figure 6. CH-47C, T55-L-11A Engine, 40-Percent Normal Power, Let-Down, 1000-fpm Descent, 1100-gal Ullage, 500 ft, 75°F Day

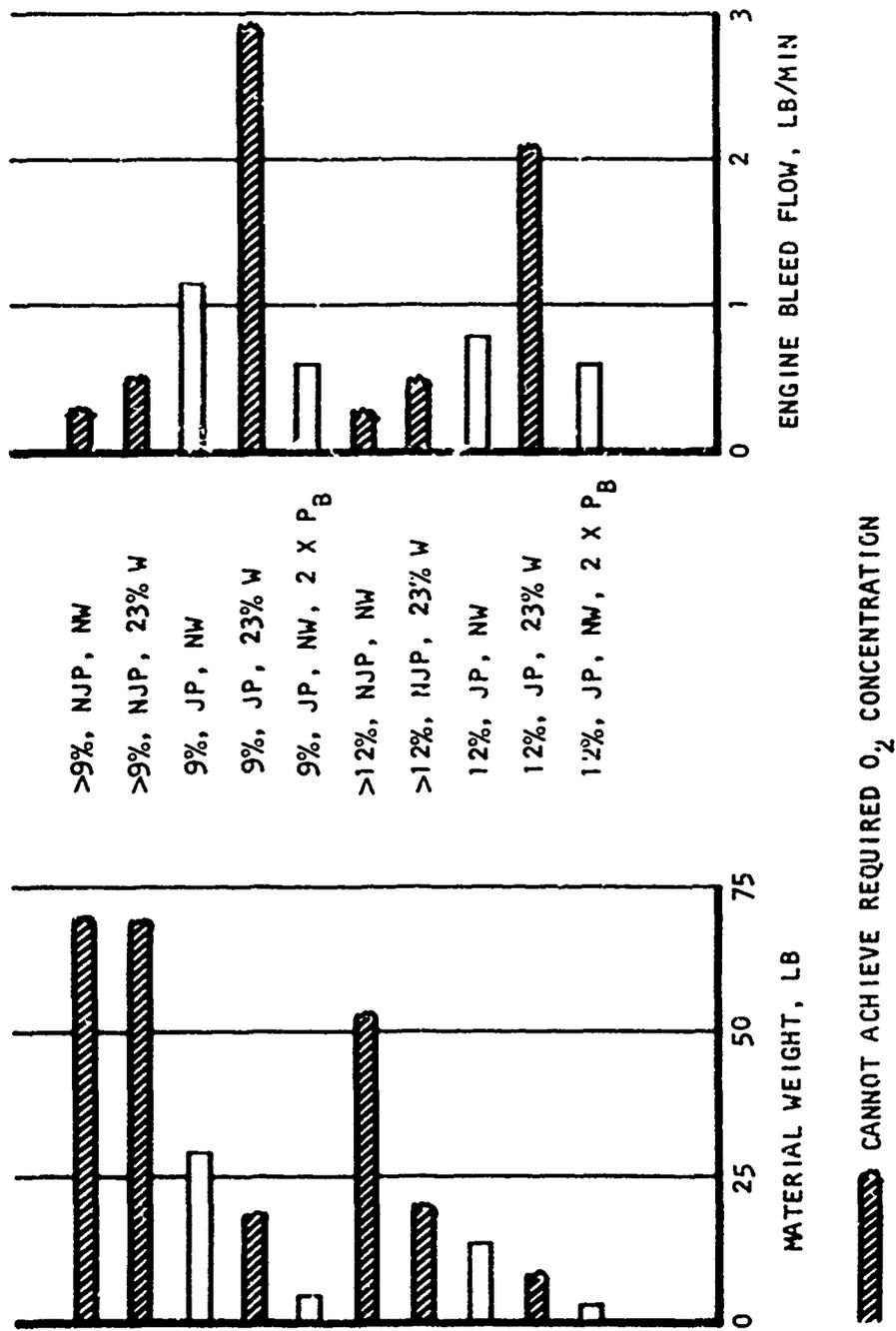


Figure 7. UH-1H, T53-L-13 Engine, Flight Idle, Troop Insertion, 3000-fpm Descent, 110-gal Ullage, 500 ft, 75°F Day

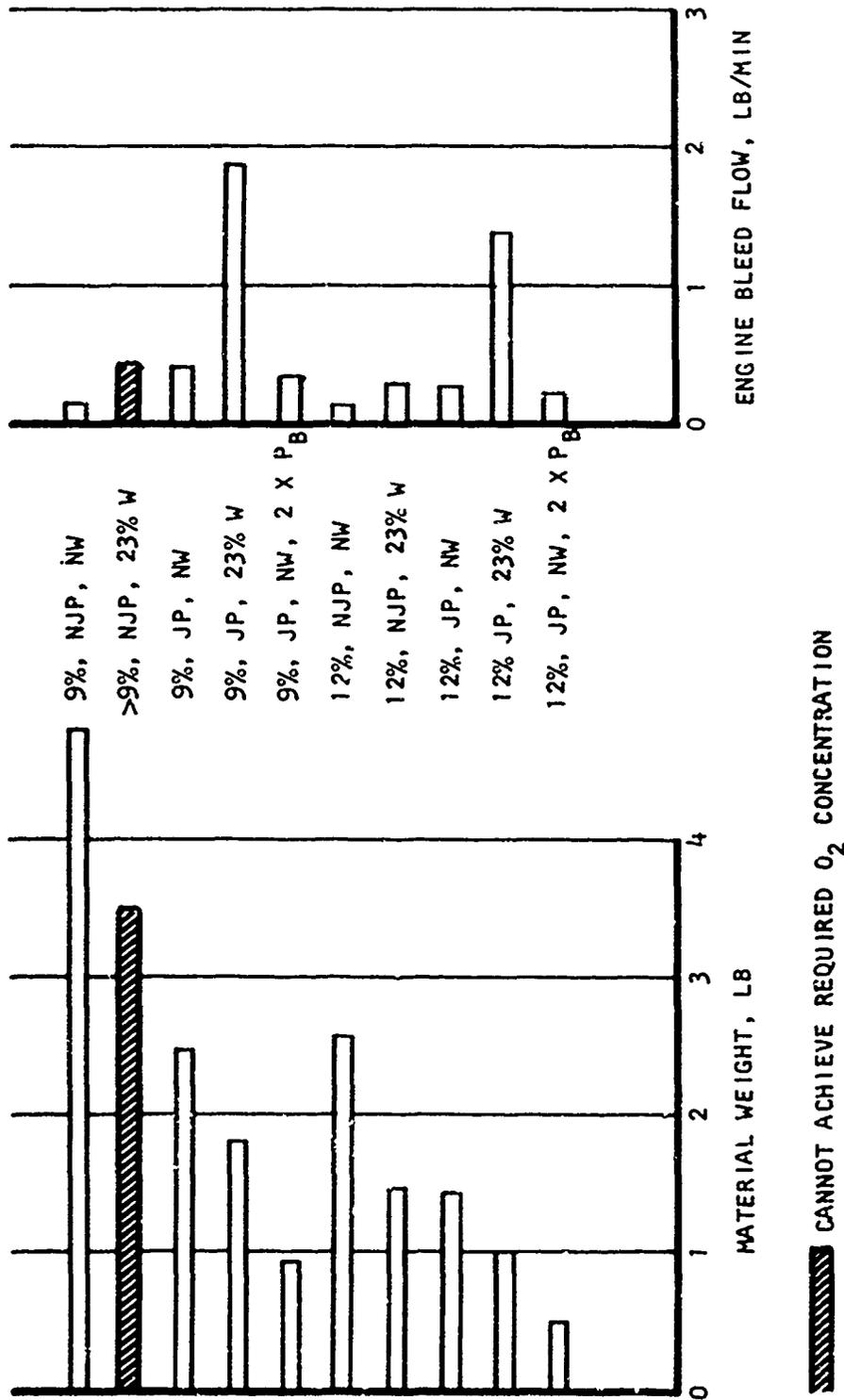
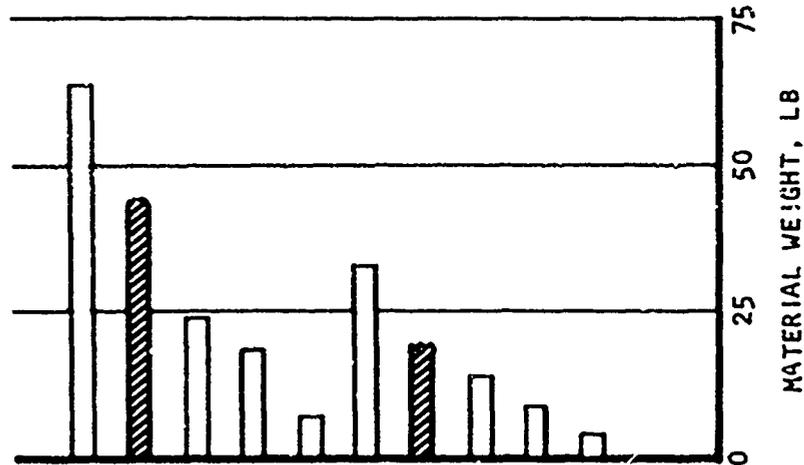
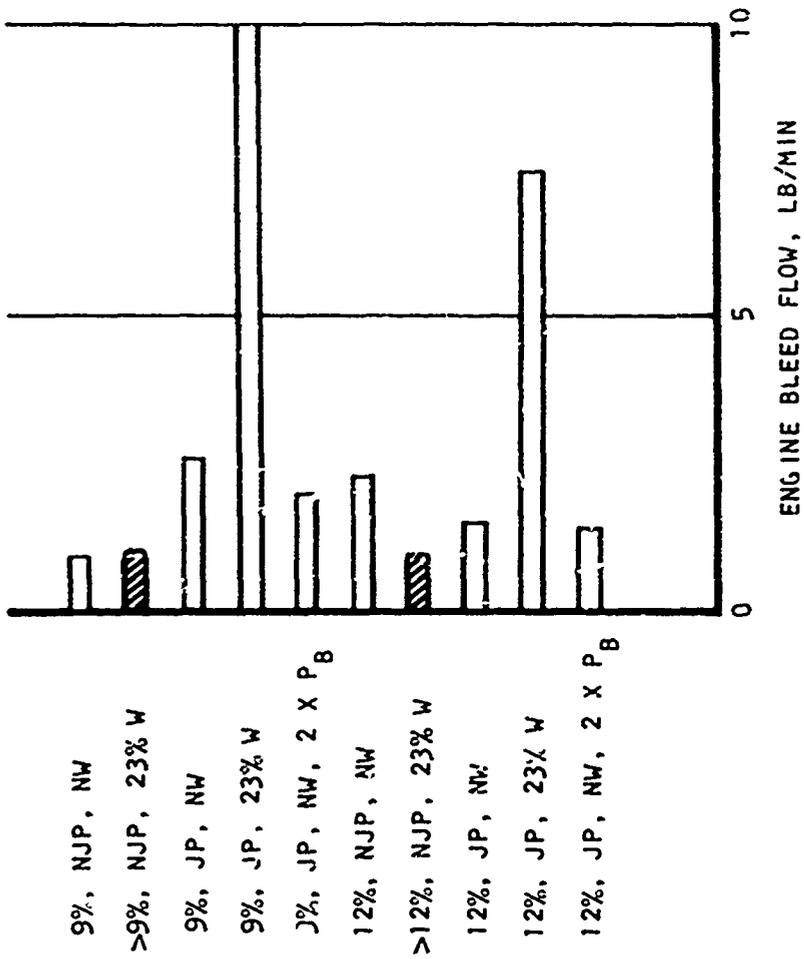


Figure 8. UH-1H, T53-L-13 Engine, 40-Percent Normal Power, Let-Down, 1000-fpm Descent, 200-gal Ullage, 500 ft, 75°F Day



▨ CANNOT ACHIEVE REQUIRED O₂ CONCENTRATION

Figure 9. Generic AAH, T700-GE-700 Engine, 30-Percent Normal Power, Attack, 6000-fpm Descent, 200-gal Ullage, 500 ft, 75°F Day

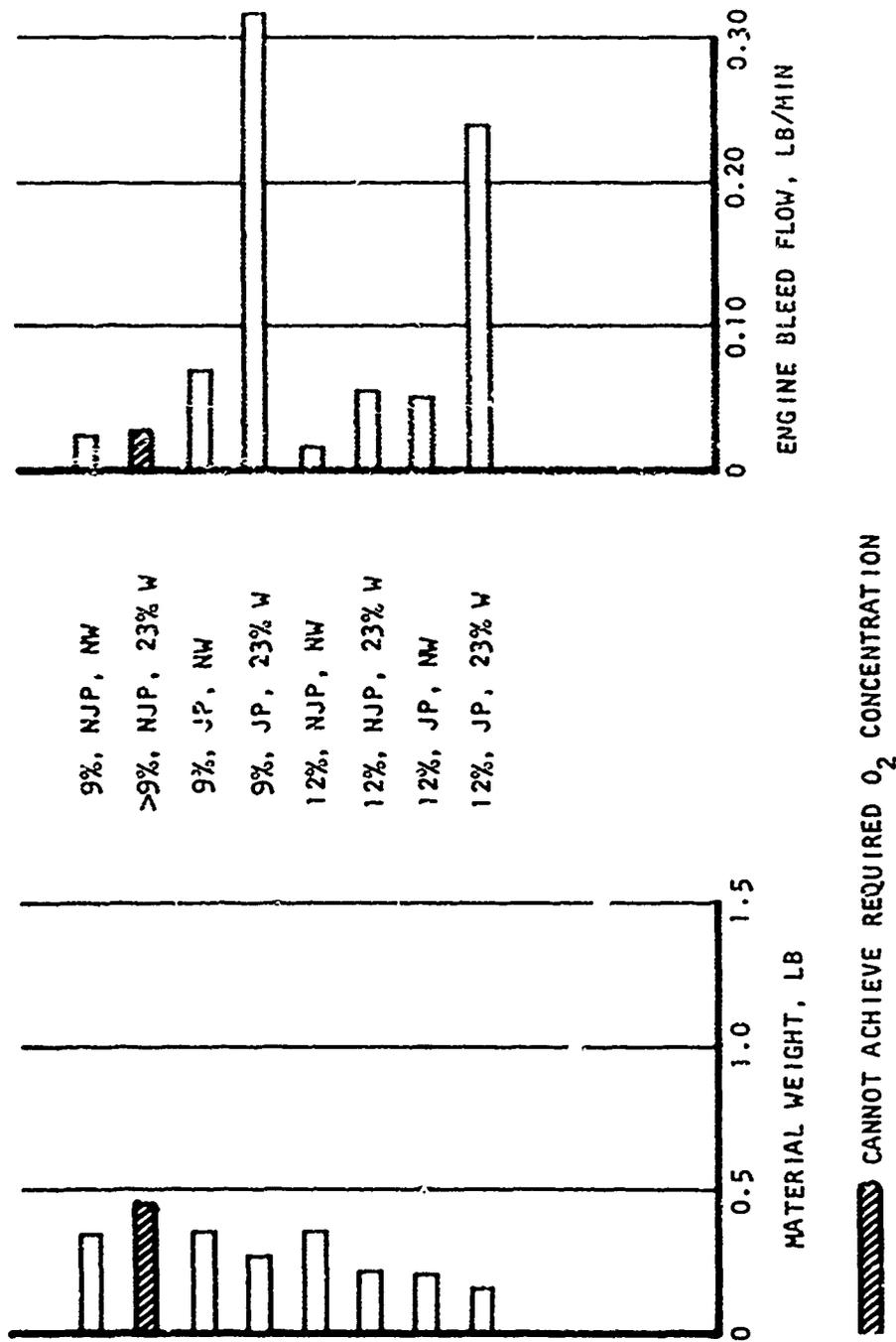
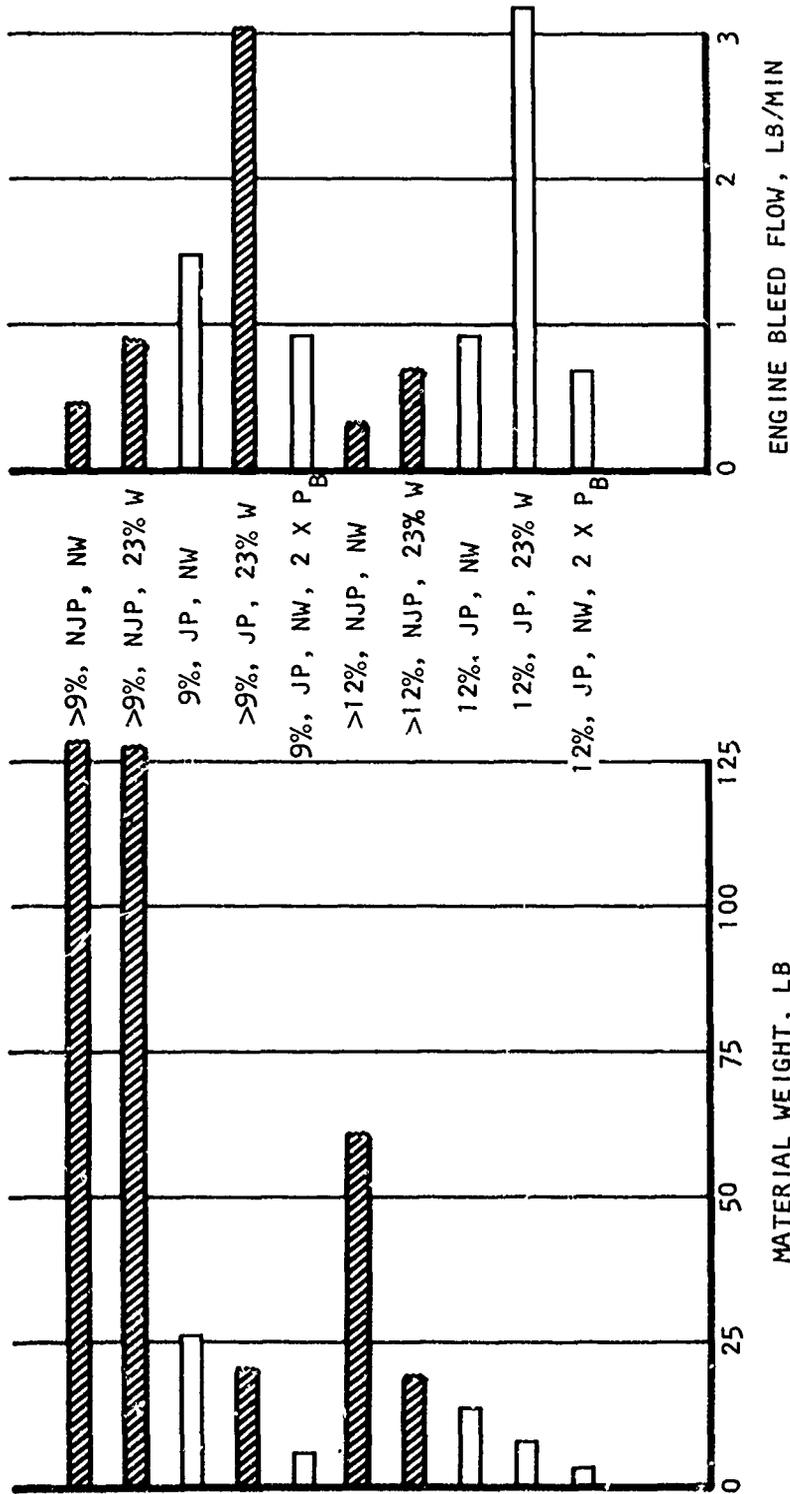


Figure 10. Generic A4H, T700-GE-700 Engine, Normal Rated Power, Nap-of-the-Earth, 200-gal Ullage, 500 ft, 75°F Day



▨ CANNOT ACHIEVE REQUIRED O₂ CONCENTRATION

Figure 11. Generic UTTAS, T700-GE-700 Engine, Flight Idle, Troop Insertion, 3000-fpm Descent, 170-gal Ullage, 500 ft, 75°F Day

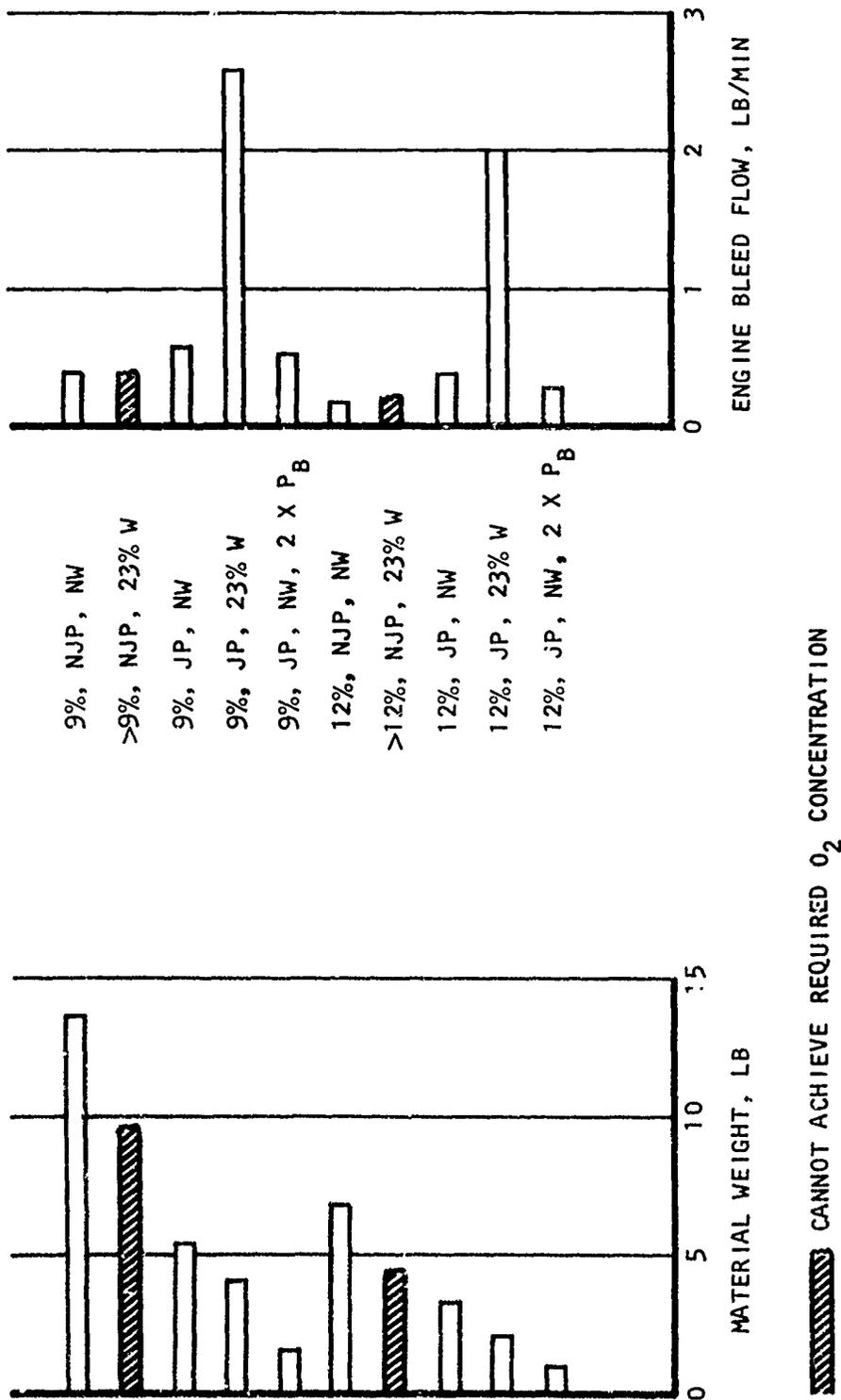


Figure 12. Generic UTTAS, T700-GE-700 Engine, 40-Percent Normal Power, Let-Down, 1000-fpm Descent, 300-gal Ullage, 500 ft, 75° F Day

TABLE 3
PENALTY EVALUATION OF PRELIMINARY DESIGNS
FOR FUEL TANK INERTING SYSTEMS

Parameter Evaluated	AH-1G: 3000-fpm Descent, 75°F Day, 140-Gal Ullage, Jet Pump, No Wash		CH-47C: 3000-fpm Descent, 75°F Day, 600-Gal Ullage, Pressure Boost, Jet Pump, No Wash		OV-10 L. op Tanks: 3000-Ft Level Flight, 75°F Day, 150-Gal Ullage Each Tank, Jet Pump, No Wash	
	O ₂ Concentration, %		O ₂ Concentration, %		O ₂ Concentration, %	
	9	12	9	12	9	12
System weight, lb	50	38	75	65	15	13.5
Bleed flow, lb/min	0.90	0.62	3.32	2.29	0.14	0.10
Turbine inlet temperature rise due to bleed air extraction, °F	7.1	4.9	26.2	18.1	1.1	0.8
Power loss due to bleed air extraction, hp	5.45	3.75	20.10	13.85	0.65	0.62
Lift loss due to power loss, lb	28.8	19.8	106.2	73.3	4.5	3.3
Increase in fuel consumption due to bleed air extraction, lb/hr	2.20	1.50	8.10	5.60	0.34	0.29
Increase in fuel consumption due to weight increase, lb/hr	3.85	2.93	5.78	5.00	1.16	1.04
Total increase in fuel consumption, lb/hr	6.04	4.43	13.88	10.60	1.50	1.33

concentration is permitted to increase to 12 percent by volume during the descent missions for the AH-1G and CH-47C. If this is permitted, it is significant to note that, for the remainder of the mission profile such as climb, cruise, hover, etc., oxygen concentration will be 9 percent or less. If weight is critical, the system could be sized to allow an increase in oxygen concentration above 9 percent, consistent with the vulnerability and survivability requirements for the mission.

SUBTASK 1(2), PRELIMINARY DESIGN

Following USAAMRDL approval of the AirResearch recommendations, preliminary designs of fuel tank inerting systems were conducted for the AH-1G and CH-47C fuel tanks and for the OV-10 drop tanks. The systems were designed to produce an inert gas having a 9-percent (by volume) maximum oxygen concentration. The designs included component arrangements and aircraft mechanical and performance interfaces. Aircraft weight and volume penalties and penalties associated with the use of aircraft services also were evaluated. Design goals were as follows:

- (a) Minimum increase in aircraft weight
- (b) Minimum change to existing center of gravity
- (c) Minimum interference with existing system and component maintenance
- (d) Aircraft operation unaffected by system failure (except for loss of protection provided by inerting system)
- (e) Maintaining or increasing current level of survivability
- (f) Automatic operation without need for in-flight man-machine interface
- (g) Maximum use of common parts

The following design parameters and mission profiles specified by USAAMRDL were used to establish the preliminary designs:

- (a) AH-1G Mission Profile--attack mission, 3000-fpm descent from 5000 ft with 1/3 fuel level and engine at 30-percent normal power (T-53-L-13 engine and ullage volume of 140 gal).

Inerting System Configuration--jet pump, no wash; constant flow, 9 percent oxygen concentration.

- (b) CH-47C Mission Profile--troop insertion mission, 3000-fpm descent from 5000 ft with engine at flight idle (T-55-L-11 engine and ullage volume of 600 gal).

Inerting System Configuration--jet pump, no wash, pressure boost; constant flow, 9 percent oxygen concentration.

- (c) OV-10 Mission Profile--level flight at 3000 ft; engines at maximum cruise, one feeding from each drop tank (T-53-L-13 engines and ullage volume of 150 gal in each tank).

Inerting System Configuration--jet pump, no wash; constant flow, 9 percent oxygen concentration.

Preliminary Design for AH-1G Helicopter

The AH-1G system schematic is shown in Figure 13a. The detailed design is discussed in Section 3.

The fuel tank inerting system is a dual ASM installation, designed to be located in the pylon area between the main rotor mast and the engine oil tank, as shown in Figure 13b. Adjacent sources of bleed air and ECU (or cabin) cooling air are available at this location. System operation is automatic.

Inert gas flow from this system is 0.16 lb/min, which will limit the oxygen concentration in the fuel tank ullage to 9 percent by volume during the specified mission profile. This profile is for the attack mission, which is defined as 3000 fpm rate of descent from 5000 ft, with 1/3 fuel level and the engine at 30 percent of normal power (T-53-L-13 engine and ullage volume of 140 gal).

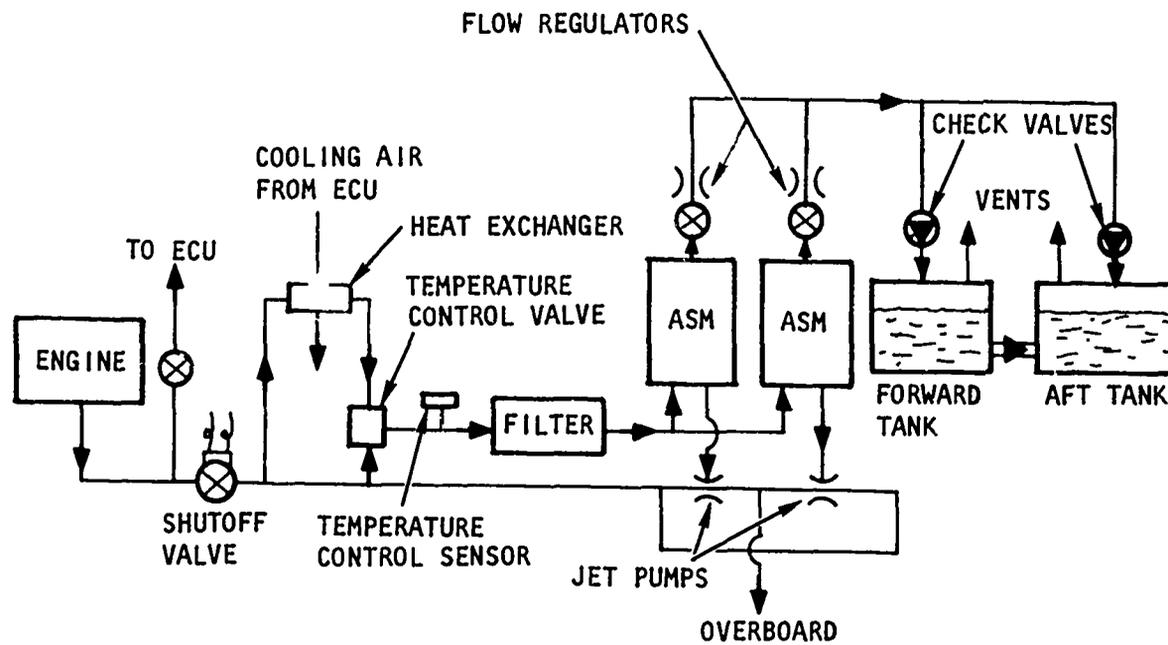
The AH-1G system will have no effect on the operation of other aircraft subsystems. A shutoff valve and check valves are provided to completely isolate the system from the aircraft if necessary. Utilization of engine bleed air will not exceed 1.0 lb/min.

System weight will be held to a minimum consistent with good design and is estimated to be 50 lb (for 9-percent oxygen concentration). By locating the system in the pylon area near the main rotor mast, the effect on the aircraft center of gravity will be minimal.

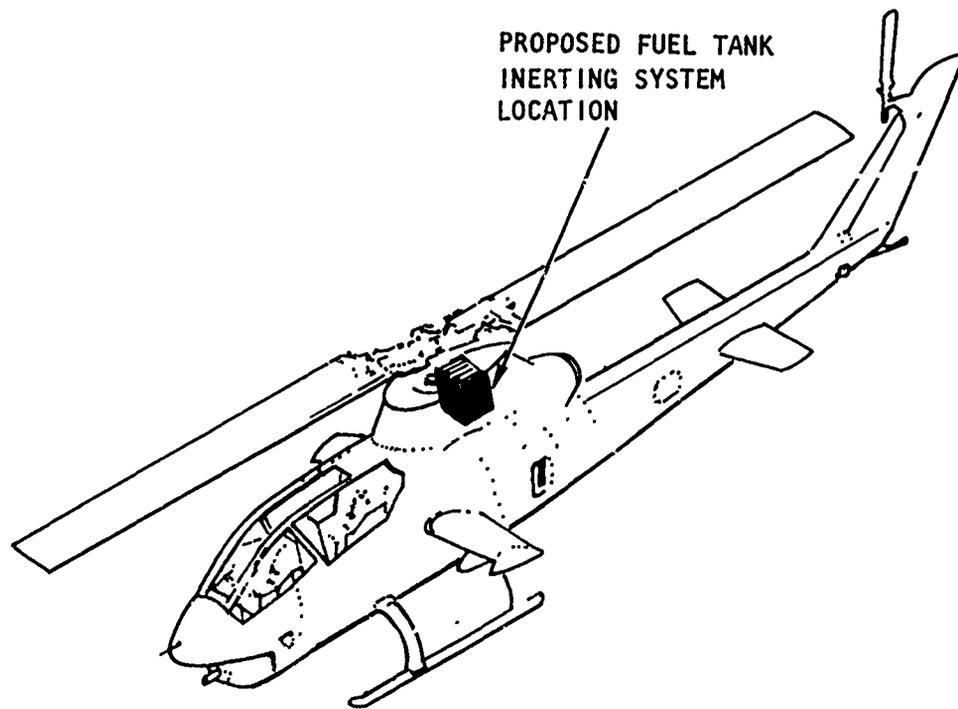
Maintenance requirements have been minimized by designing the ASM with a quick-disconnect clamp to facilitate removal of the fiber insert. The air filter element is removable from the cartridge for servicing. A manifold has been designed to reduce the number of connections and to simplify line routing.

Location of the system in the pylon area also minimizes interference with access to other components. An additional access door is recommended for engine oil tank service.

Although its purpose is to reduce vulnerability and to increase survivability by eliminating explosive gas mixtures in the fuel tank ullage, failure of the AH-1G system at any time in the mission will not impair aircraft operation.



a. SYSTEM SCHEMATIC DIAGRAM



b. SYSTEM LOCATION

Figure 13. AH-1G Fuel Tank Inerting System Schematic Diagram and Location in Aircraft

The system does not contain, use, or supply any materials or substances that will increase vulnerability or decrease survivability. The use of common parts for the AH-1G and other aircraft using an IGG system is discussed later in this section.

Preliminary Design for CH-47C Helicopter

The preliminary design for the CH-47C system is defined by Figures 14 and 15 and the system schematic shown in Figure 16.

The fuel tank inerting system is designed to be located below the cargo floor between the most forward and most aft centers of gravity for the aircraft and adjacent to the fuel tanks. Bleed air lines would have to be routed from the engine bleed manifolds currently used for engine inlet anti-icing. Because very low pressures are generated for the specified mission profile, the inlet bleed air pressure must be boosted by a turbocompressor, which also will provide cooling air for the bleed air entering the IGG. System operation is automatic.

Inert gas flow from this system is 0.65 lb/min, which will limit the oxygen concentration in the fuel tank ullage to 9 percent by volume during the specified mission profile. This profile is for the troop insertion mission, which is defined as 3000-fpm rate of descent from 5000 ft, with 1/2 fuel level and the engines at flight idle (T55-L-11 engine and ullage volume of 600 gal).

The CH-47C system will have no effect on the operation of other aircraft subsystems. Shutoff valves and check valves are provided to completely isolate the system from the aircraft if necessary. Utilization of engine bleed air will not exceed 3.5 lb/min.

System weight will be held to a minimum consistent with good design and is estimated to be 75 lb (for 9-percent oxygen concentration). By locating the system under the cargo floor near the center of gravity, the effect on the aircraft center of gravity will be minimal.

Maintenance requirements have been minimized by designing the ASM with a quick-disconnect clamp to facilitate removal of the fiber insert. The air filter element is removable from the cartridge for servicing. The filter, temperature control components, jet pump, turbocompressor, and flow regulator are all installed for easy accessibility.

Location of the system under the cargo floor also minimizes interference with access to other components. Access panels are already installed in the floor.

Although its purpose is to reduce vulnerability and increase survivability by eliminating explosive gas mixtures in the fuel tank ullage, failure of the CH-47C system at any time during the mission will not impair aircraft operation. In addition, the system can be completely isolated by closing the shutoff valve provided for this purpose.

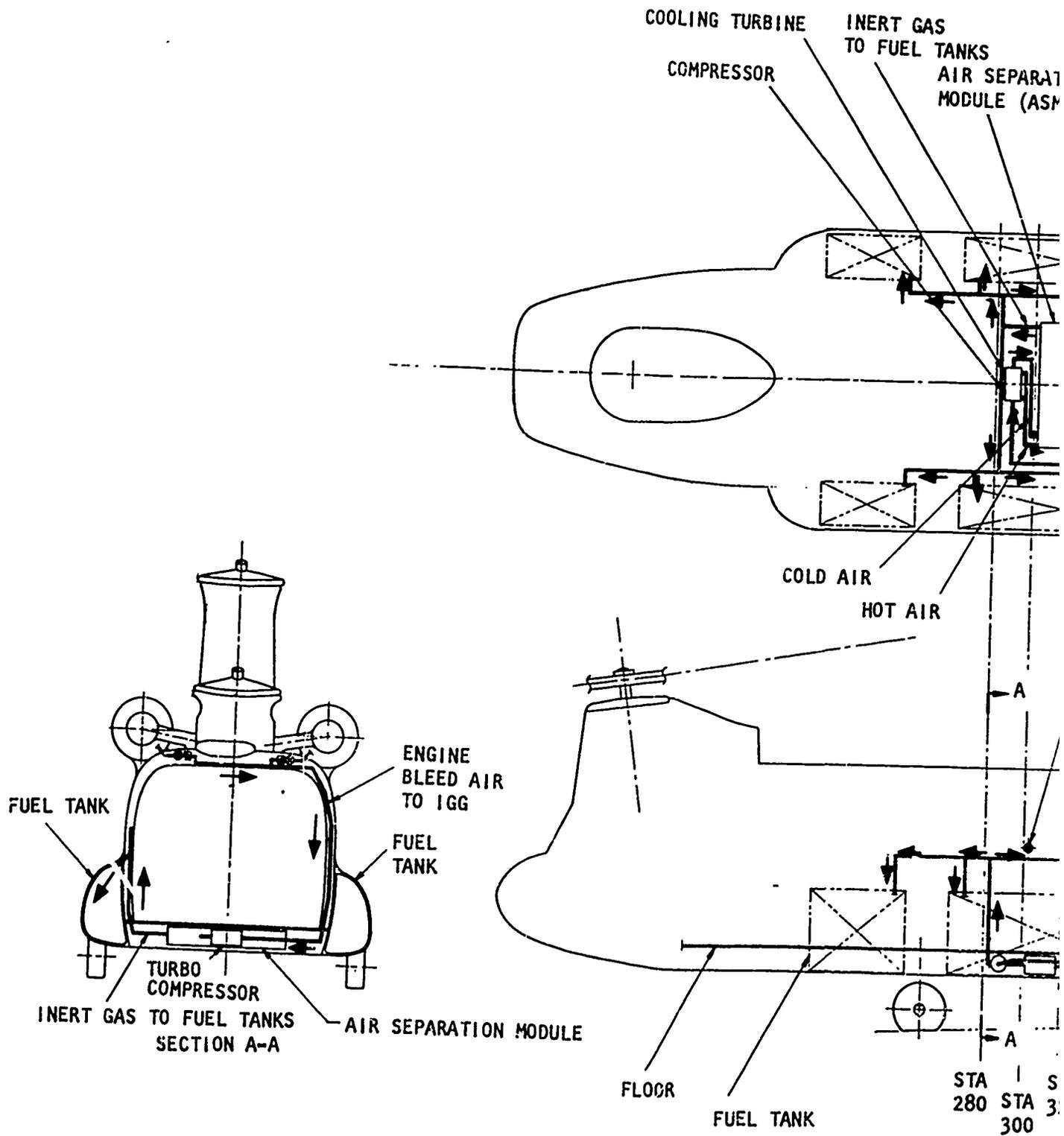
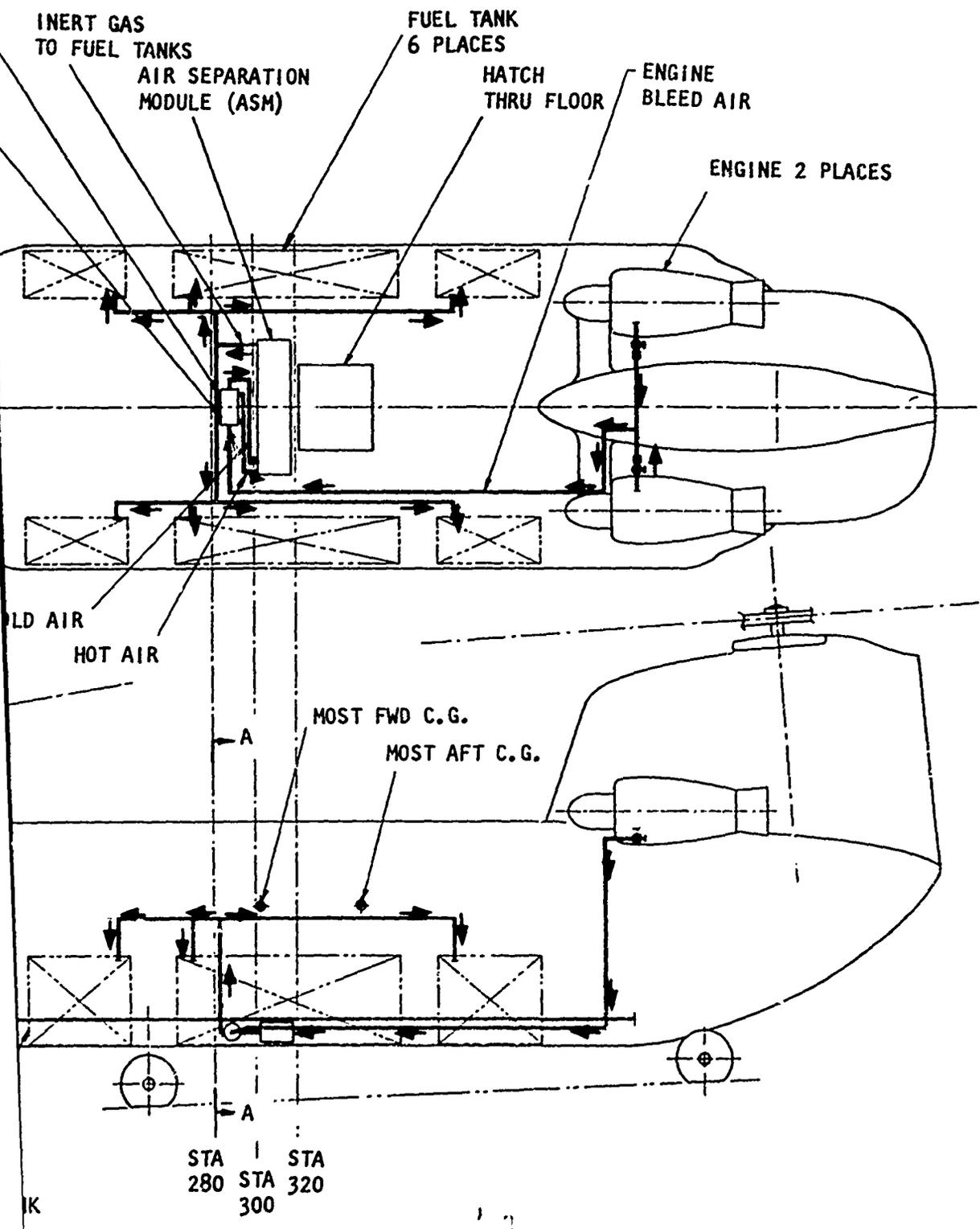


Figure 14. Fuel Inerting System Concept, CH-47C



12

2

NOTE: ALL DIMENSIONS ARE IN INCHES

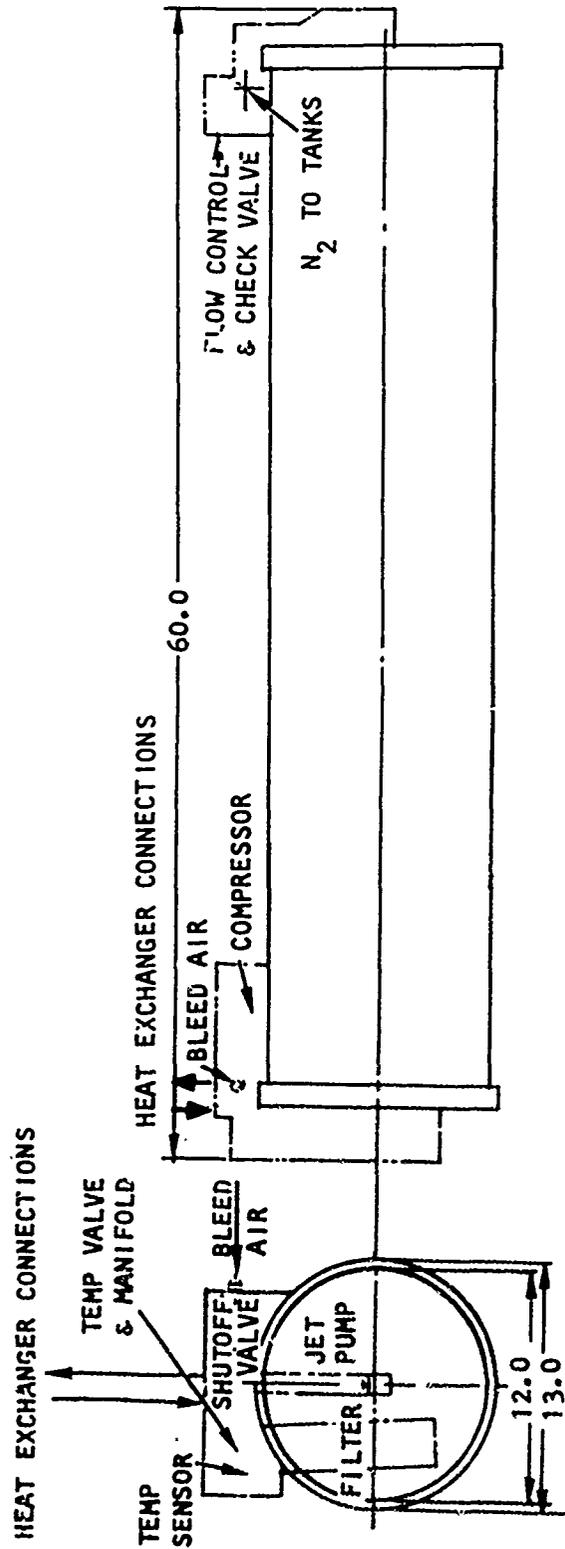


Figure 15. Fuel Inerting System, CH-47C 12.0-Inch-Diameter Module

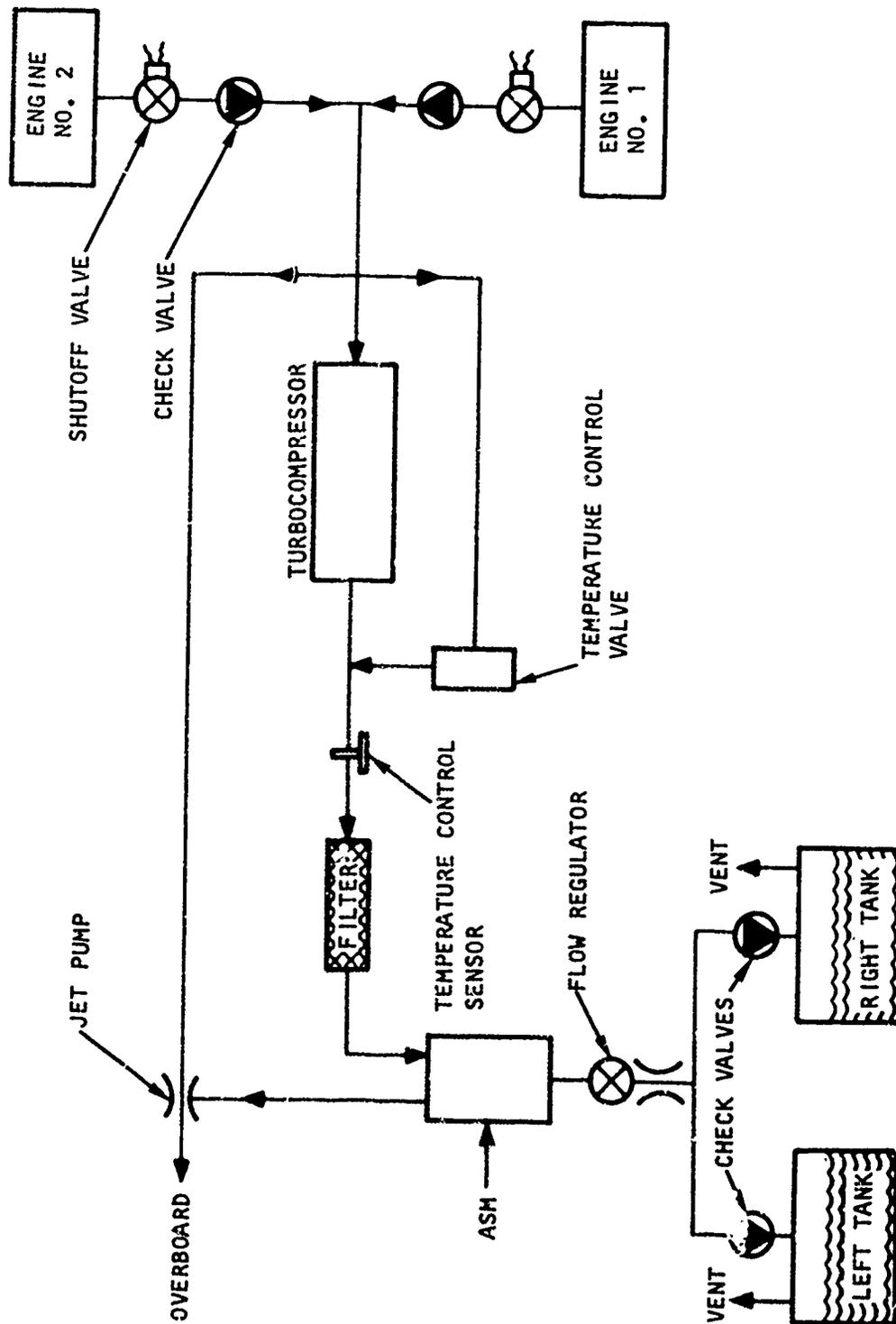


Figure 16. Schematic Diagram of Fuel Tank Inerting System for CH-47C

The system does not contain, use, or supply any materials or substances that will increase vulnerability or decrease survivability. The use of common parts for the CH-47C and other aircraft using an IGG system is discussed later in this section.

Preliminary Design for OV-1D Drop Tanks

The preliminary design of the OV-1D drop tanks system is defined by Figures 17 and 18 and the system schematic shown in Figure 19.

The fuel tank inerting system is designed to be located adjacent to the ECU, just forward of the main fuel tank and station 111.5. Adjacent sources of bleed air and ECU (or cabin) cooling air are available at this location. System operation is automatic.

Inert gas flow from this system is 0.034 lb/min, which will limit the oxygen concentration in the fuel tank ullage to 9 percent by volume over the specified mission profile. This profile is for level flight at 3000 ft, with 150 gal of ullage in each tank (T-53-L-13 engines at maximum cruise, one feeding from each drop tank).

The OV-1D IGG system will have no effect on the operation of other aircraft subsystems. A shutoff valve and check valves are provided to completely isolate the system from the aircraft if necessary. Utilization of engine bleed air will not exceed 0.14 lb/min.

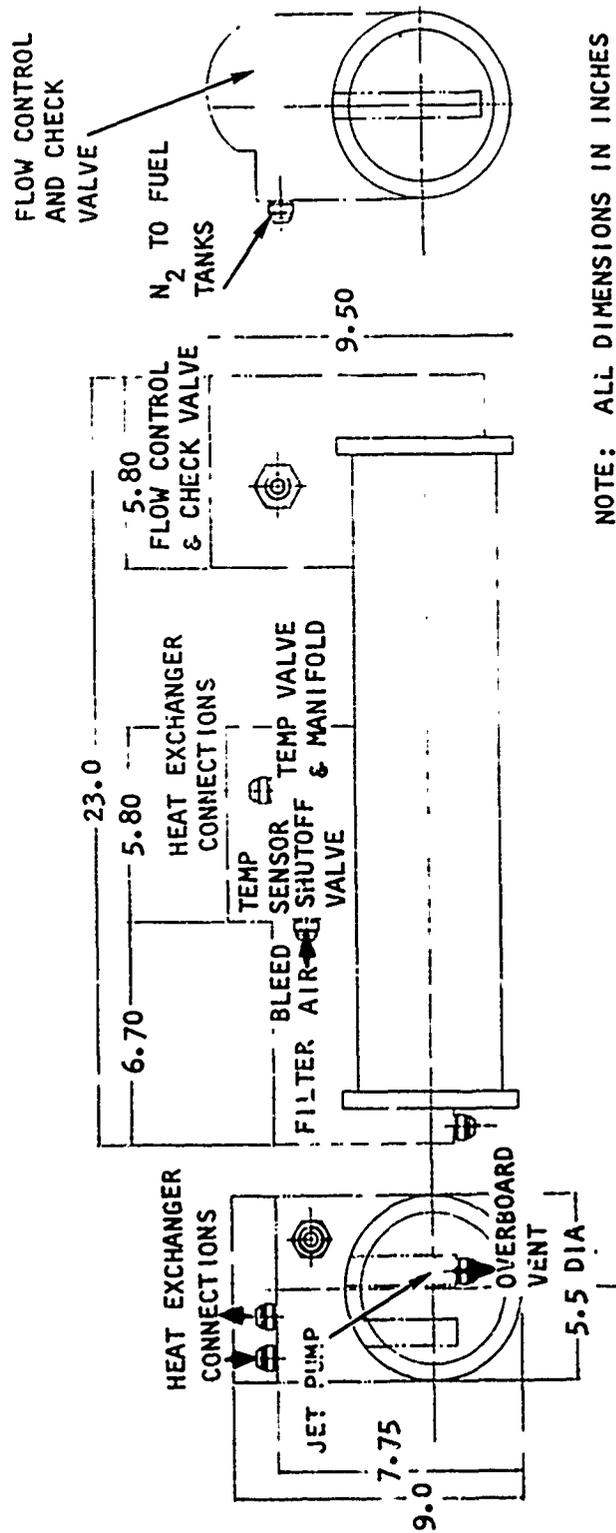
System weight has been held to a minimum consistent with good design and is estimated to be 15 lb (for 9-percent oxygen concentration). System location is approximately at the aircraft center of gravity.

Maintenance requirements have been minimized by designing the ASM with a quick-disconnect clamp to facilitate removal of the fiber insert. The air filter element is removable from the cartridge for servicing. The filter, temperature control components, jet pump, and flow regulator are all installed for easy accessibility.

Because the OV-1D system is very compact, it can be located adjacent to the ECU to minimize interference with access to other components. Access can be achieved through the existing ECU access panel.

Although its purpose is to reduce vulnerability and increase survivability by eliminating explosive gas mixtures in the drop tank ullage, failure of the OV-1D system at any time during the mission will not impair aircraft operation. In addition, the system can be completely isolated by closing the shutoff valve provided for this purpose.

The system does not contain, use, or supply any materials or substances that will increase vulnerability or decrease survivability. The use of common parts for the OV-1D and other aircraft using an IGG system is discussed later in this section.



NOTE: ALL DIMENSIONS IN INCHES

Figure 17. Fuel Inerting System, OV-1D 4.5-Inch-Diameter Module

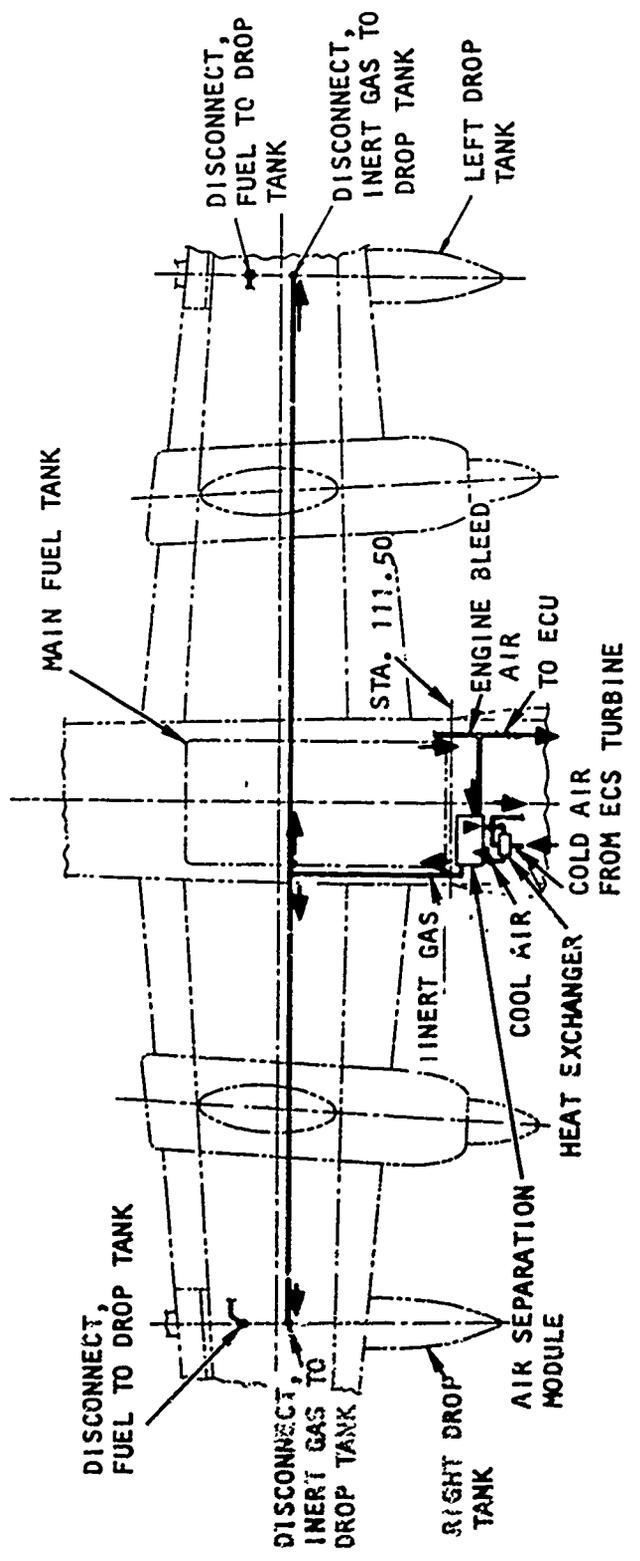


Figure 18. Fuel Inerting System Concept, OV-10 Drop Tanks

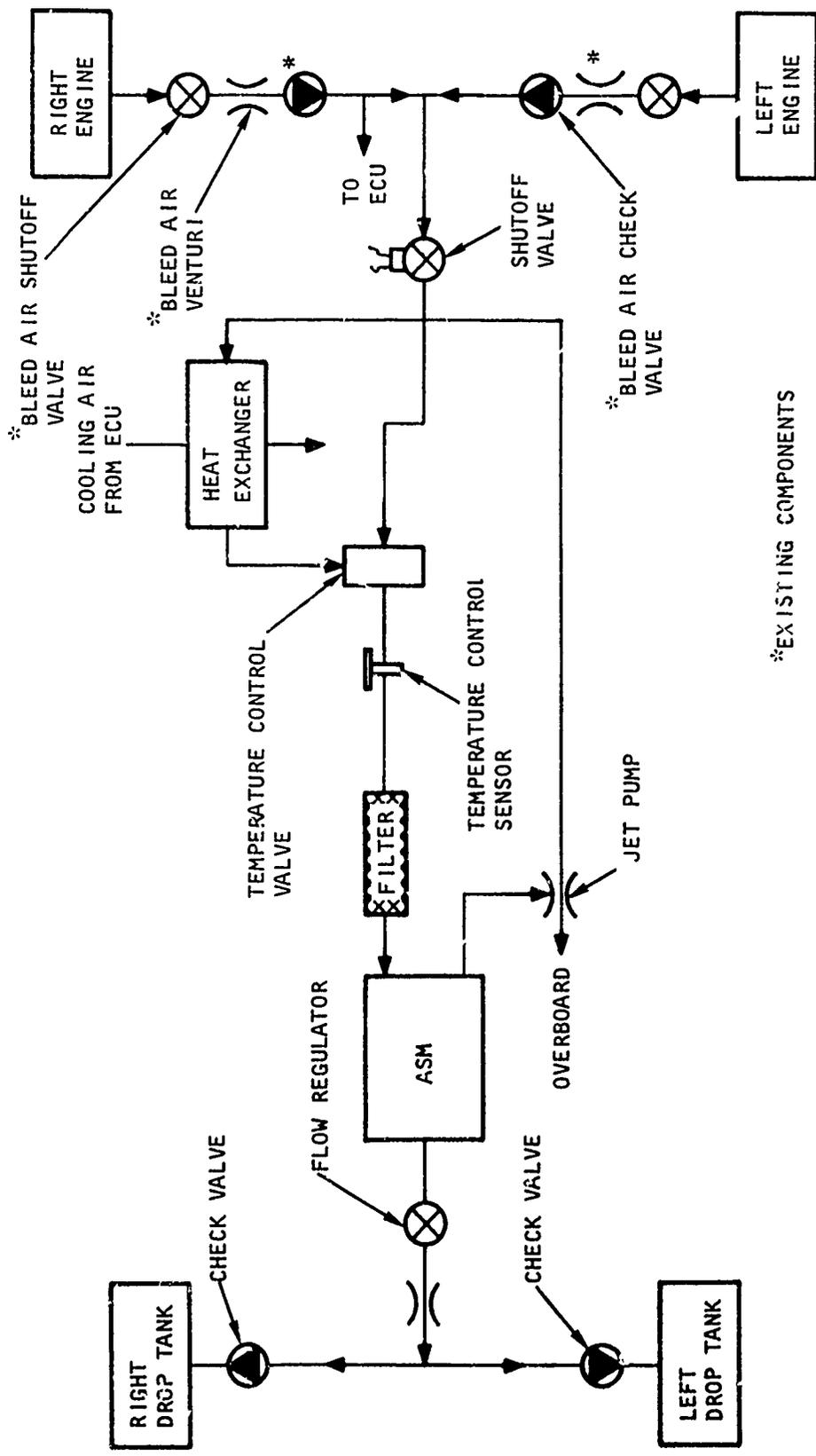


Figure 19. Schematic Diagram of Fuel Tank Inerting System for OV-10 Drop Tanks

SYSTEM OPERATION AND CONTROLS

AH-1G Helicopter Fuel Tank Inerting System

The system is shown schematically in Figure 13. System operation is fully automatic except for the solenoid-operated shutoff valve provided to isolate the system.

The temperature control subsystem is all pneumatic and automatically controls the air supply temperature to the ASM's at $75^{\circ}\text{F} \pm 5^{\circ}$. Cooling air for temperature control purposes is supplied by a small air-to-air heat exchanger, which cools the bleed air with ECU discharge air or ambient air, depending upon ambient temperature conditions and the ECU control mode. On cold days, when the ECU is in a heating mode, cooling of the bleed air can be achieved with ambient airflow from the transmission-driven blower.

Jet pump operation is continuous whenever the bleed air shutoff valve is open. Primary bleed flow is determined by the primary nozzle area, the bleed air pressure, and the bleed air temperature. The induced, or secondary flow, is sufficient to exhaust the permeant flow and to maintain a shell-side pressure of 8.5 psia in the ASM's at the specified mission profile conditions.

Flow regulation is automatic, with each control set to flow 0.08 lb/min of inert gas downstream of each ASM.

CH-47C Helicopter Fuel Tank Inerting System

The system is shown schematically in Figure 16. System operation is fully automatic except for the two solenoid-operated shutoff valves provided to isolate the system. The system is arranged to allow bleed flow from both engines simultaneously, or from either engine; however, depending upon installation losses and flow sharing, it may be desirable to bleed only one engine.

A small turbocompressor package is provided to boost the engine bleed pressure by a factor of two. The compressor power is produced by an expansion turbine, which also provides the cooling air required for ASM inlet temperature control. Small heat exchangers are included in the turbocompressor package.

The temperature control subsystem is all pneumatic and automatically controls the air supply temperature to the ASM to $75^{\circ}\text{F} \pm 5^{\circ}$. Cooling air for temperature control purposes is supplied by a small air-to-air heat exchanger, which cools the compressed bleed air with the cold discharge air from the turbocompressor turbine.

Jet pump operation is continuous whenever one or both of the bleed air shutoff valves are open. Primary bleed flow is determined by the primary nozzle area, bleed air pressure, and bleed air temperature. The

induced, or secondary flow, is sufficient to exhaust the permeant flow and to maintain a shell-side pressure of 8.5 psia in the ASM at the specified mission profile.

Flow regulation is automatic, with the control set to flow 0.65 lb/min of inert gas downstream of the ASM.

OV-1D Drop Tanks Inerting System

The system is shown schematically in Figure 19. System operation is fully automatic except for the solenoid-operated shutoff valve provided to isolate the system. In the OV-1D, both engines are bled and the ASM supply can be taken from the existing bleed manifold.

The temperature control subsystem is all pneumatic and automatically controls the air supply temperature to the ASM to $75^{\circ}\text{F} \pm 5^{\circ}$. Cooling air for temperature control purposes is supplied by a small air-to-air heat exchanger, which cools the bleed air with ECU discharge air or ambient air, depending upon ambient temperature conditions and ECU control mode. On cold days, when the ECU is in a heating mode, cooling of the bleed air can be achieved with ambient air from the ECU cooling air inlet.

Jet pump operation is continuous whenever the bleed air shutoff valve is open. Primary bleed flow is determined by the primary nozzle area, bleed air pressure, and bleed air temperature. The induced, or secondary flow, is sufficient to exhaust the permeant flow and to maintain a shell-side pressure of 8.5 psia in the ASM at the specified mission profile.

IGG Systems Parts Commonality

Although the use of common parts for the AH-1G, CH-47C, and OV-1D systems is a desirable goal, it must be recognized that the different mission profiles dictate a wide range of inert gas and bleed air flows. Therefore, the highest flow requirement (for the CH-47C) results in the use of the largest ASM. This, in turn, imposes weight and fuel consumption penalties on the other systems, if the largest components also are used for the AH-1G and OV-1D systems.

The following components can be considered as candidates for commonality for the AH-1G, CH-47C, and OV-1D missions:

- Temperature control sensor
- Temperature control valve
- Shutoff valve
- Flow regulator (with calibration adjustment)
- Check valves
- Filters
- Jet pumps (with orifice changes)

Although it is not considered feasible to have common ASM's for the specified missions of the AH-1G, CH-47C, and OV-10 aircraft, it is very likely that the size ranges required for these missions would be suitable for other Army helicopters, such as the AAH, UTTAS, and UH-1H.

SECTION 3
TASK 11, DETAILED DESIGN OF GROUND
AND FLIGHT TEST SYSTEMS

Task 11 involved the design of a breadboard IGG system and a flight-worthy fuel tank inerting system for the AH-1G helicopter.

SUBTASK 11(1), BREADBOARD SYSTEM DESIGN

The breadboard IGG system, shown schematically in Figure 20, was designed to operate with 100 psi maximum inlet air pressure. The system will provide a minimum of 0.25 lb/min inert gas flow and incorporates the means to independently vary the inert gas oxygen concentration between 8 and 12 percent by volume. At its design point, the breadboard IGG system produces an inert gas output of 0.25 lb/min with 8 percent oxygen concentration by volume, when operated with a nominal ASM inlet air pressure of 66 psia at 75°F and a shell-side air pressure of 8.5 psia.

The breadboard IGG system was designed to facilitate removal of the fiber insert from the ASM housing by disassembling the quick-disconnect V-band coupling and end plate assembly. It is readily adaptable for use with ground test chambers and with the ground-test UH-1B helicopter located at Fort Eustis.

In the design of the fiber insert shown in Figure 21, the permeant exhaust (purge air outlet) gas originally was intended to flow from the center purge tube through the end port. Testing showed that the shell-side pressure drop was excessive, so an alternate port was provided on the ASM case to provide a reduced pressure drop. (Test results are discussed in detail in Section 4.)

Although the center purge tube was not used to exhaust the permeant gas flow, it performs the function of absorbing the axial compressive stresses due to pressure in the module. Grooves and holes were machined into the purge tube to ensure adequate shear strength between the tube sheets and purge tube. A stress analysis showed that additional supporting members were not required on the outside of the tube bundle.

O-ring seals are provided between the fiber insert tube sheets and the inside of the ASM case. An adjustable seal plate with O-rings is provided to prevent leakage between the purge tube and end plate. A face type O-ring seal also is provided between the V-band flanges.

The breadboard IGG system consists of the following components:

- 1 Air separator module
- 1 Test panel with engraved schematic

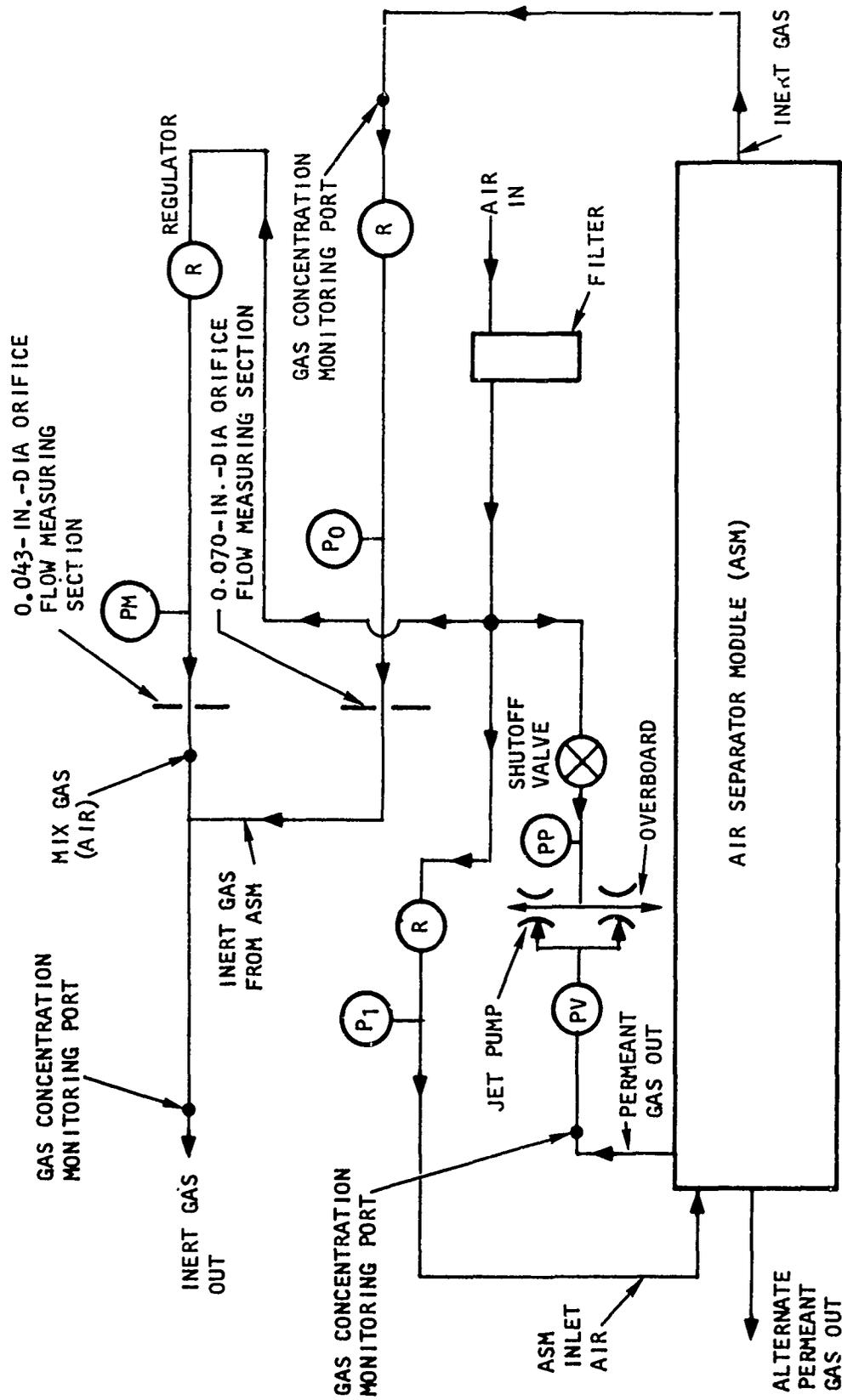


Figure 20. Schematic Diagram of Breadboard IGG System

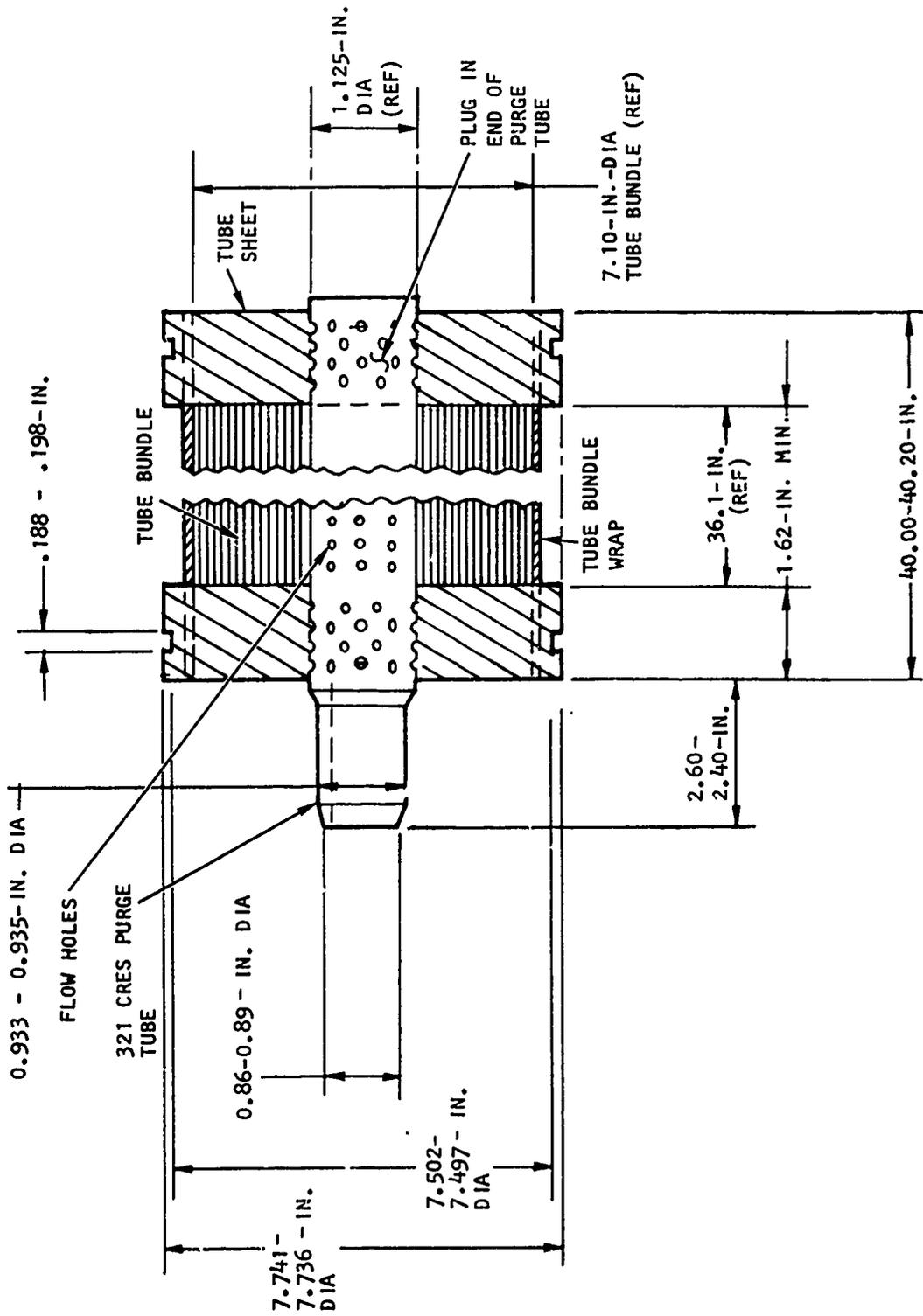


Figure 21. Details of Fiber Insert for ASM

- 1 Frame assembly
- 1 Filter
- 2 Jet pumps
- 1 Flow measuring orifice, 0.070-in. dia
- 1 Flow measuring orifice, 0.043-in. dia
- 3 Pressure regulators
- 1 Shutoff valve
- 1 Relief valve
- 4 Pressure gages
- Miscellaneous tubing and fittings

SUBTASK 11(2), FLIGHTWORTHY FUEL TANK INERTING SYSTEM DESIGN

System Design

The flightworthy fuel tank inerting system for the AH-1G is a dual ASM installation, designed to be located in the pylon area between the main rotor mast and the engine oil tank. By locating the system near the main rotor mast, the effect on the aircraft center of gravity will be minimal. Location of the system in the pylon area also minimized interference with access to other components. Adjacent sources of bleed air and ECU cooling air are available at this location.

The preliminary design for the AH-1G fuel inerting system was based upon preliminary installation information obtained from USAAMRDL-supplied aperture cards, Technical Manual TM55-1520-221, and inspection of an AH-1G helicopter at Palomar, California. To supplement the available data and to define more adequately the selected available space in the pylon area, measurements made on the helicopter were initially used to establish the available space. To ensure adequate clearance from the helicopter structure, the ASM's were connected in parallel, but were physically positioned to provide the required clearance.

Prior to initiation of the detailed design of the flightworthy inerting system, the following additional drawings were requested from USAAMRDL and were used for the packaging and installation design of the fuel tank inerting system in the AH-1G helicopter.

<u>Drawing No.</u>	<u>Title</u>
209-470-002	General Arrangement
209-060-001	Power Plant Installation
209-060-500	Oil System Installation
209-060-807	Aft Pylon Assembly
209-060-811	Center Pylon Assembly
209-060-880	Cowling Support Assembly
209-060-900	Forward Firewall Assembly
209-060-902	Upper Horizontal Firewall Assembly
209-200-005	Pylon Installation

To supplement the information given on these drawings, some dimensions were determined by scaling.

The detailed design of the AH-1G flightworthy inerting system is shown in Figure 22. With the space availability in the pylon area more clearly defined by the additional drawings, it was possible to design the system with the ASM's placed physically in parallel.

The following important design features are incorporated in the AH-1G flightworthy system:

- (a) The system is located between stations 213.81 and 227.86 above water line 100 in the pylon area.
- (b) Installation and access is through the existing pylon access door.
- (c) The filter is readily accessible for servicing and has a removable element.
- (d) All aircraft pneumatic interfaces are located on a lower panel integral with the system.
- (e) Common ASM's are used for both right- and left-hand locations. To facilitate this commonality, an additional inlet port is provided.
- (f) Each ASM has a quick-disconnect clamp to facilitate removal of the fiber insert following removal of the system from the helicopter.

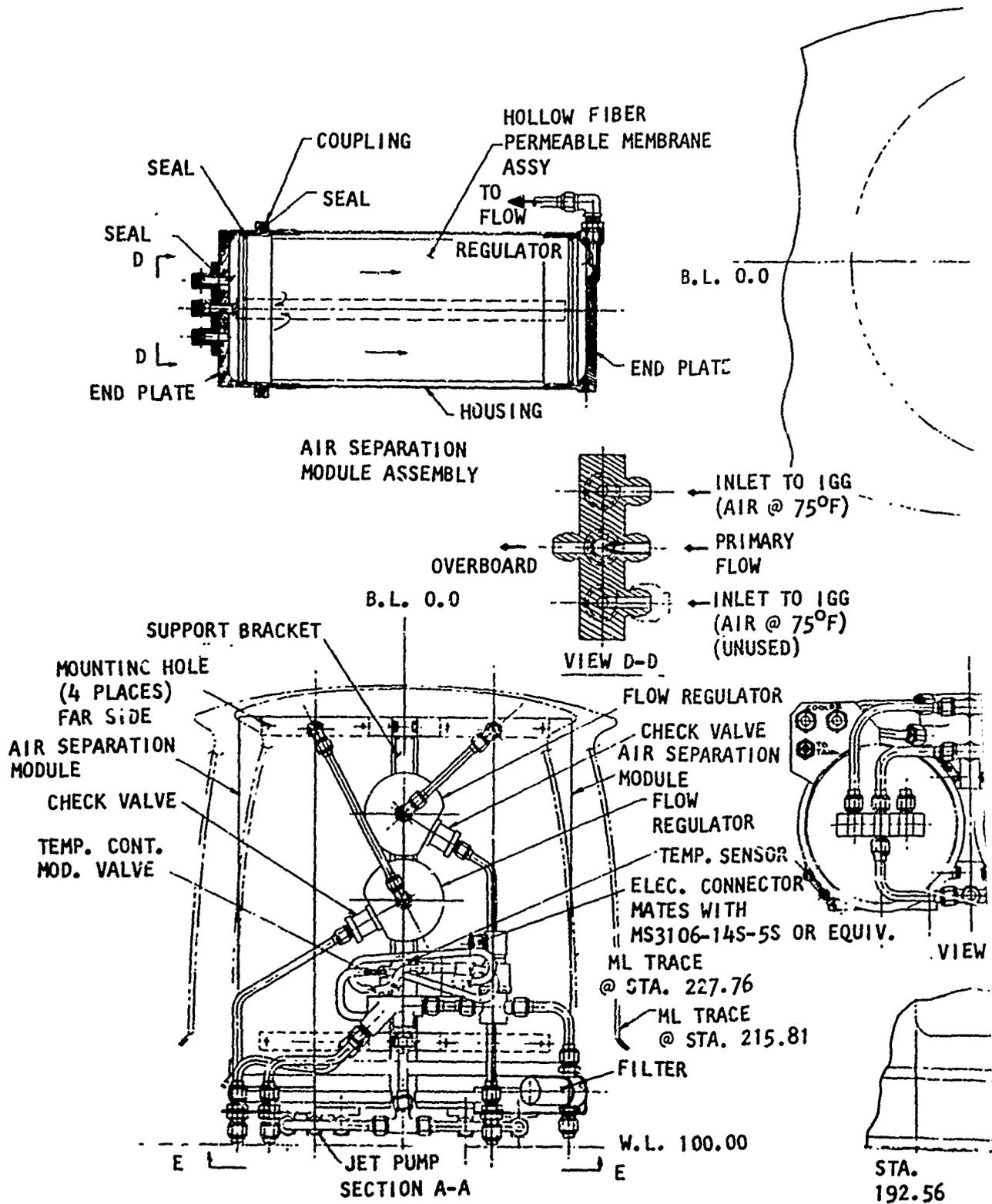
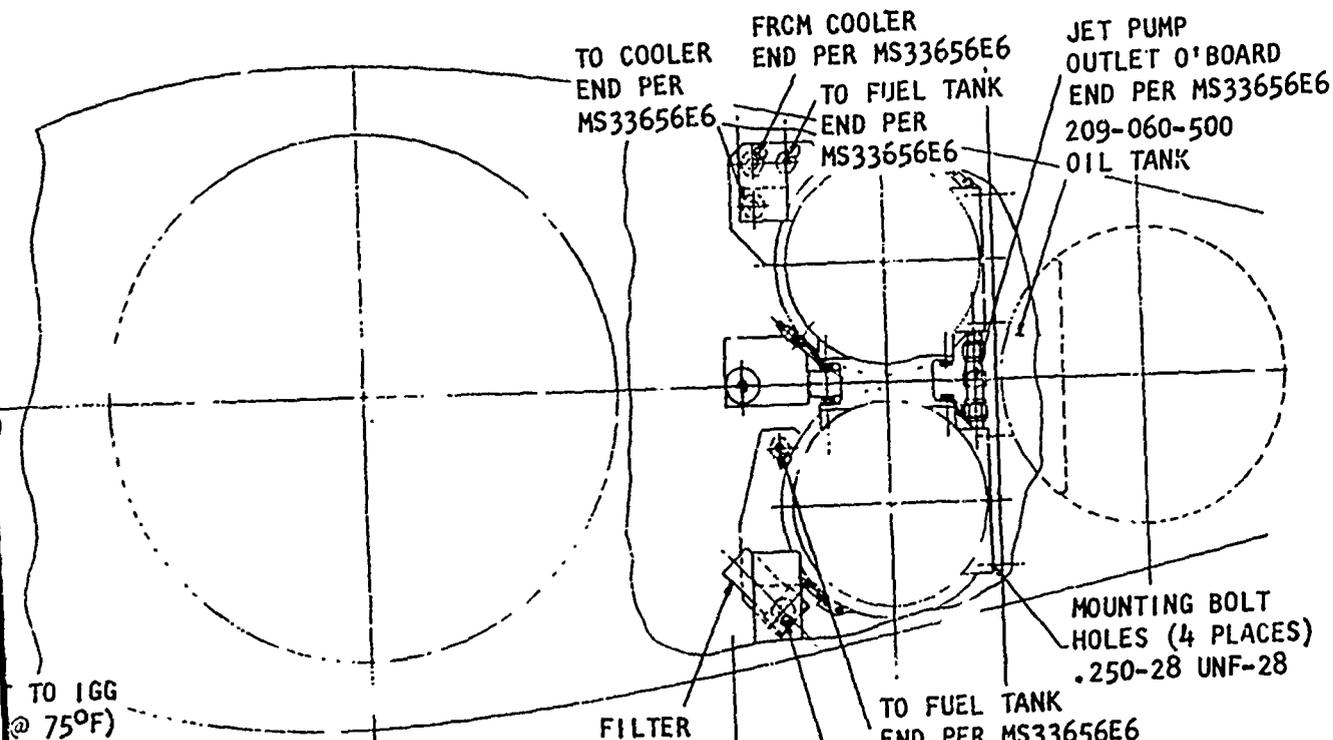


Figure 22. Fuel Inerting System Installation, AH-1G



PYLON SECTION B-B
(PLUMBING, ETC. OMITTED
FOR CLARITY)

BLEED AIR FROM ENGINE
END PER MS33656E6

209-060-811
CENTER FAIRING

PYLON
ACCESS
DOOR

48

2

- (g) Manifolds and integral bosses are provided to minimize the number of joints and potential leaks.
- (h) All controls, sensors, and valves are mounted directly to the ASM's.
- (i) The entire system mounts to the helicopter structure with eight 1/4-in. bolts.

As shown in Figure 23, the AH-1G flightworthy fuel tank inerting system differs slightly from the preliminary design, in that the filter is located upstream of the system shutoff valve.

System Penalty Assessment

The penalties for the AH-1G flightworthy fuel tank inerting system are listed in Table 4. These penalties are based on an inert gas flow requirement of 0.16 lb/min, with a 9-percent oxygen concentration by volume. The AH-1G helicopter mission profile is defined as a 3000-fpm rate of descent on a 75°F day with 140-gal ullage in accordance with preliminary design requirements. Substantial penalty reductions can be provided with full protection at lesser rates of descent, or if tests show a higher oxygen concentration (i.e., greater than 9 percent) is sufficient.

TABLE 4.

AH-1G FLIGHTWORTHY FUEL TANK
INERTING SYSTEM PENALTIES

Parameter	Penalty
System weight	50 lb
Bleed airflow	0.90 lb/min
Turbine inlet temperature rise due to bleed air extraction	7.1°F
Power loss due to bleed air extraction	5.45 hp
Lift loss due to power loss	28.8 lb
Increase in fuel consumption due to bleed air extraction	2.20 lb/hr
Increase in fuel consumption due to weight increase	3.85 lb/hr
Total increase in fuel consumption	6.04 lb/hr

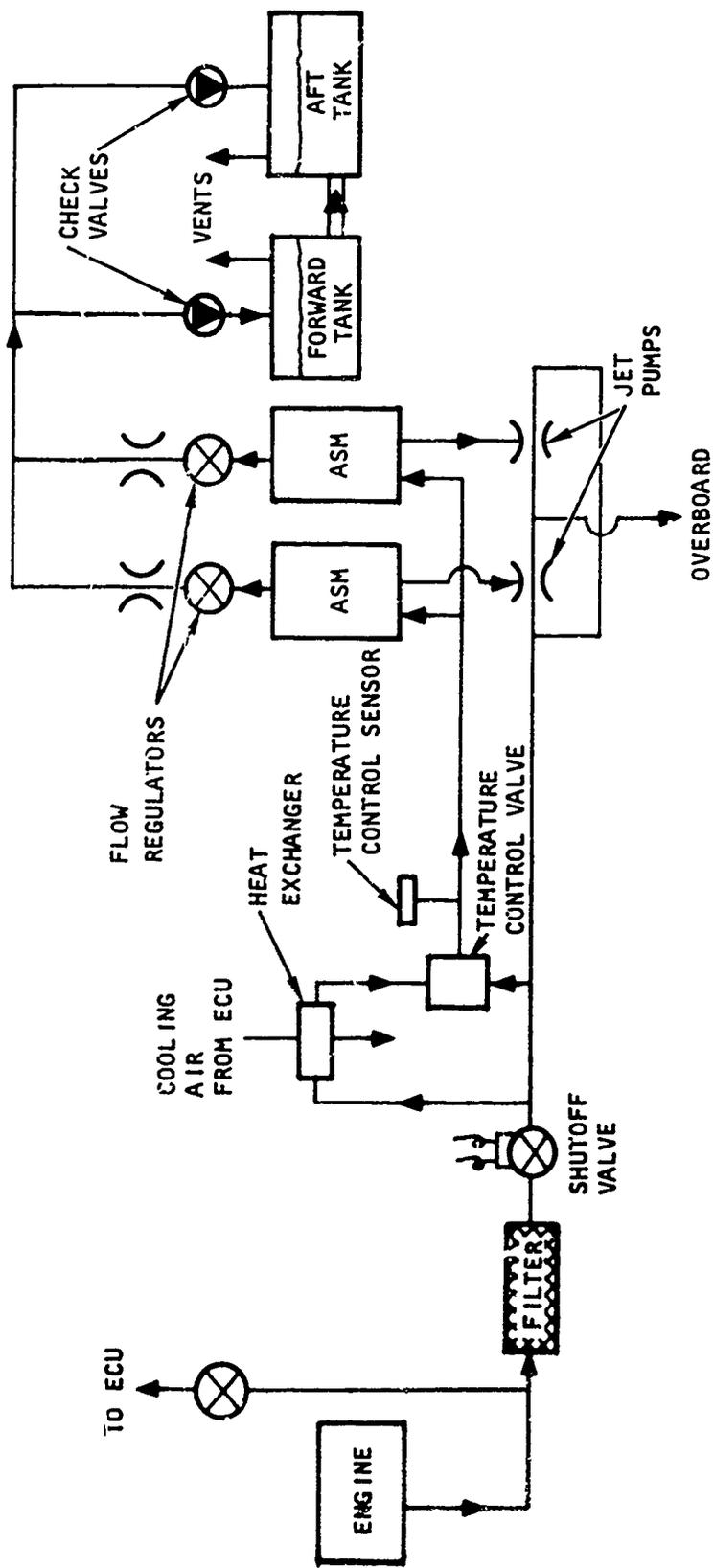


Figure 23. Schematic Diagram of AH-1G Fuel Tank Inerting System

SECTION 4

TASK III, BREADBOARD SYSTEM FABRICATION AND TEST

Task III involved fabrication, test, and delivery to the Government of one ground-test breadboard IGG system.

SYSTEM FABRICATION

Following USAAMRD L approval of the detailed design generated in Task II(1), a breadboard IGG system suitable for ground test was fabricated. The breadboard system assembled and tested by AiResearch as part of this subtask is shown in Figures 24, 25, and 26.

The fiber insert for the ASM was fabricated under an AiResearch sub-contract by Dow Chemical USA, Western Division Laboratory, to an AiResearch specification.

AiResearch-supplied components for the ASM include the case with appropriate flanges, the center purge tube and end plates, as well as O-rings and the V-band coupling. The ASM was assembled and initially tested by Dow Chemical for compliance with AiResearch specification requirements.

All parts for the breadboard IGG system frame and test panel were fabricated by AiResearch. The pressure regulators, gages, relief valve, shutoff valve, and jet pumps were laboratory-type equipment supplied by AiResearch.

As required by Task III, the ASM and breadboard IGG system were tested to ensure compliance with performance requirements established in Task II(1).

All performance requirements were satisfactorily met. In initial testing of the ASM, an excessive shell-side pressure drop was experienced with the permeant gas flowing radially inward and exhausting through the end of the center purge tube. Later testing showed that a satisfactory pressure drop could be obtained with the permeant gas flowing radially outward and exhausting through a port located on the outside of the case. Test results for the radial inward and outward permeant gas flow configurations are shown in Figure 27. The inert gas output achieved using the radial outward flow of the permeant gas showed close agreement with the design performance.

TESTING

Testing at AiResearch was conducted in two phases: Phase 1, performance mapping and evaluation of the ASM; and Phase 2, breadboard IGG system operation and calibration.

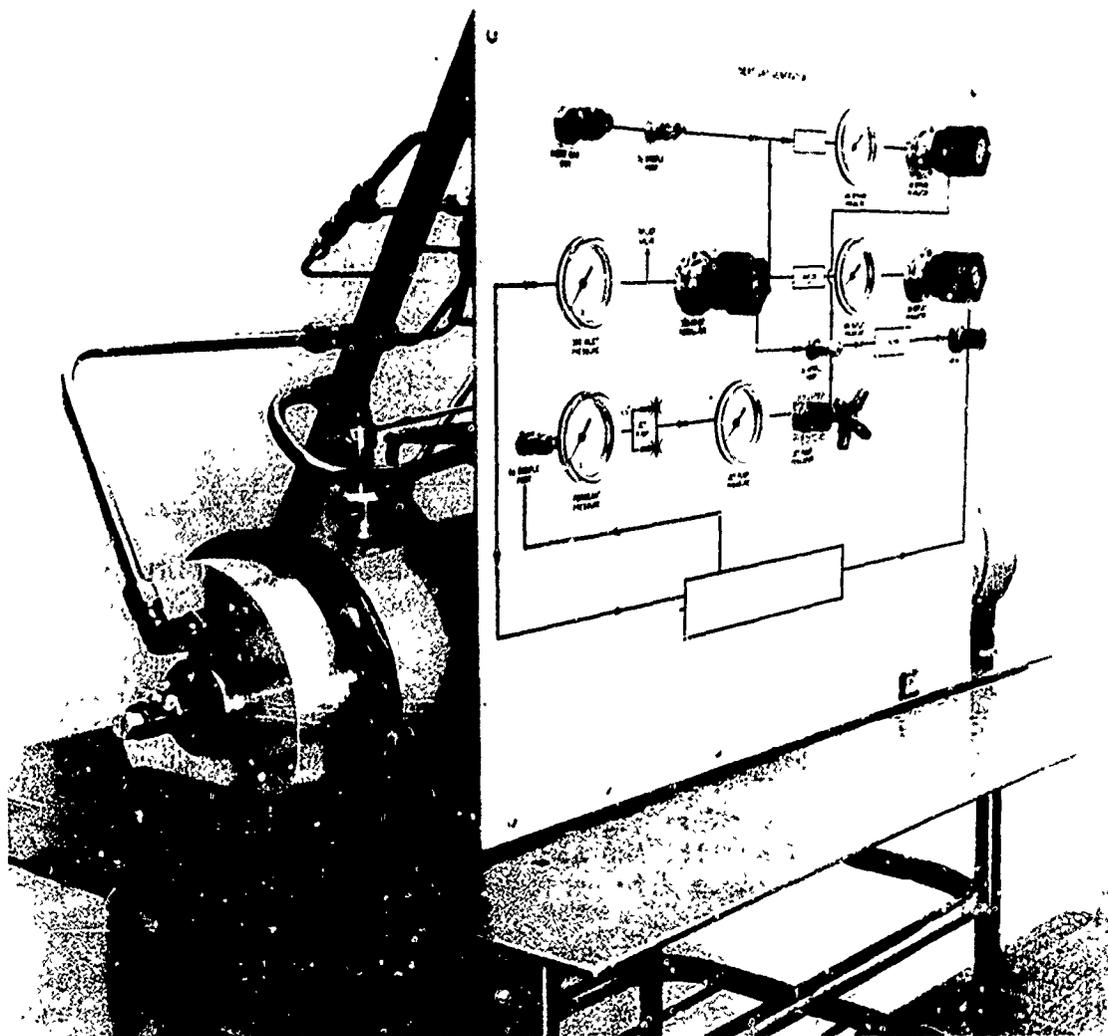


Figure 24. View of Breadboard IGG System

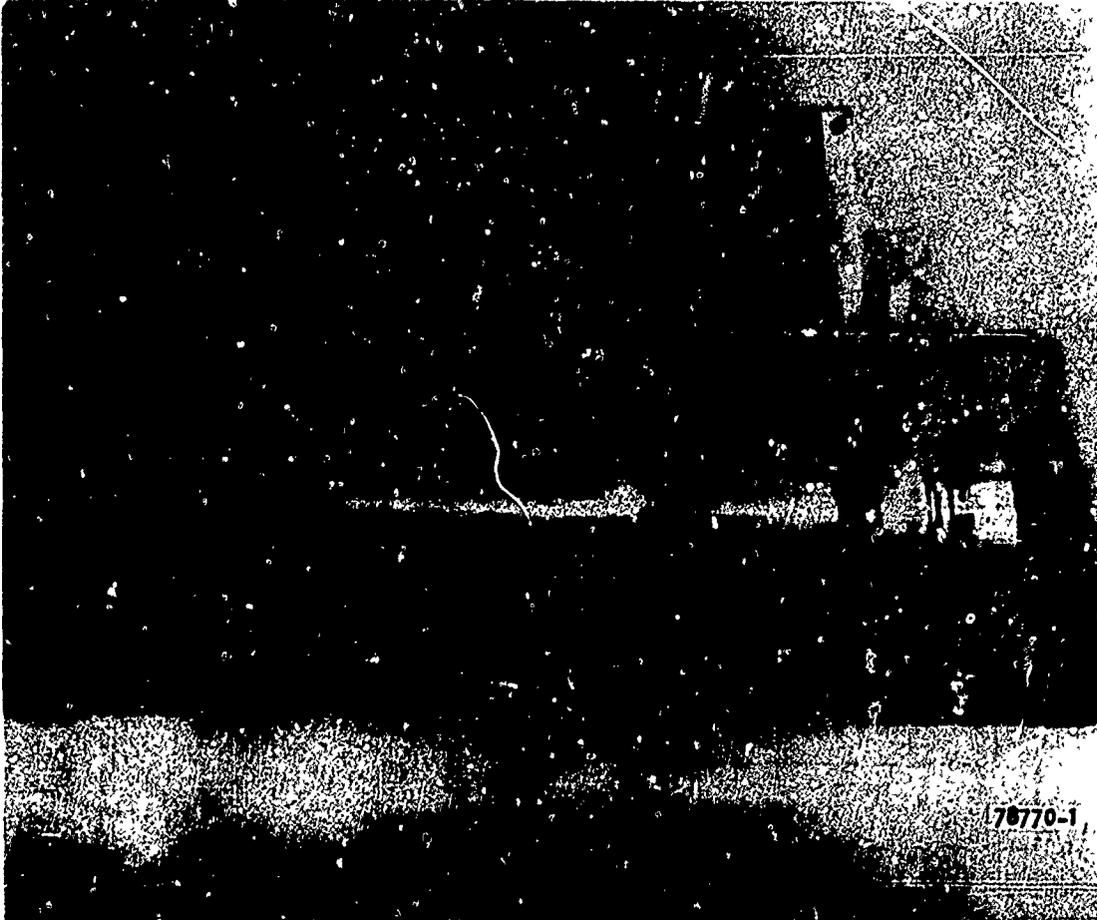


Figure 26. Rear View of Breadboard IGG System

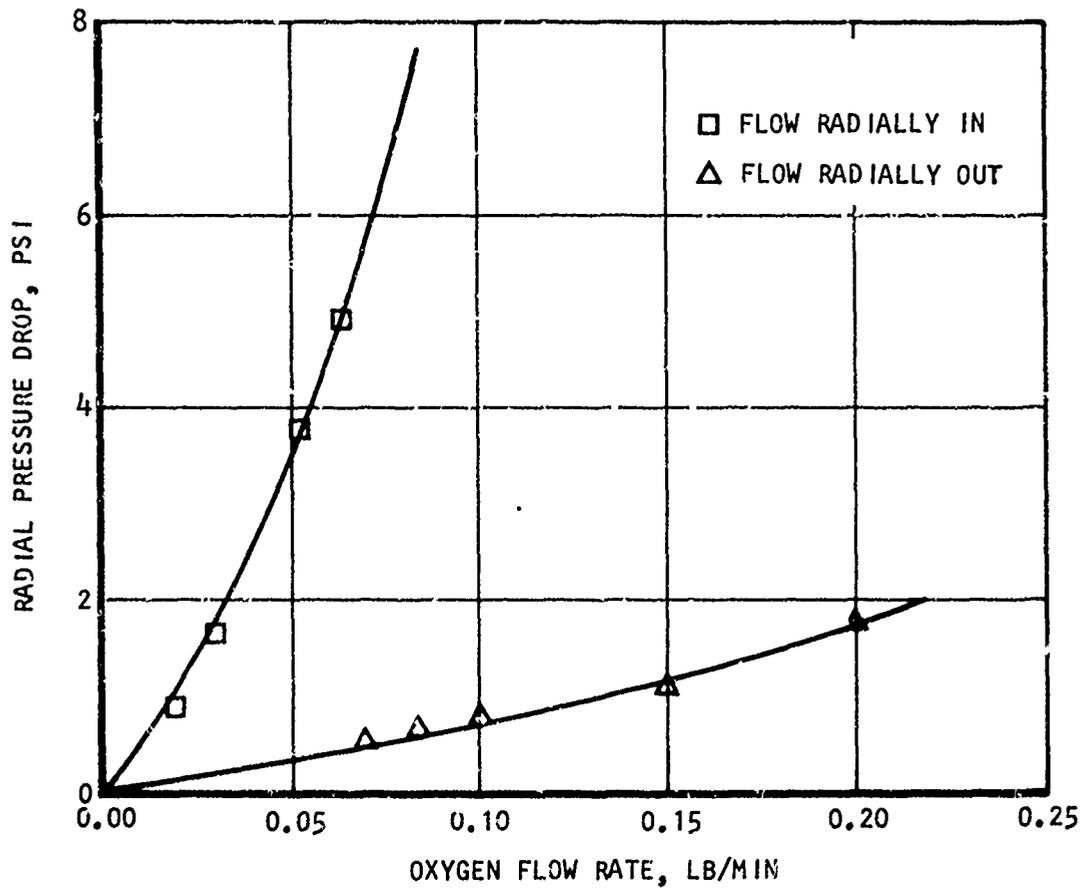


Figure 27. Pressure Drop Comparison of Radial Inward Flow and Radial Outward Flow Methods of Permeant Gas Exhaust

Test Program Phase 1, Performance Mapping and Evaluation of ASM

Although airborne IGG systems, and to a somewhat lesser extent breadboard IGG systems, depend upon proper selection and performance of components for pressure control, flow control, temperature control, etc., the basic component of the IGG system is the ASM. The breadboard IGG test system, designed to deliver a minimum of 0.25 lb/min of inert gas flow and to provide a means for varying the inert gas concentration between 8 and 12 percent by volume, utilizes a permeable membrane type of ASM to produce inert gas from pressurized air. The first phase in evaluating breadboard IGG system performance was performance mapping and evaluation of the ASM.

Upon completion of its manufacture, the ASM was tested to establish its integrity and to determine the apparent permeability coefficients for both oxygen and nitrogen gases. These test objectives were accomplished by eliminating all but the test gas from the unit so that the measured pressures were the driving potential for permeant gas transfer. The solution of the permeable gas transfer equation to calculate the permeability coefficient is as follows:

$$TP = \frac{Q \Delta X}{A \Delta P} \quad (\text{from Reference 1})$$

where TP = apparent permeability coefficient

\dot{Q} = gas permeation rate

ΔX = membrane wall thickness

A = log-mean membrane surface area

ΔP = transmembrane pressure differential

Calculation of the apparent permeability coefficient, TP, for both oxygen and nitrogen requires a knowledge of the physical characteristics of the test unit and measurement of test pressures and permeation rates at a particular temperature. For the ASM developed in this program, the characteristics and measured flux shown in Table 5 resulted in calculated apparent permeability coefficients of 20.28×10^{-10} and 5.10×10^{-10} (cm³/sec at NTP) (cm)/(cm²) (cm Hg) for oxygen and nitrogen, respectively, at 20°C.

1. Manatt, Scott A., Appendix A of FEASIBILITY STUDY AND DEMONSTRATION OF NITROGEN GENERATION FOR FUEL TANK INERTING, DOT Report FAA-RD-74-112, U.S. Department of Transportation, Washington, DC, June 1974.

TABLE 5.
AIR SEPARATOR MODULE PHYSICAL CHARACTERISTICS AND FLUX MEASUREMENTS

Parameter	Value
Total no. of fibers	4.28×10^6
No. of active fibers	3.93×10^6 (minimum)
Active fiber length	36.0 in.
Fiber inside diameter	50 μm
Fiber wall thickness	7 μm
Measured oxygen flux	5826 std $\text{cm}^3/\text{min}/\text{psid}$
Measured nitrogen flux	1465 std $\text{cm}^3/\text{min}/\text{psid}$

The oxygen-to-nitrogen permeability coefficient ratio is 3.98. At the same test temperature, early development tests conducted under previous contracts indicated that, in the absence of all leak paths, a permeability coefficient ratio of about 4.29 is obtainable. Therefore, about 2.5 percent of the observed oxygen flux can be attributed to leakage paths, such as fiber flaws, tube sheet porosity, and external leakage. Because leakage is away from the nitrogen-enriched, high-pressure inert gas product, small leakage values have little effect beyond an imperceptible increase in source airflow.

To map and evaluate IGG performance, the test setup shown schematically in Figure 28 was constructed. This setup permitted the generator inlet pressure, permeant gas pressure, and inert gas flow rate to be independently controlled. Test procedures were prepared to establish the permeant gas pressure at 8.5 psia (12.65-in. Hg vacuum) and to set the transmembrane ΔP at 75, 60, 45, and 30 psid. Flow rates were varied to achieve oxygen concentrations of 8, 9, 10, and 12 percent (by volume), as well as to establish a near-zero inert gas flow concentration (200 std cm^3/min used by the oxygen concentration meter). Data, including generator inflow and outflow rates, were recorded after the oxygen concentration had stabilized.

A second series of tests was performed with an ambient exhaust gas pressure (no jet pump, and the capped port of the permeant gas flow tube open to ambient atmosphere). During these tests, generator inlet pressures were maintained at the same nominal values that resulted from each of the four controlled transmembrane pressures set previously. Test results for both permeant exhaust gas pressures are presented in Table 6.

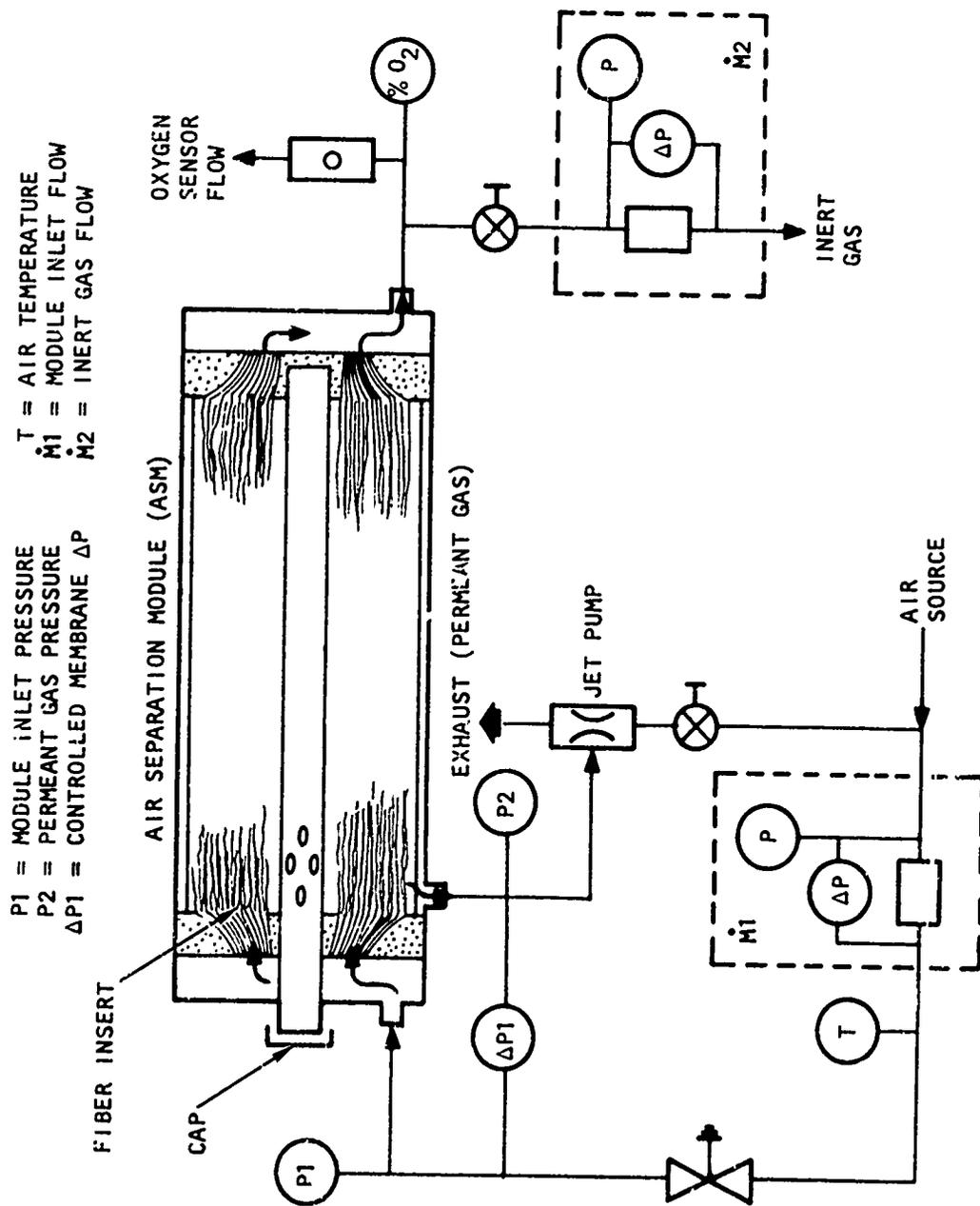


Figure 28. ASM Test Schematic Diagram

TABLE '6.

AIR SEPARATOR MODULE PERFORMANCE

Module Inlet Pressure (P1), psig	Controlled Transmembrane Pressure Drop ($\Delta P1$), psid	Air Temp (T), °F	Permeant Gas Press (P2), in. Hg vac	Module Inlet Flow (M1), lb/min	Inert Gas Flow (M2), lb/min	Inert Gas O ₂ Concentration (%O ₂), percent by volume
69.3	75	72.4	11.2	0.322	*	1.0
69.5	75	74.0	10.3	0.698	0.345	8.0
70.2	75	74.0	10.0	0.760	0.400	9.0
70.4	75	74.0	9.98	0.819	0.455	10.0
70.4	75	75.5	9.8	0.996	0.606	12.0
53.5	60	74.3	12.8	0.257	*	1.0
53.7	60	74.5	12.3	0.516	0.246	8.0
53.5	60	74.5	12.3	0.570	0.300	9.0
53.5	60	74.5	12.3	0.662	0.354	10.0
52.9	60	74.5	12.2	0.805	0.494	12.0
38.6	45	74.5	12.8	0.175	*	1.0
38.6	45	74.5	12.8	0.355	0.157	8.0
38.6	45	74.5	12.8	0.430	0.208	9.0
38.3	45	74.5	12.6	0.443	0.251	10.0
38.6	45	74.3	12.6	0.550	0.344	12.0
23.5	30	74.3	12.6	<0.130	*	1.3
23.5	30	74.0	12.6	0.190	0.078	8.0
23.5	30	74.0	12.6	0.230	0.108	9.0
23.5	30	74.0	12.6	0.257	0.135	10.0
23.6	30	73.5	12.6	0.310	0.187	12.0
70.2	--	73.5	--	0.372	*	1.0
70.2	--	73.5	--	0.585	0.263	8.0
70.2	--	73.5	--	0.643	0.314	9.0
70.2	--	71.0	--	0.705	0.360	10.0
70.2	--	70.0	--	0.838	0.580	12.0
53.5	--	70.0	--	0.200	*	1.0
53.5	--	70.0	--	0.399	0.180	8.0
53.5	--	70.0	--	0.430	0.212	9.0
53.5	--	70.0	--	0.468	0.250	10.0
53.5	--	70.0	--	0.592	0.342	12.0
38.5	--	70.0	--	<0.130	*	1.0
38.5	--	70.0	--	0.259	0.093	8.0
38.5	--	70.0	--	0.287	0.110	9.0
38.5	--	70.0	--	0.311	0.140	10.0
38.5	--	70.0	--	0.364	0.198	12.0
23.5	--	70.0	--	<0.130	*	1.2
23.5	--	70.0	--	0.140	0.029	8.0
23.5	--	70.0	--	0.153	0.031	9.0
23.5	--	70.0	--	0.163	0.045	10.0
23.5	--	70.2	--	0.175	0.071	12.0

*Zero except for O₂ sensor flow of 200 cm³/min ($\approx 5.2 \times 10^{-4}$ lb/min)

Inert gas oxygen concentration as a function of inert gas flow at representative ASM inlet pressures is shown for 8.5 and 14.7 psia exhaust pressures in Figures 29 and 30, respectively. The pressures required to establish the desired inert gas flow rates for various concentrations can be determined for these exhaust pressures by reference to Figures 31 and 32. As can be seen by reference to Table 6 and Figure 29, the minimum specified inert gas concentration of 8 percent can be met at a generator inlet pressure of about 55 psig. Table 6 test results also indicate that the generator has the ultimate capacity to reduce the inert gas oxygen concentration to about 1 percent.

The air separator module fabricated and tested under this contract is the first such unit in which a jet pump was used in lieu of wash flow to reduce the shell-side oxygen concentration. To check ASM performance and the accuracy of the mathematical model, sample data from Table 6 were used as an input to a digital computer program for designing and predicting performance of hollow fiber permeable membrane types of ASM's.

As a prerequisite to using the mathematical model for the design of subsequent flight hardware, physical characteristic data, along with measured values of permeability coefficients and test pressure are utilized as input parameters to evaluate the ability of the model to predict laboratory performance. Figure 33 shows the results of this analysis for the nominal 55-psig inlet pressure, when combined with test results plotted on Figure 29.

As can be seen by the similarity of analytical predictions to actual laboratory test data, both absolute values of oxygen concentration and the general trends are in close agreement. At the 9-percent level, the predicted flows are over 93 percent of the measured flows, when the reduced permeant exhaust gas pressure of the jet pump is used, and about 95 percent of the measured flows at ambient permeant exhaust gas pressures. More importantly, at the measured flows the oxygen concentration is within 0.5 percent of predicted values. By making slight adjustments in design on the basis of these data, even closer agreement between analytical predictions and ASM performance can be anticipated for future designs.

Operating Life Limits

The 8.5-psia exhaust pressure results in a transmembrane ΔP of 61.2 psid (i.e., $55.0 + 14.7 - 8.5$). To avoid performance degradation due to overstressing the fibers, careful consideration and control of the transmembrane pressure has been practiced in the AirResearch test program and is recommended during subsequent Army testing. During a previous development test program conducted under Federal Aviation Administration/U.S. Air Force Aero Propulsion Laboratory sponsorship, small test samples were used to evaluate the onset of structural failure in 50- μm by 7- μm methylpentene hollow filers under hoop stress loading. Figure 34, which is based on test sample results, shows the maximum transmembrane pressures as a function of operating temperature for the onset of structural failures at 3000

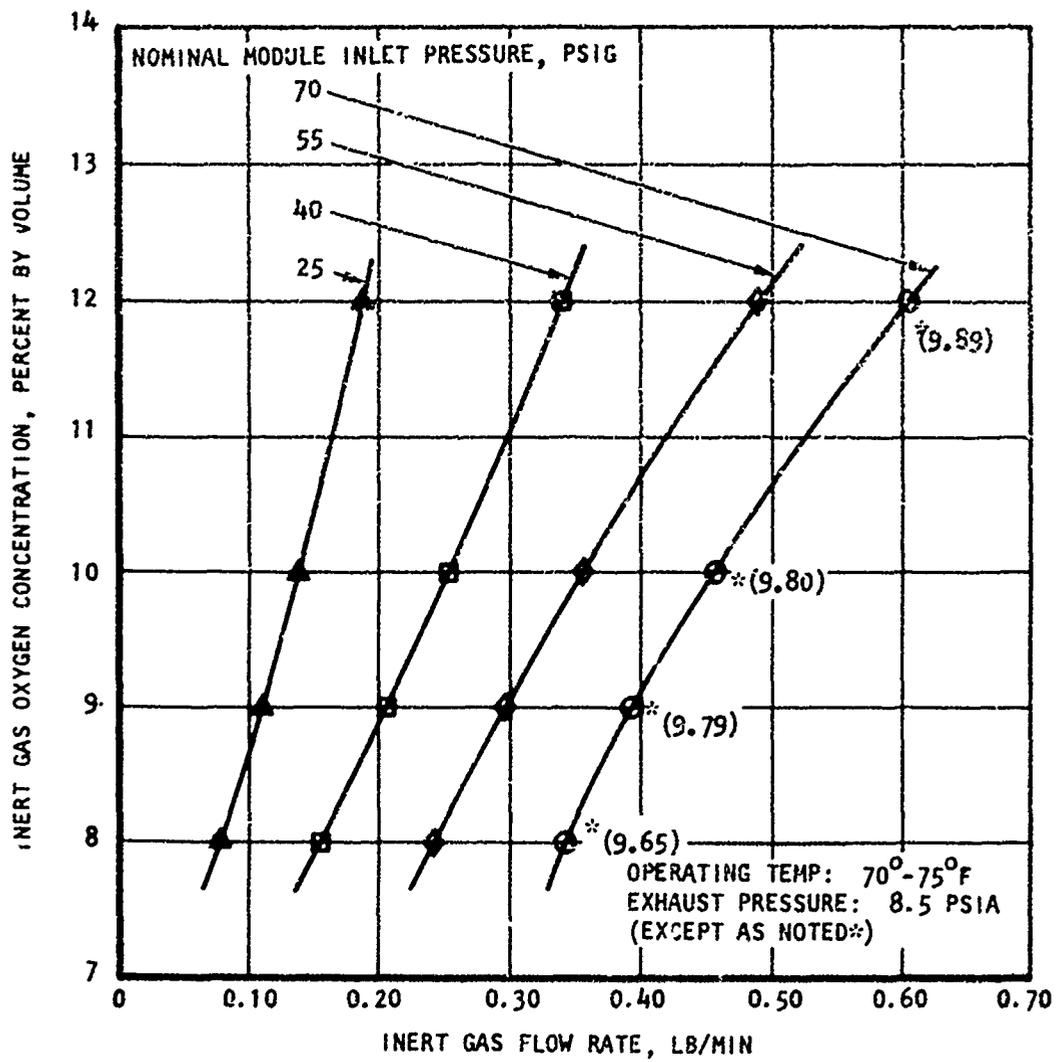


Figure 29. Reduced Permeant Exhaust Gas Pressure Performance

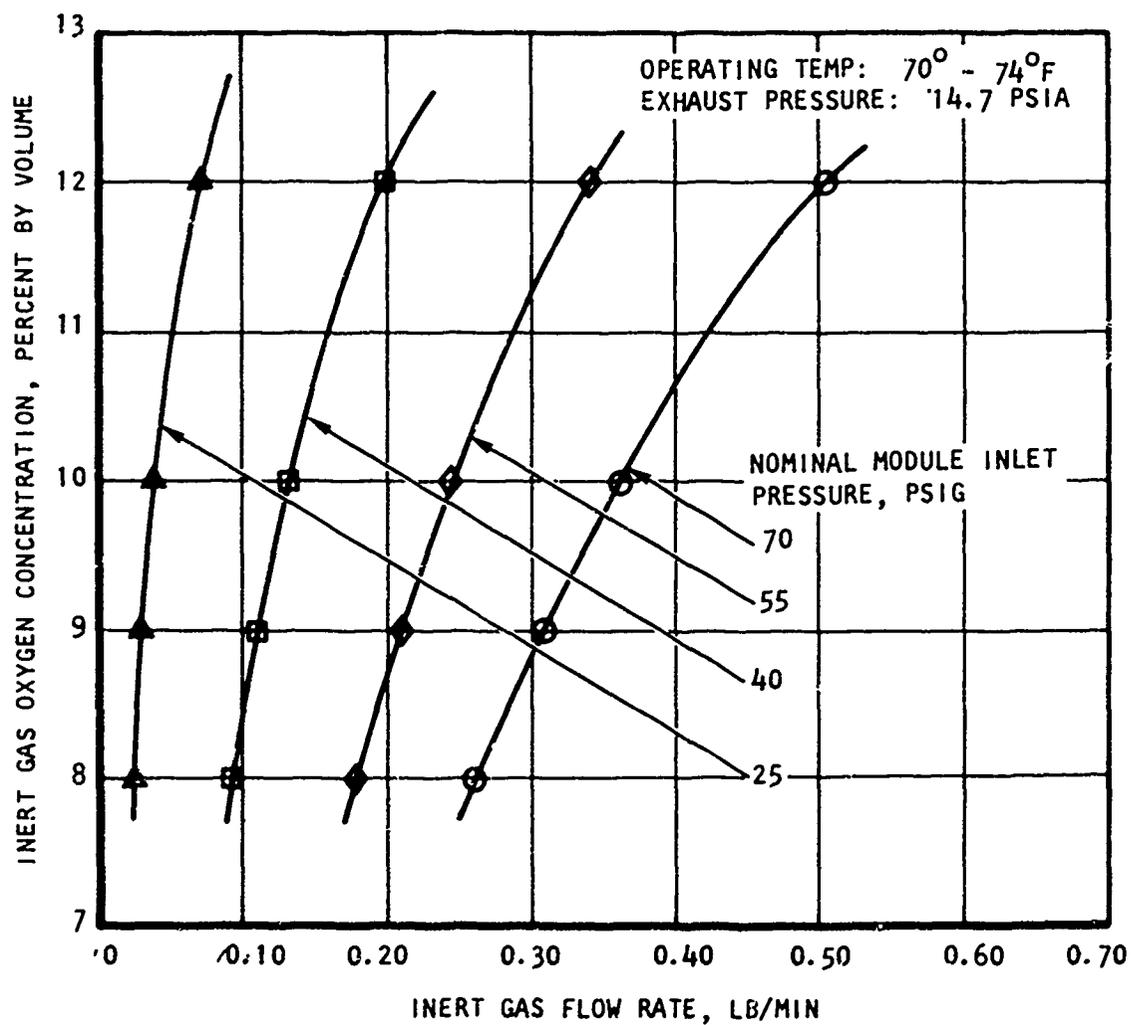


Figure 30. Ambient Permeant Exhaust Gas Pressure Performance

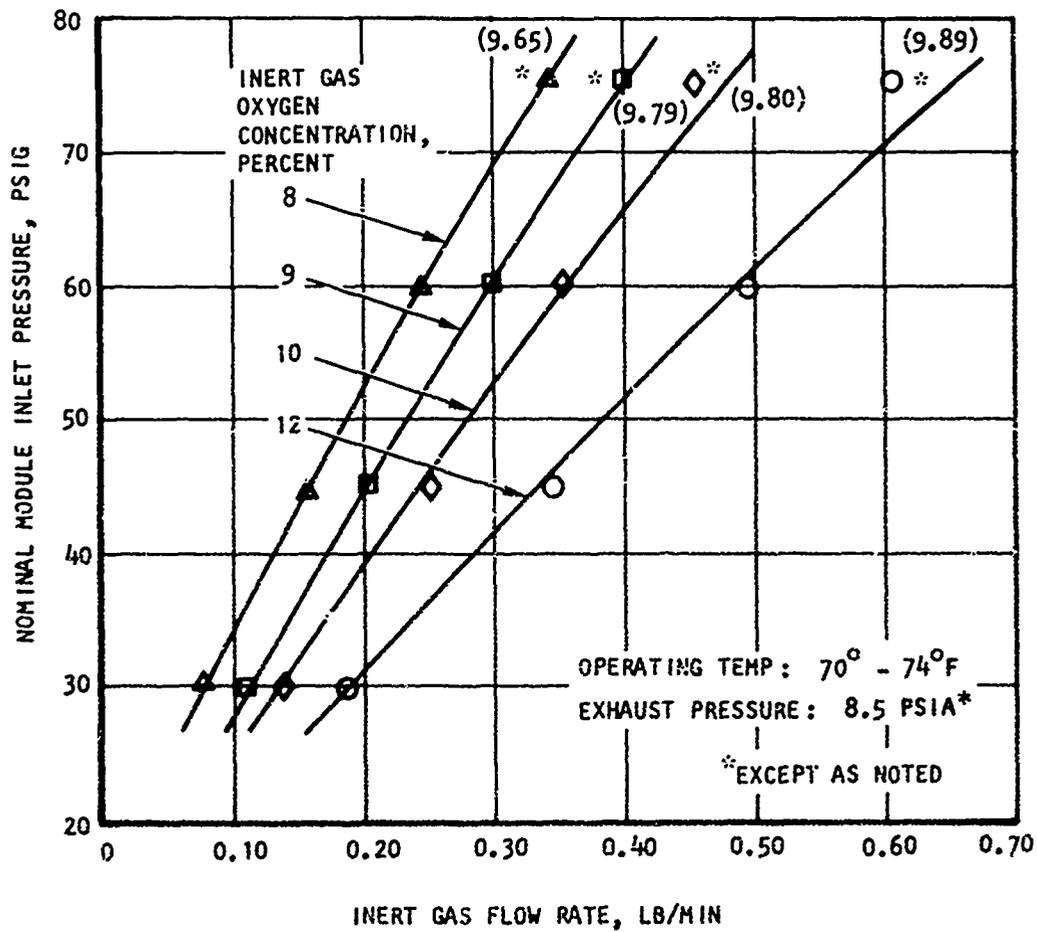


Figure 31. Inlet Pressure Requirement with Reduced Permeant Exhaust Gas Pressure

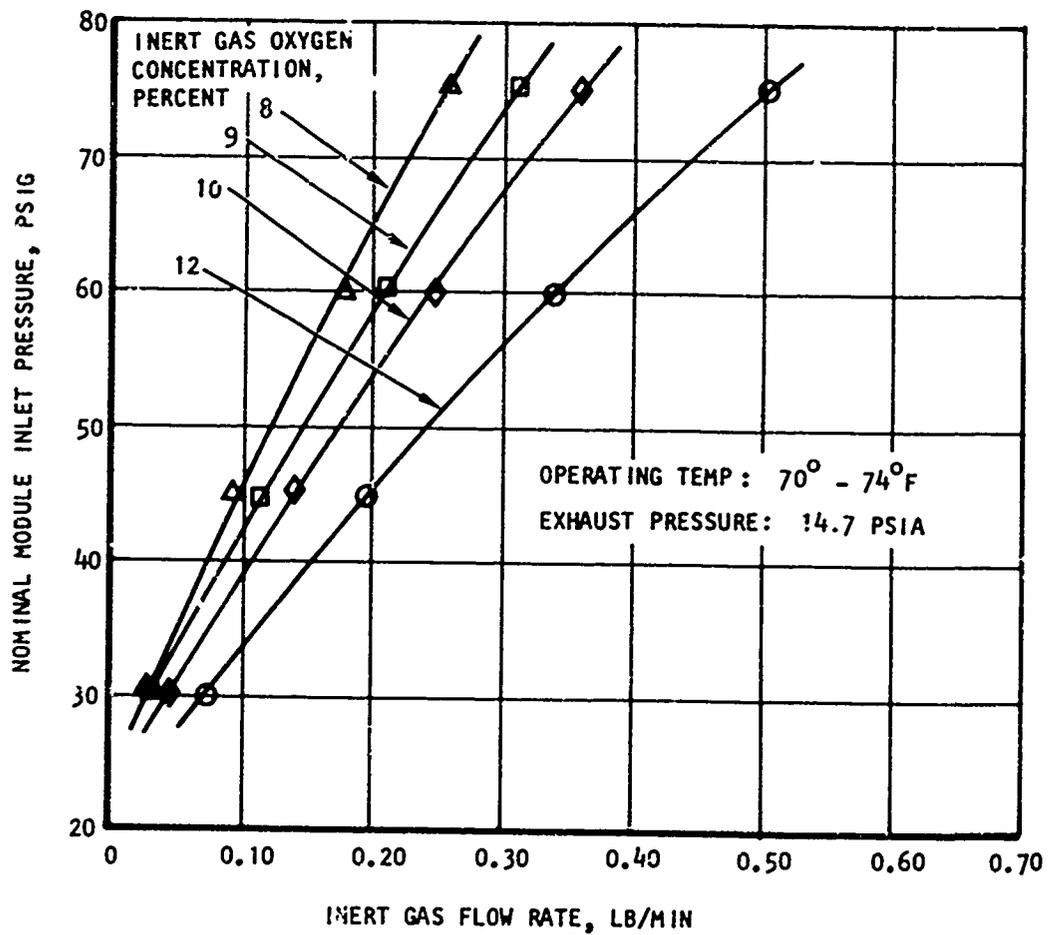


Figure 32. Inlet Pressure Requirements with Ambient Permeant Exhaust Gas Pressure

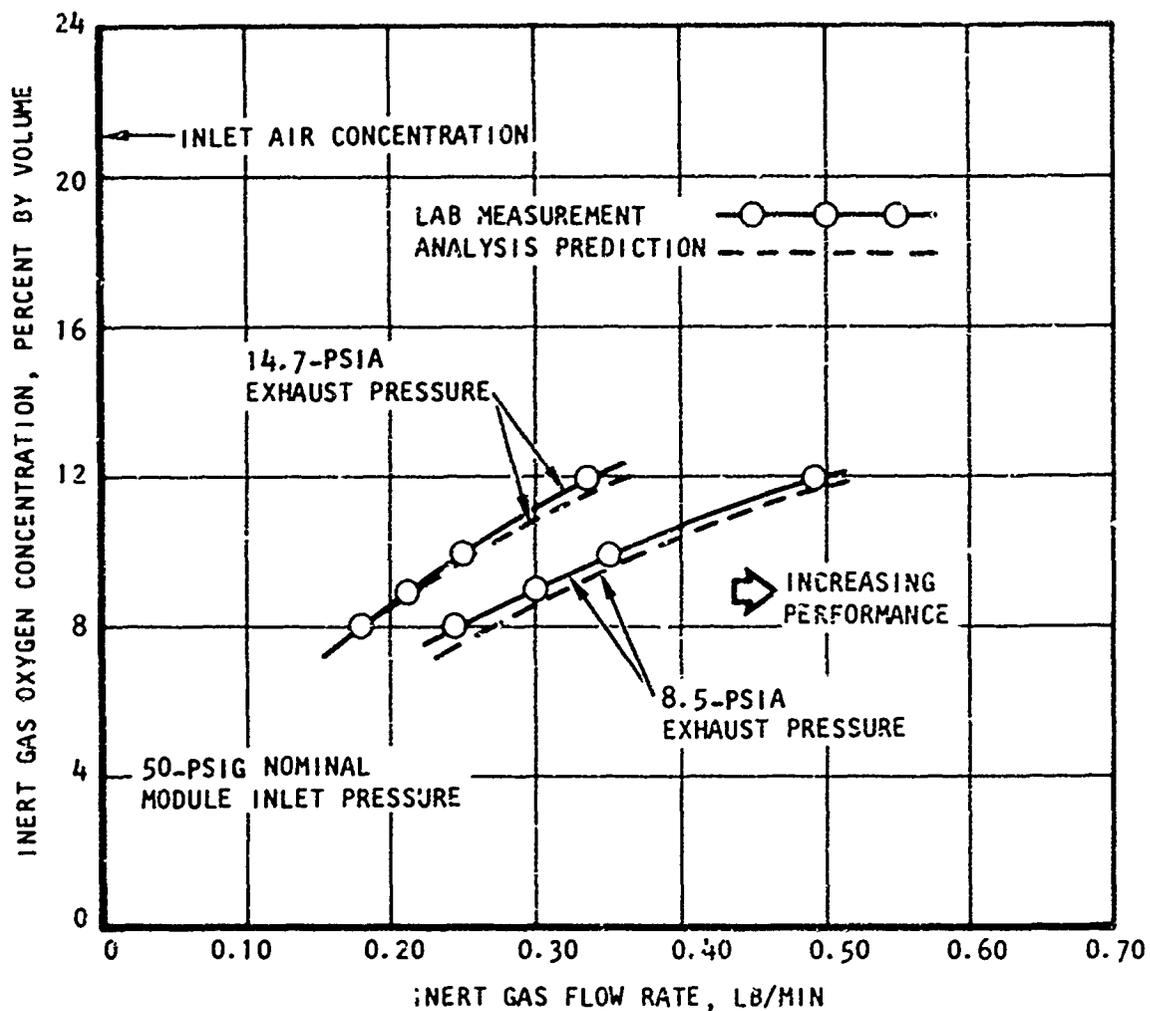


Figure 33. Comparison of Analytical Predictions and Laboratory Test Data

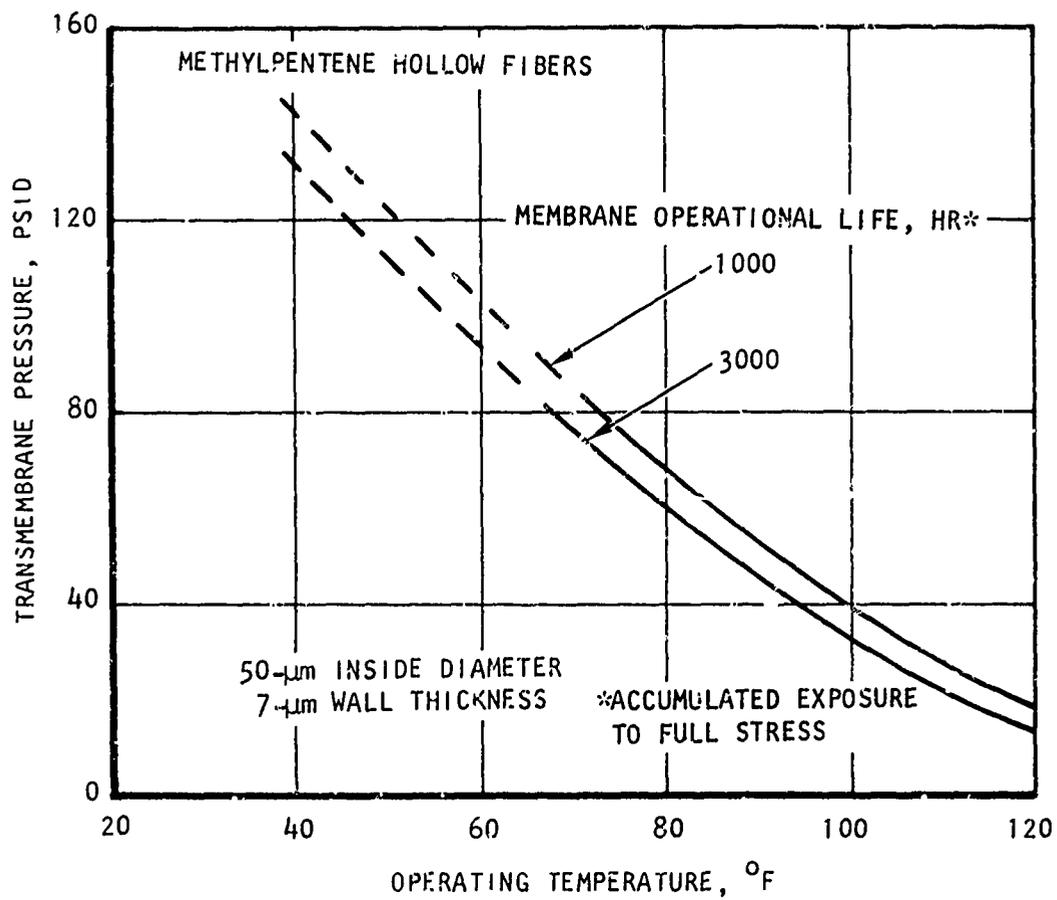


Figure 34. Limiting Transmembrane Pressures Based on Structural Life Consideration

and 1000 hours. Operation below the pressure and temperature limits represented by these curves will result in extended fiber life.

Test Program Phase 2, Breadboard IGG System Operation and Calibration

The system, shown schematically in Figure 20, incorporates a means for varying the inert gas oxygen concentration between 8 and 12 percent by volume at a minimum inert gas flow of 0.25 lb/min. Its operation is described below.

1. Inlet supply air passes through a 2-micron filter.
2. The filtered air takes three paths:
 - (a) Through a pressure regulator to the ASM for inert gas generation
 - (b) Through a shutoff valve to the primary sides of two jet pumps to reduce the ASM permeant exhaust gas pressure, then overboard
 - (c) Through a pressure regulator to an 0.043-in.-dia flow orifice
3. From the ASM, the inert gas passes through a pressure regulator to an 0.070-in.-dia flow measuring orifice.
4. Inert gas from the ASM (via the 0.070-in.-dia orifice) mixes with system inlet air (via the 0.043-in.-dia orifice) to vary the oxygen concentration and flow rate of the inert gas leaving the system.
5. Permeant gas is exhausted through secondary side of the jet pump.

Pressure regulators and gages are installed upstream of each orifice and the orifices are calibrated for flow (in lb/min) as a direct function of inlet pressure (in psig). The 70°F calibration curves for the two orifices are shown in Figure 35.

System calibration tests were then conducted and test results were plotted in Figure 36. This figure shows the breadboard IGG system inert gas oxygen concentration as a function of inert-to-mix gas flow ratio. For these tests, the following parameters were held constant:

Unit inlet air pressure = 58 psig

Unit inlet air temperature = 80°F

Jet pump primary pressure = 72 psig

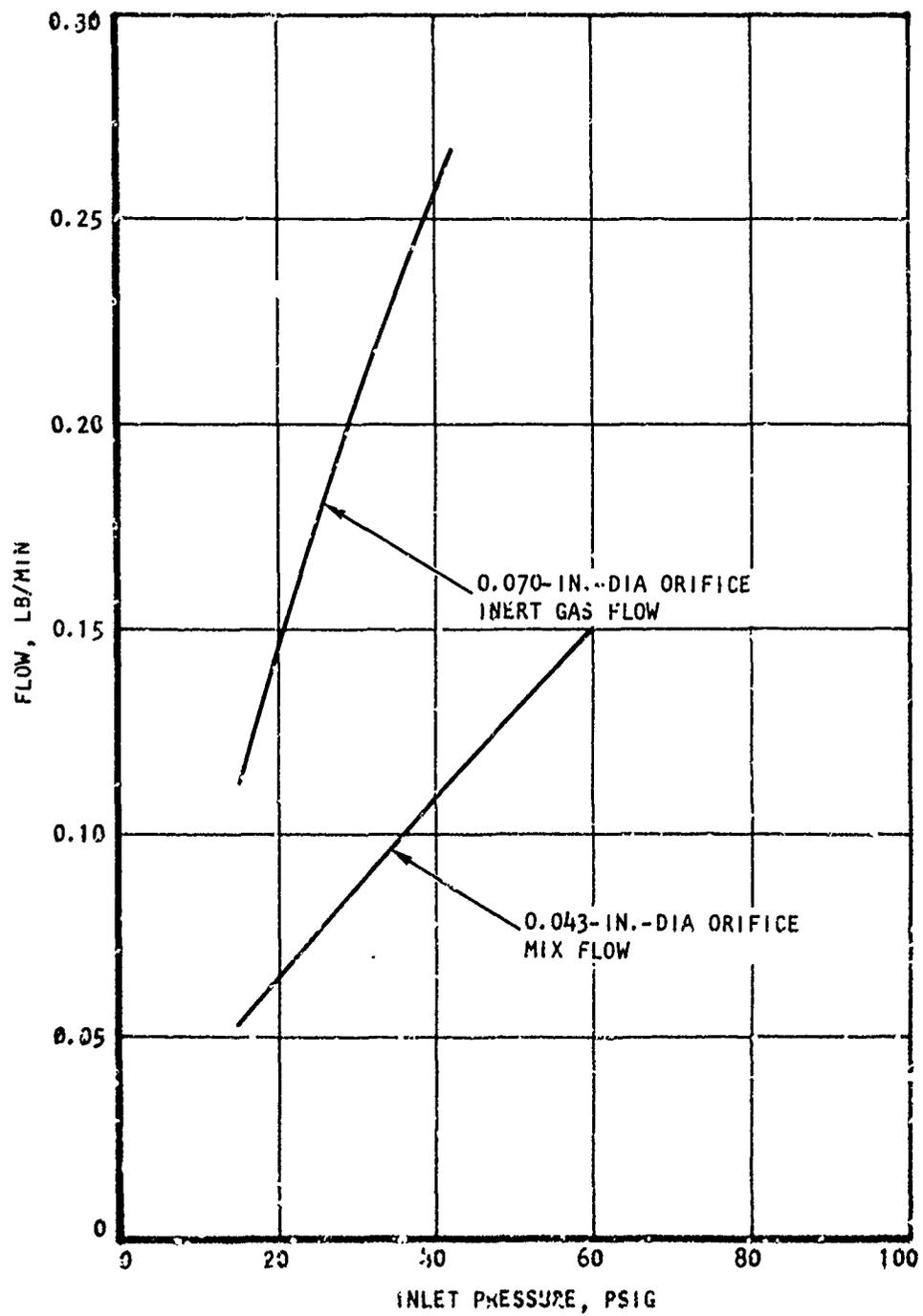


Figure 35. Breadboard IGG Flow-Measuring Orifice Calibration

TEST DATA: IGG INLET = 58 PSIG, 75°F
 7/18/77 IGG SHELL SIDE PRESS. = 9.8 PSIA (10 IN. HG VACUUM)
 JET PUMP PRIMARY PRESS. = 12 PSIG
 INERT GAS OUTFLOW = 0.25 LB/MIN

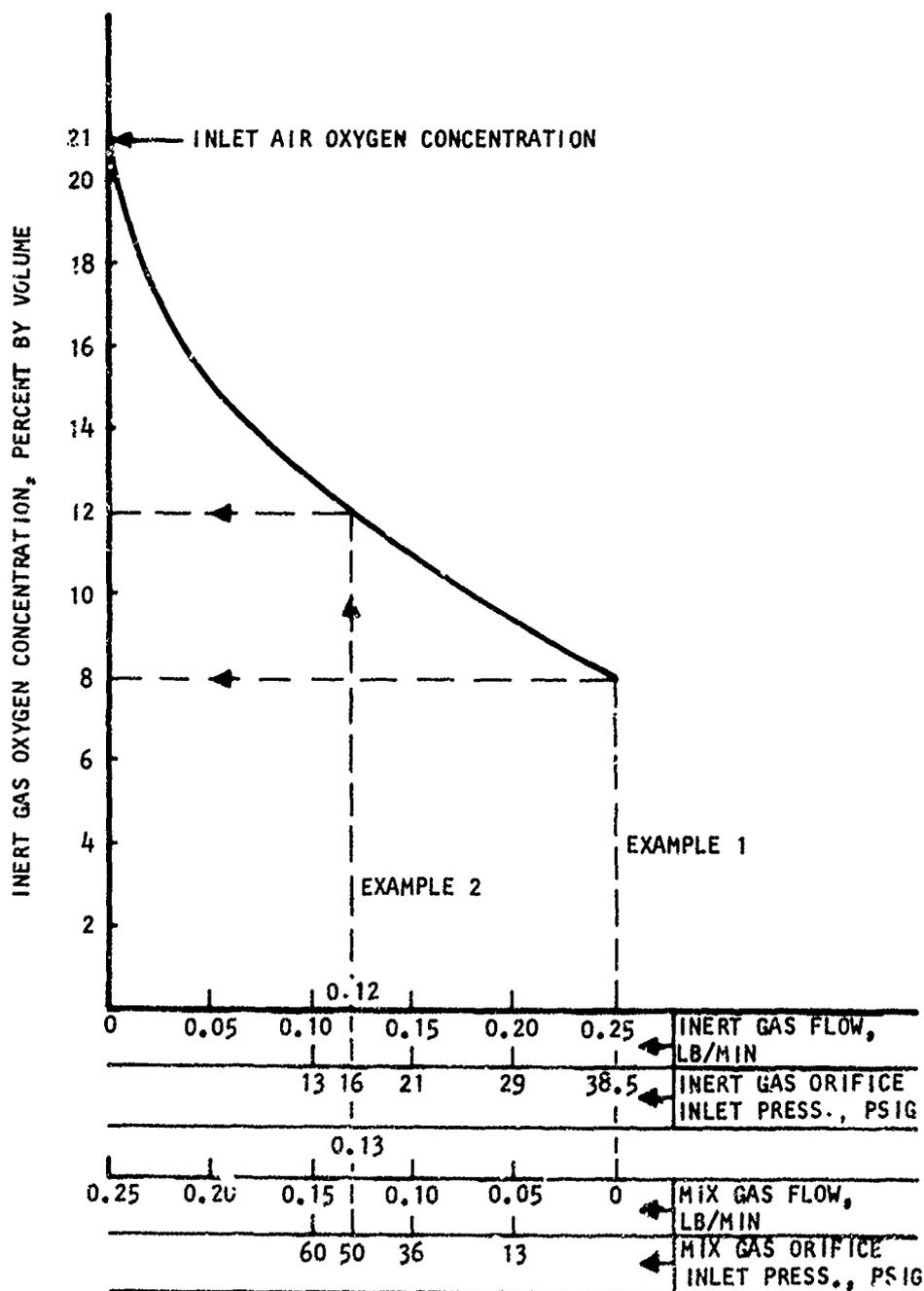


Figure 36. Breadboard IGG System Oxygen Concentration vs Inert-to-Mix Gas Flow Ratio

ASM shell side pressure = 10 in. Hg vacuum (9.78 psia)

Inert gas flow from unit = 0.25 lb/min total

The Figure 31 abscissa shows the inert gas flow from the ASM, the mix gas (air) flow required for a particular oxygen concentration of the inert gas flow from the system, and the orifice inlet pressures required to obtain these flows. Note that the total flow (the sum of the inert gas flow and mix gas flow) is always 0.25 lb/min. Therefore, by utilizing Figure 36, the inert gas oxygen concentration can be varied between 8 and 12 percent, at 0.25 lb/min total flow, by setting the orifice inlet pressures to the values obtained from the curve.

The following examples are shown in Figure 36:

1. Total inert gas flow = 0.25 lb/min
Inert gas oxygen concentration = 8 percent
ASM inert gas flow = 0.25 lb/min
ASM inert gas orifice inlet pressure = 38.5 psig
Mix gas flow = 0 lb/min
Mix gas orifice inlet pressure = 0 psig
2. Total inert gas flow = 0.25 lb/min
Inert gas oxygen concentration = 12 percent
ASM inert gas flow = 0.12 lb/min
ASM inert gas orifice inlet pressure = 16 psig
Mix gas flow = 0.13 lb/min
Mix gas orifice inlet pressure = 50 psig

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

As a result of completion of the technical tasks reported in the previous sections, data have been developed and additional experience has been gained to generate conclusions and to make recommendations for future Army effort in related areas. The conclusions that follow are separated by program task and may be related to the technical effort discussed in Sections 2, 3, and 4. Based on the overall integrated program effort, recommendations for future activity have been established for Army consideration. These recommendations are presented following discussion of the conclusions.

CONCLUSIONS

Task 1--Concept Evaluation and Overall Design Feasibility Determination

1. Descent rate and sequence in the mission profile, where full protection is required, are the deciding factors in establishing inert gas flow and generator size and weight for helicopter missions.
2. Significant reductions in weight and bleed flow penalties can be achieved if the inert gas oxygen concentration can be permitted to increase above 9 percent. This is especially apparent during the helicopter descent missions.
3. Aircraft penalties due to bleed air extraction are low because the required bleed flows are minimal.
4. IGG non-washed operating modes are favored for the missions analyzed. The increased bleed flow required for the jet pumps during wash operating modes does not result in a sufficient weight reduction to offset the bleed extraction penalties.
5. Because the systems were sized for the descent mission, the flow regulators are set for a high constant delivery rate. If the system is not sized for full flow at peak load conditions, a demand flow regulator can be added to provide additional inert gas flow at somewhat higher than 9 percent oxygen concentration during the short-duration descent portion of the mission profile.

Task 2--Detailed Design of Ground and Flight Test Inerting Systems

1. The detailed design of the flightworthy system for the AH-1G is based largely on the preliminary design completed in Task 1, but incorporates notable improvements and refinements.

2. Inert gas system weight and size are compatible with the AH-1G helicopter. Alternate system requirements can result in a further reduction of system penalties; as noted above, significant reductions in weight and bleed flow penalties are possible if the inert gas oxygen concentration is allowed to increase above 9 percent during the short-duration descent portion of the mission profile.

Task 3--Breadboard System Fabrication and Test

1. Test results obtained on the breadboard IGG system confirm the analytical predictions, thereby providing additional confidence in the estimates of the size and weight of airborne system designs.
2. The breadboard IGG system provides a convenient means of controlling the oxygen concentration between 8 and 12 percent for a total inert gas flow of 0.25 lb/min from the system for test and demonstration purposes.
3. By reference to the ASM performance curves, additional oxygen concentration and inert gas flow rates may be established for laboratory testing.
4. The breadboard IGG system meets the specified requirements.

RECOMMENDATIONS

1. Since weight and space allocations are at a premium on Army helicopters, careful consideration of system requirements may be used as a means for reducing these penalties without severe compromise to the protection provided by the system. A key consideration is seen to be the oxygen concentration of the inert gas. It is recommended that tests to establish fuel tank pressure rise as a result of ullage gas ignition be established throughout a range of oxygen concentrations, and that the inert gas generation system product requirement be set as high as these data show is feasible.
2. Since system design and its associated penalties are largely dictated by the inert gas concentration requirements during rapid descents with minimum fuel, careful consideration should be given to these requirements. As a means of further reducing system size and weight, it is recommended that the oxygen concentration transients be allowed to peak slightly above normal limits during rapid descents. In addition, it is recommended that system requirements exclude full protection for rapid descents when hostile fire is unlikely, such as return to base following mission completion.

3. The breadboard system delivered under the contract provides a flexible piece of test gear. It is recommended that the test system be set up in the Army laboratories to provide experience and operating data and that it be used to inert fuel tanks for firing range test programs.
4. The air separation module delivered with the breadboard test system is suitable for flight testing. Since early flight test data can be expected to be useful in future system designs, it is recommended that the Army consider an early, low-cost flight test program, using this unit.
5. A program to design, fabricate, and flight test a system optimized for Army helicopter application is recommended. The program should consider a new inventory helicopter in order to allow subsequent systems to be installed as part of the aircraft at the time of initial delivery to the Army.