REPORT MDC E2548

COPY NO. 23

(NASA-CR-171656) LOX/HYDROCARBON AUXILIARY PROPULSION SYSTEM STUDY Final Report (McDonnell-Douglas Astronautics Co.) 166 p HC A08/MF A01 CSCL 21H

N83-24551

Unclas
G3/20 03670

LOX/HYDROCARBON Auxiliary Propulsion System Study

Prepared By: G. F. Orton
T. D. Mark
D. D. Weber

FINAL REPORT
JULY 1982

SUBMITTED TO: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER, HOUSTON, TEXAS 77058
UNDER CONTRACT NO. NAS9—16305

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY · ST. LOUIS DIVISION
Box 516, Saint Louis, Missouri 63166 (314) 232-0232

MCDONNELL DOUGLAS CORPORATION

ABSTRACT

This report describes a study to evaluate liquid oxygen (LOX)/hydrocarbon (HC) propulsion concepts for a "second generation" Shuttle Orbiter auxiliary propulsion system. The auxiliary propulsion system consists of an Orbital Maneuvering Subsystem (OMS), an Aft Reaction Control Subsystem (ARCS), and a Forward Reaction Control Subsystem (FRCS). The primary goals of this effort were to identify the most attractive fuel and system design approach and to determine technology advancements that are needed to provide high confidence for a subsequent system development. The work was performed by the McDonnell Douglas Astronautics Company in St. Louis, Missouri (MDAC-STL) for the NASA-Lyndon B. Johnson Space Center under contract NAS9-16305. Aerojet liquid Rocket Company provided engine system data under a subcontract to MDAC-STL.

The study consisted of a Phase I--Preliminary System Evaluation and a Phase II--In-Depth System Evaluation. The fuel candidates were ethanol, methane, propane, and ammonia. Even though ammonia is not a hydrocarbon, it was included for evaluation because it is clean burning and has a good technology base as a result of its use with LOX in the X-15 rocket engine system. The major system design options were pump versus pressure feed, cryogenic versus ambient temperature RCS propellant feed, and the degree of OMS-RCS integration.

On the basis of the Phase I and Phase II evaluations, ethanol was determined to be the best fuel candidate. It is an earth-storable fuel with a vapor pressure slightly higher than monomethyl hydrazine. The LOX/ethanol propellant combination does not produce free carbon contaminant in the engine exhaust gases and, because of its high bulk density--specific impulse product, provides the most efficient packaging and highest total impulse capability of all the propellants considered.

A pump-fed OMS was recommended because of its high specific impulse, enabling greater velocity change (ΔV) and greater payload capability than a pressure-fed system. Oxygen is fed to the OMS engine in a liquid state at cryogenic temperature, and the OMS oxygen feedline is vented between burns. Common OMS/ARCS propellant tanks were recommended to conserve weight, provide higher total impulse capability, and provide increased mission flexibility.

For the RCS, a hybrid feed system (liquid ethanol—and gaseous oxygen) was recommended to preclude the requirement for RCS feed system insulation. —The recommended RCS feed system employs ambient temperature, blowdown accumulators for supplying propellants to the thrusters. Propellants are fed to the accumulators using small electric pumps which operate at low flowrates and low discharge pressures. The energy to thermally condition the RCS oxygen flow to a gaseous state is derived from a passive ethanol tank heat exchanger. The heat exchanger is a tubular coil attached to the outside surface of the ethanol tank. The electric pump supplies liquid oxygen to the heat exchanger where the oxygen absorbs heat from the tank wall, the liquid ethanol inside the tank, and the environment. The oxygen exits the heat exchanger in a gaseous state and is then routed to the RCS accumulator. This passive thermal conditioning approach is attractive because of its simplicity (no active gas generator--heat exchanger assemblies) and high specific impulse (no gas generator vent loss).

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF PAGES

Title Page

ii thru xiii

1 thru 153

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

NOMENCLATURE

AE/AT	nozzle area ratio
Al	aluminum
Ag	silver
ALRC	Aerojet Liquid Rocket Company
APS	auxiliary propulsion system or aft propulsion system
APSDS	advanced propulsion system design and sizing computer code
ARCS	Aft Reaction Control Subsystem
BTU	British Thermal Unit
CH_4	methane
Cu	copper
C_2H_5OH	ethanol (ethyl alcohol)
C_3H_8	propane
D	diameter
F	thrust
FDLINE	feedline heat transfer computer code
FIB	fiberous insulation (TG-15000)
FRCS	Forward Reaction Control Subsystem
FSYS	system thrust, lb_f
ft	feet
ft^3	cubic feet
GG	gas generator
HC	hydrocarbon
H_e	helium
HR	hours
H_2	hydrogen
in.	inches
I_{SP}	specific impulse, lb_f-sec/lbm
I_t	total impulse, lb_f-sec
JSC	Johnson Space Center
L	length
lb	pounds
lbf	pounds-force
lbm	pounds-mass

NOMENCLATURE (Continued)

LH_2	liquid hydrogen
Li	lithium
liq	liquid
LOX	liquid oxygen
$\dot{M}$	mass flow rate
max	maximum
MDAC-STL	McDonnell Douglas Astronautics Company - St. Louis
min	minimum
MLI	multi-layer insulation
MMH	monomethyl hydrazine
MR	mixture ratio by mass (oxidizer-to-fuel)
N	number of line segments
NASA	National Aeronautics and Space Administration
NBP	normal boiling point
NH_3	ammonia
Ni	nickel
NPSP	net positive suction pressure
N_2	nitrogen
N_2H_4	hydrazine
N_2O_4	nitrogen tetroxide
O/F	mixture ratio by mass (oxidizer-to-fuel)
OME	Orbital Maneuvering Engine
OMS	Oribtal Maneuvering Subsystem
ox	oxygen
O_2	oxygen
p	pressure
P_c	chamber pressure
psi	pounds per square inch
psia	pounds per square inch - absolute
$\dot{Q}$	heat transfer rate
RCE	Reaction Control Engine
RCS	Reaction Control Subsystem
RP-1	rocket propellant-1

NOMENCLATURE (Continued)

R/V	relief valve
°R	degrees Rankine
sec	seconds
SS	stainless steel
T	temperature
TG-15000	silica fiber insulation
Ti	titanium
TKHEAT	tank heat transfer computer code
TPA	turbopump assembly
TVS	thermodynamic vent system
V	volume
XFEED	crossfeed
Zr	zirconium
Zn	zinc
$\Delta \ell$	incremental length
ΔP	pressure drop
ΔV	velocity change
ε	nozzle area ratio
%	percent

1.0 INTRODUCTION

During the last two decades, spacecraft propulsion systems have employed simple pressure fed systems using earth-storable propellants such as nitrogen tetroxide (N_2O_4) and monomethyl hydrazine (MMH). These systems have been reliable and have afforded low development risk. However, their disadvantages are that the propellants are highly toxic and corrosive and impose high operational costs for reusable applications such as the Space Shuttle Orbiter. Furthermore, MMH is a possible carcinogen and is expensive to produce.

Over the years numerous studies have considered the use of LOX/H_2 for spacecraft auxiliary propulsion systems. However, two inherent characteristics of liquid H_2--a low density and a very low storage temperature--impose severe penalties on a reusable system such as the Shuttle Orbiter in the form of additional spacecraft volume and weight.

Liquid oxygen/hydrocarbon (LOX/HC) propellants possess many of the desirable characteristics of the LOX/H_2 combination while avoiding its disadvantages. They are low in toxicity, non-corrosive, low in cost and can be vented or purged from the system to facilitate system maintenance. The hydrocarbon fuels also have a high density compared to liquid H_2 which allows much lower fuel tank volumes. During evolution of the Shuttle design in the early 1970's LOX/HC propellants were considered for the Orbiter OMS/RCS. Even though they offered operational advantages over N_2O_4/MMH, they were not selected because they lacked the necessary technology base to support the development schedule and development cost criteria for the Orbiter. However, to achieve the ultimate Shuttle goal of economic, aircraft-like operations, it will be necessary to replace the toxic and corrosive N_2O_4/MMH propellants with a more passive LOX/HC propellant combination.

To begin building a technology base for LOX/HC engines NASA-JSC sponsored two previous research and development efforts: Photographic Combustion Characterization of LOX/HC Type Propellants (NAS9-15724) and Combustion Performance and Heat Transfer Characterization of LOX/HC Type Propellants (NAS9-15958). These efforts were a first step in addressing engine technology deficiencies.

The purpose of this study was to provide a corresponding technology evaluation for the overall system. The general study approach was to compare LOX/HC propulsion systems applicable to a second generation Orbiter OMS/RCS and to evaluate major system/component options.

The technical effort for this study was conducted in two phases. Phase I was a preliminary evaluation to screen a large number of propellant combinations and system concepts. Phase II was an in-depth evaluation of the most promising propellants and system concepts resulting from Phase I. Both study phases were divided into three major tasks. Task I defined the groundrules in terms of candidate propellants, system/component design options, and design requirements. In Task II, system and engine component math models were incorporated into existing computer codes for system evaluations. Aerojet Liquid Rocket Company (ALRC), under a subcontract to MDAC-STL, provided characterization data for both the OMS and RCS engines. Finally, in Task III, the detailed system evaluations and comparisons were performed to identify the recommended propellant combination and system approach.

The detailed data dump reports for Phase I and Phase II were provided in References (1) and (2), respectively. This report provides a summary description of all technical effort conducted during the study.

2.0 TASK I.1 -- PHASE I GROUNDRULES

The overall study approach was to use the Space Shuttle Orbiter OMS and RCS requirements as a framework for comparing alternate LOX/HC propulsion system concepts. The current Orbiter aft propulsion subsystem pod is shown in Figure 1. Each pod contains OMS/ARCS propellant and pressurant tankage, propellant distribution networks, a 6000 lb-thrust OMS engine, twelve 870 lb-thrust primary RCS thrusters, and two 25 lb-thrust vernier RCS thrusters. The propellants are N_2O_4 and MMH.

The OMS and ARCS are designed to operate independently, but are equipped with interconnecting plumbing to allow OMS propellant tanks in either pod to supply propellants to the OMS engines or ARCS thrusters in both pods. ARCS propellant tanks in either pod can also supply propellants to ARCS thrusters in both pods. A FRCS module, which is similar in design to the ARCS, is installed in the nose of the Orbiter.

Because of the large number of possible LOX/HC propulsion system alternatives for the OMS and RCS the major challenge of the Task I.1 groundrules effort was to limit the number of system/propellant concepts to a manageable level. To accomplish this effort Task I.1 was divided into three primary areas:

- definition of propellant candidates
- definition of system/component design options
- definition of system design requirements and constraints.

These are discussed in the following paragraphs.

2.1 Propellant Candidates

The candidate propellant combinations selected for the study were:

- oxygen/ethanol (O_2/C_2H_5OH)
- oxygen/propane (O_2/C_3H_8)
- oxygen/ammonia (O_2/NH_3)
- oxygen/methane (O_2/CH_4).

As shown in Table I, the candidate fuels represent each of the major propellant classes. Ethanol (ethyl alcohol) represents the earth storable propellant class

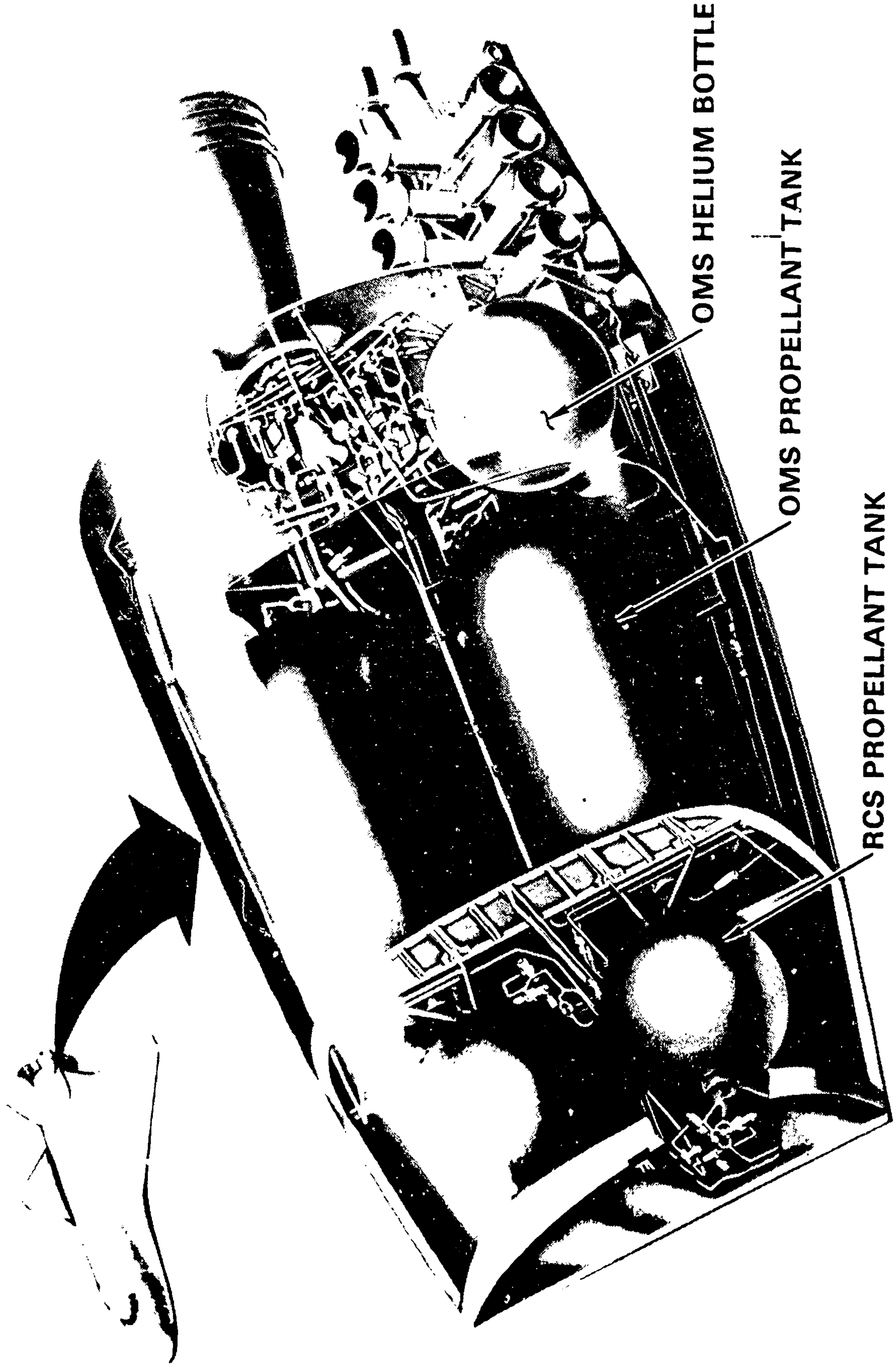


FIGURE 1 CURRENT ORBITER AFT POD OMS/RCS PACKAGING ARRANGEMENT

TABLE I
CANDIDATE FUEL MATRIX

EARTH STORABLE (BOILING POINTS MUCH GREATER THAN AMBIENT)		**FUELS SELECTED FOR PHASE I**
EXAMPLES:	RP-1 ETHANOL HEPTANE BENZENE METHANOL n-OCTANE	ETHANOL (C_2H_5OH)
SPACE STORABLE (BOILING POINTS SLIGHTLY LESS THAN AMBIENT)		
EXAMPLES:	PROPANE BUTANE ISOBUTANE PROPYLENE AMMONIA	PROPANE (C_3H_8) AMMONIA (NH_3)
CRYOGENIC (BOILING POINTS LESS THAN − 100°F)		
EXAMPLES:	ETHANE METHANE ETHYLENE CYCLOPENTANE	METHANE (CH_4)

because it is non-coking, has a good technology base for engine development (was used in the original X-15 engine system), and has an acceptably high vapor pressure. (The vapor pressure of ethanol is slightly greater than MMH.) RP-1 was not a candidate because it produces excessive free carbon in the combustion process and does not possess good restart characteristics for a regeneratively cooled OMS engine due to its low vapor pressure. Propane and ammonia represented the space storable propellant class because they were being tested under engine technology efforts sponsored by NASA-JSC (NAS9-15724 and NAS9-15958). Even though ammonia is not a hydrocarbon, it was included because it is clean burning (no contaminating carbon compounds in the exhaust products) and was used with LOX in the uprated X-15 rocket engine system. The final fuel candidate, methane, represents the cryogenic storage class because it is non-coking and was also being tested under NASA-JSC engine technology contracts (NAS9-15724 and NAS9-15958).

2.2 System Design Options

A list of major system and component design options applicable to LOX/HC propulsion systems is presented in Table II. In order to limit the number of options to be evaluated, only the key elements (system, tankage, and feedline) listed in Table III were selected for evaluation in Phase I. (The rationale for deleting design options from the Phase I evaluations is presented in Table IV.) The following paragraphs describe each Phase I design option of Table III and provide the rationale for the Phase I system evaluation matrix.

2.2.1 Pump Versus Pressure Feed - The primary issue associated with this option is the development complexity associated with a turbopump feed system versus the heavier system weight associated with a helium pressure fed system. Simplified schematics illustrating pump and pressure fed systems concepts are shown in Figure 2. The pressure fed concept is similar to that employed in the current OMS-RCS with the exception that the helium bottle is stored inside the LOX tank to conserve bottle volume and weight and minimize LOX heating during propellant tank pressurization. Net positive suction pressure (NPSP) for the pump fed concept is provided by a small helium pressurization system. Since helium pressurization weight is a function of propellant temperature, this option was evaluated for all

TABLE II

LOX/HC OMS-RCS DESIGN OPTIONS

- Overall system options
  - pump versus pressure feed
  - cryogenic versus ambient-temperature propellant feed
  - common versus separate OMS/RCS tanks
  - helium versus boost pump NPSP
  - NBP versus subcooled propellant storage
  - propulsive versus non-propulsive gas generator vents
  - subcritical versus supercritical propellant storage
- Pressurization assembly options
  - ambient versus LOX stored helium tank
  - separate versus common helium supply for fuel and oxidizer tanks
  - hydraulic versus electric boost pumps
- Propellant tankage options
  - insulation options
  - conventional versus non-conventional tank snape
  - conventional versus thermodynamic tank vent (cryogenic tanks)
  - propellant acquisition options
  - propellant gaging options
  - internal versus external entry propellant sumps (common OMS/aft RCS tanks)
- Propellant feedline options
  - insulation options
  - separated versus thermally shorted fuel and oxidizer lines
- Accumulator options
  - blowdown versus helium pressure regulated liquid accumulators
- Engine conditioner assembly options
  - electric motor versus turbine pump drive
  - gas generator versus engine expander cycle turbine drive

TABLE III —

OPTIONS SELECTED FOR PHASE I EVALUATION

- pump versus pressure feed
- NBP versus subcooled fuel storage
- cryogenic versus ambient temperature propellant feed
- common versus separate OMS/RCS tanks
- propellant tank insulation options
- feedline insulation options

TABLE IV

OPTIONS DELETED FROM PHASE I EVALUATION

- Helium versus boost pump NPSP -

  This option was initially deferred for Phase II evaluation. Helium NPSP was baselined for Phase I. (Subsequent evaluations prior to the start of Phase II showed that helium NPSP was desirable for implementing an overboard propellant dump in the event of an abort and for providing propellant crossfeed between pods in the event of a turbopump failure. As such, helium NPSP was baselined for Phase II, and this option was ultimately deleted.)

- Propulsive versus non-propulsive gas generator vents -

  Propulsive vents were baselined for the OMS to maximize overall system specific impulse. Non-propulsive vents were baselined for the RCS to preclude translational thrust during attitude control.

- Subcritical versus supercritical propellant storage -

  Previous Space Shuttle Auxiliary Propulsion System studies (NAS8-26248) have shown that tank weight penalties are excessive for supercritical propellant storage. Since the critical pressures for all the propellants of this study are greater than 600 psia, subcritical storage assemblies were baselined.

- Ambient versus LOX stored helium tank -

  LOX stored helium tanks were baselined for this study to minimize helium tank volume and minimize the heat input to the cryogenic tanks during pressurization.

- Separate versus common helium supply for fuel and oxidizer tanks -

  Since the propellant candidates considered in this study are not hypergolic, propellant vapor mixing upstream of the check valves in the helium pressurization sytem will not form reaction products. Therefore, a common helium supply was baselined to ensure accurate mixture ratio control and minimize helium pressurization system weight. Anti-migration screens would be provided in the propellant tank helium inlet diffusers to prevent liquid migration into the helium pressurization lines.

TABLE IV (Continued)

OPTIONS DELETED FROM PHASE I EVALUATION

- Hydraulic versus electric boost pumps -

  This option was tentatively deferred for Phase II evaluation. (Subsequent evaluations prior to the start of Phase II showed that helium NPSP was desirable for implementing an overboard propellant dump in the event of an abort and for providing propellant crossfeed between pods in the event of a turbopump failure. As such, helium NPSP was baselined for Phase II, and this option was deleted.)

- Conventional versus non-conventional tank shape -

  Evaluation of this option was deferred for Phase II evaluation. Conventional tank shapes were baselined for Phase I.

- Conventional versus thermodynamic tank vent (cryogenic tanks) -

  Conventional vents in which vapor is vented from the propellant tank were considered impractical due to the difficulty associated with positioning the vapor bubble inside the tank in low-g. As such, a thermodynamic vent system was baselined in which liquid is withdrawn from the tank through the propellant acquisition system to relieve tank pressure.

- Propellant acquisition system options -

  Because of the current technology status of the OMS and RCS tanks and the requirement for system reuse, surface tension screen propellant acquisition systems were baselined for this study. The detailed design of a surface tension screen system for cryogenic propellants is a key issue that should be addressed in future technology efforts.

- Propellant gaging options -

  Because of their current technology status, a capacitance gaging system was baselined for the OMS and a pressure-temperature-volume measurement system was baselined for the RCS. The propellant gaging system is also a key issue that should be addressed in future technology efforts.

TABLE IV (Continued)

OPTIONS DELETED FROM PHASE I EVALUATION

- Internal versus external entry propellant sumps (common OMS/aft RCS tanks) -
  Propellant acquisition systems for common OMS/aft RCS tanks were evaluated previously by MDAC-STL under a contract with Rockwell International during the Orbiter design phase. It was concluded in that evaluation that external, in-line entry propellant sumps were superior to internal sumps. The external sump is easier to service and check-out and remains full of propellant during the launch and orbital mission phases. Because of these advantages the external sump was baselined for common OMS/aft RCS tanks.

- Separate versus thermally shorted fuel and oxidizer lines -
  Evaluation of this option was deferred for Phase II evaluation. Separate feedlines were baselined for Phase I.

- Blowdown versus helium pressure regulated liquid accumulators -
  Previous auxiliary propulsion system studies conducted under Contract NAS9-12013 have shown that blowdown liquid accumulators are superior to helium pressure regulated accumulators. They are lower in weight, afford lower design, development, and operational complexity and are less costly. Because of these advantages, blowdown liquid accumulators were baselined for this study.

- Electric motor versus turbine pump drive -
  Evaluation of this option was deferred for Phase II evaluation. Turbine pump drives were baselined for Phase I.

- Gas generator versus engine expander cycle turbine drive -
  Evaluation of this option was also deferred for Phase II evaluation. Gas generator turbine cycles were baselined for Phase I.

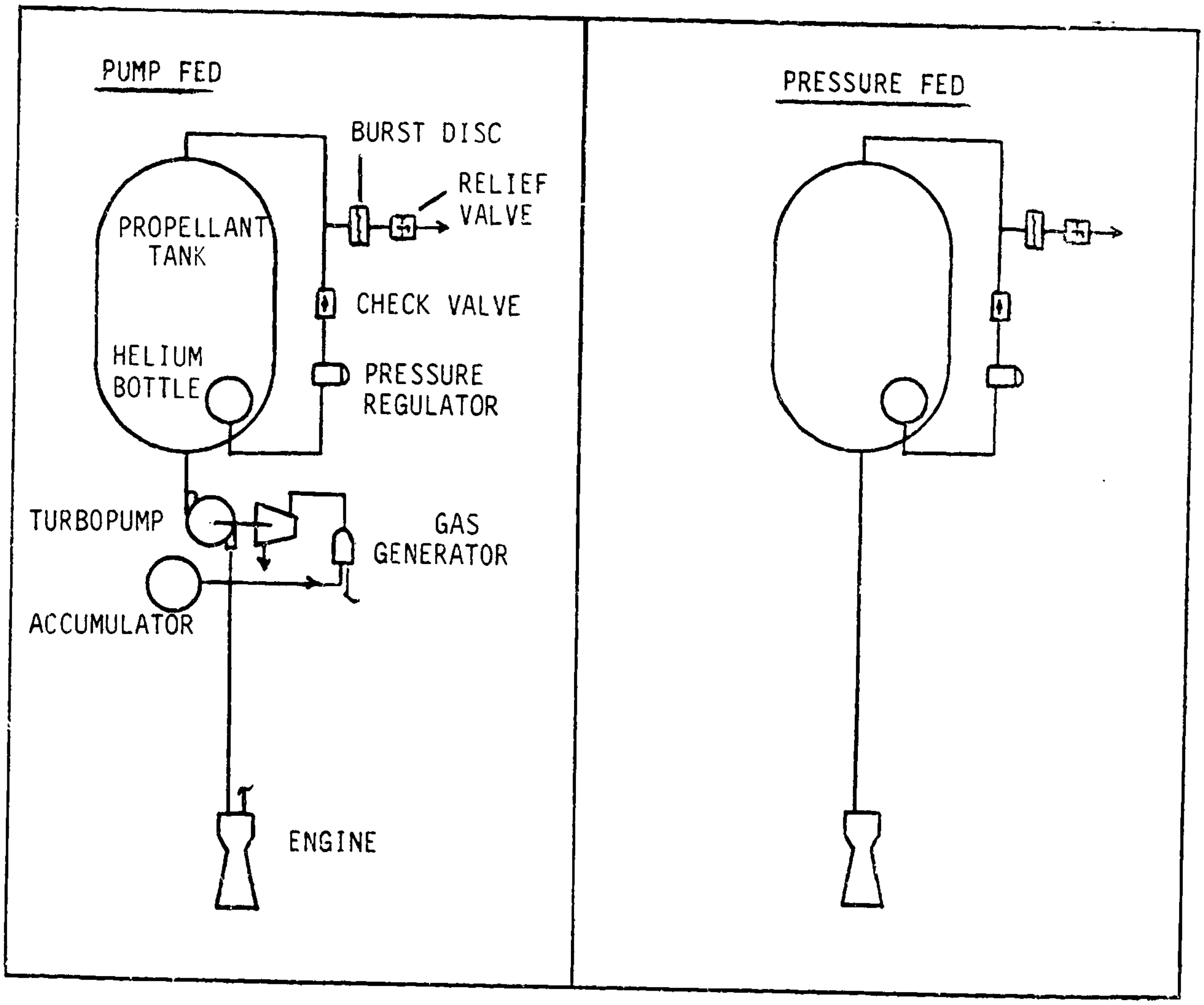


FIGURE 2 PUMP AND PRESSURE FED SYSTEM CONCEPTS

four fuel candidates. Furthermore, since helium pressurization system weight is also a function of the total impulse requirement, this option was evaluated for both the OMS and RCS.

2.2.2 Normal Boiling Point (NBP) Versus Subcooled Fuel Storage - The primary issue associated with this option is the increased system total impulse capability with subcooled fuel storage (due to increased fuel density) versus the lower thermal control complexity associated with normal boiling point storage. Because of the large density variation between its normal boiling point and freezing temperatures, this option was evaluated for propane only. Since the freezing temperature of propane is less than the normal boiling temperature of oxygen propane can be stored at LOX temperatures with an attendant density increase of 25 percent. The corresponding total impulse benefit is significant in large volume systems such as the OMS, and, as such, this option was evaluated for the OMS only.

2.2.3 Cryogenic Versus Ambient Temperature RCS Propellant Feed - The primary issue associated with this option is the feedline insulation complexity with cryogenic propellant delivery systems versus the thermal conditioning energy penalty (specific impulse loss) associated with ambient temperature, gaseous propellant feed. Simplified schematics illustrating these system concepts are shown in Figure 3. In the cryogenic feed system, the propellant is delivered to the thrusters as a liquid at temperatures near the normal boiling point. In the ambient temperature feed system, the cryogenic propellants are thermally conditioned to a gaseous state in a heat exchanger supplied with gas generator exhaust products. The advantage of the ambient temperature feed system is the elimination of insulation on the accumulators and propellant feedlines.

This design option is only applicable to the RCS feed system. OMS feedline lengths are very short compared to the RCS and only a limited number of engine firings are required per mission. As such, the cryogenic propellants were assumed to be vented from the OMS feedlines between engine burns. The RCS feedlines are very long, however, and there are a large number of thruster firings required for attitude control. Because of this it is not practical to vent the feedlines between firings. Therefore, insulated feedlines are required to prevent propellant

• SEE SCHEMATIC NOMENCLATURE OF FIGURE 2

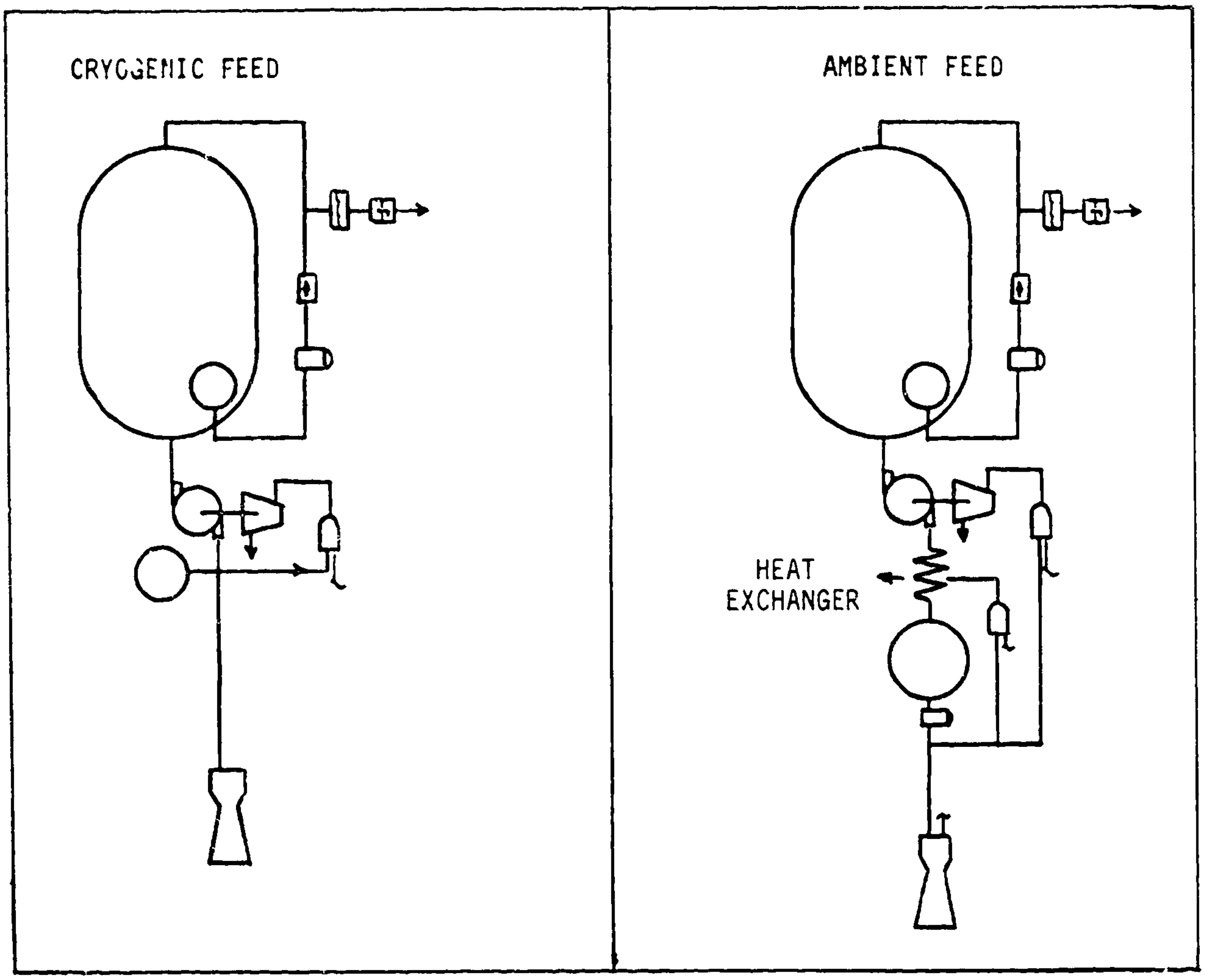


FIGURE 3 CRYOGENIC AND AMBIENT TEMPERATURE PROPELLANT FEED SYSTEM CONCEPTS

vaporization during idle periods, otherwise the cryogenic propellants must be thermally conditioned to a gaseous state for thruster feed. Since thermal conditioning energy requirements depend on the propellant type and thruster mixture ratio, this option was evaluated for all four fuel candidates. In the LOX/methane RCS both propellants are thermally conditioned to a gaseous state. However, in the LOX/ethanol, LOX/propane, and LOX/ammonia systems only the LOX is thermally conditioned to a gaseous state. This is because the fuels are stored as liquids at near ambient temperatures.

2.2.4 Common Versus Separate OMS/RCS Tanks - As mentioned previously the current aft propulsion pods are interconnected to allow OMS tanks in either pod to supply OMS engines and RCS thrusters in both pods and RCS tanks in either pod to supply RCS thrusters in both pods. To further enhance propellant utilization flexibility common tanks can be employed for OMS and ARCS propellants, as well as for OMS, ARCS, and FRCS propellants. In the latter approach the FRCS would be interconnected with the OMS and ARCS by feedlines routed along the length of the Orbiter as illustrated in Figure 4. Because of varying performance capabilities, integrated OMS-RCS tankage options were evaluated for all four fuel candidates.

2.2.5 Tank and Feedline Insulation Options - Alternate insulation materials for the OMS and RCS tanks and RCS feedlines were selected for investigation to complete the Phase I evaluation matrix. The candidate insulation materials were aluminized mylar multi-layer insulation (MLI), TG-15000 silica fiber insulation, which is currently employed on the aft pod internal moldline, and polystyrene foam insulation. Because of the low boiling point and low heat of vaporization for LOX, insulation options were evaluated for the LOX tanks and feedlines only.

2.2.6 Phase I System Evaluation Matrix - Based on the preceeding discussion the Phase I system evaluation matrix of Table V was established. To complete the Task I.1 groundrules definition task system design requirements were established as described below.

2.3 Design Requirements

Requirements employed for the Phase I system evaluations were divided into mission, envelope, reliability, and component weight and sizing categories.

ORIGINAL PAGE IS
OF POOR QUALITY

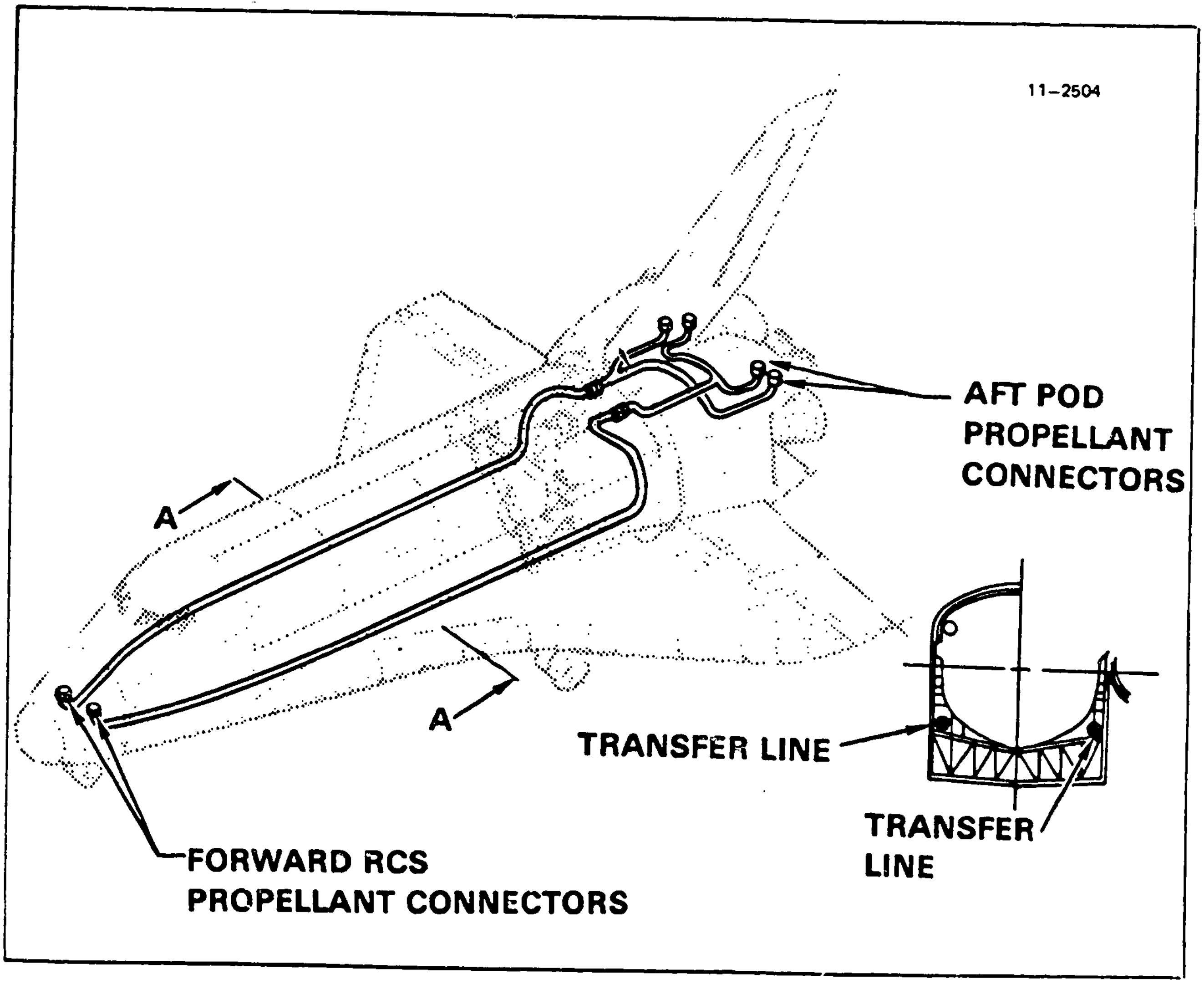


FIGURE 4 INTERCONNECTED FORWARD AND AFT PROPULSION SYSTEMS

TABLE V

PHASE I SYSTEM EVALUATION MATRIX

DESIGN OPTIONS	CANDIDATE FUELS			
	ETHANOL	PROPANE	AMMONIA	METHANE
PUMP VERSUS PRESSURE FEED (OMS AND RCS)	X	X	X	X
COMMON VERSUS SEPARATE OMS/RCS TANKAGE	X	X	X	X
CRYOGENIC VERSUS AMBIENT TEMPERATURE RCS PROPELLANT FEED	X	X	X	X
NBP VERSUS SUBCOOLED FUEL STORAGE (OMS)		X		
TANK INSULATION OPTIONS	} LOX			
FEEDLINE INSULATION OPTIONS				

Generic OMS and RCS mission duty cycles consisting of engine and thruster on/off times were provided by the MDAC-STL APS Project. These duty cycles were originally developed by NASA-JSC and were employed for the APS static firing tests at NASA-White Sands Test Facility. In this study they were used to perform tank and feedline thermal analyses. For comparing ΔV and total impulse capabilities of the candidate propellants and system concepts the forward RCS module and aft pod envelopes were constrained to the current dimensions. In addition OMS engine and RCS thruster lengths and diameters were constrained to the current values. Feed system schematics were prepared for each system concept to reflect the same "fail operational/fail safe" component redundancy as the current OMS and RCS. The detailed requirements and constraints employed for Phase I component weight and sizing are summarized in Table VI.

TABLE VI

DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

- Helium pressurization system
  - Common helium supply for fuel and oxidizer tanks
  - Current OMS/RCS line lengths
  - Line Mach number = 0.1 (maximum)
  - Real gas effects
  - Solubility effects
  - Vapor pressure effects
  - Line Materials: 2219-T87 Al or 304L SS
  - Polytropic exponent = 1.0 (helium bottle inside LOX tank)
  - Regulator pressure ratio = 0.7 (outlet/minimum inlet)
  - Tank shape: spherical
  - Tank Materials: LOX storage--2219-T87 Al
  - Storage pressure: 3000 psia
  - Ultimate factor of safety = 1.5

- Propellant tanks
  - Propellant dump through OMS and RCS engines
  - Tank volume determination:
    - impulsive propellant volume
    - 2% liquid residuals by volume
    - 98% vapor residuals by volume
    - tank boil-off loss
    - OMS line chilldown/vent loss
    - 5% ullage volume at storage temperature
  - Shape:
    - OMS: cylindrical with oblate spheriod end domes
    - RCS and entry sump: spherical
    - Common OMS/RCS: cylindrical with oblate spheriod end domes
    - OMS and Common OMS/RCS fuel and oxidizer tanks are constrainted to equal lengths to permit attachment to common aft pod bulkhead.

TABLE VI (Continued)

DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

- Materials:
  - LOX: 2219-T87 AL
  - Fuel: 2219-T87 Al or 6Al-4V Ti (whichever is lighter)
- Minimum gage:
  - Aluminum: 0.03 in. } Per NASA Direction
  - Titanium: 0.02 in. }
- Ultimate factor of safety = 1.5
- Thermal control: silica fiber, foam, or multilayer insulation with thermodynamic vent
- Propellant acquisition: surface tension screens
- OMS propellant gaging: capacitance probes
- RCS propellant gaging: P-V-T

- Accumulators
  - Pump startup response = 0.5 sec
  - Number of RCS accumulator recharge cycles = 50/mission
  - Blowdown accumulator operation (isentropic blowdown process)
  - Shape: spherical or cylindrical with hemispherical end domes
  - Materials:
    - LOX: 2219-T87 Al
    - Fuel: 2219-T87 Al or 6 Al-4V Ti (whichever is lighter)
  - Minimum gage
    - Aluminum: 0.03 in.
    - Titanium: 0.02 in.
  - Ultimate factor of safety = 1.5
  - Thermal control: silica fiber or multilayer insulation (no vent)
  - Propellant acquisition: surface tension screens for liquid feed

- Propellant feedlines
  - Current OMS/RCS line lengths
  - Pressure drop:

TABLE VI (Continued)

DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

- 0.5 psi/ft for pressure fed system
- 1.0 psi/ft for pump fed system

- Darcy friction factor
- Isenthalpic expansion process
- Materials:
  - LOX: 2219-T87 Al
  - Fuel: 2219-T87 Al or 304L SS
- Minimum gage = 0.028 in.
- Ultimate factor of safety:
  - 4.0 for D < 1.5 in.
  - 1.5 for D $\geq$ 1.5 in.
- Thermal control: silica fiber or multi layer insulation
- Linear and angular deflection compensation joints

- Gas generator exhaust vent line
  - Line Mach number = 0.3 (maximum)
  - Fanno line analyses
  - Line length: 20 ft
  - Exhaust nozzle area ratio = 2.0
  - Propulsive vent for OMS, non-propulsive vent for RCS
  - Line material: 304L stainless steel
  - Minimum gage and ultimate factor of safety: same as feedlines

3.0 TASK I.2 --PHASE I COMPONENT CHARACTERIZATION

Three proprietary MDAC-STL computer codes were used to evaluate the candidate system concepts:

- Advanced Propulsion System Design and Sizing Code (APSDS)
- Tank Heat Transfer Code (TKHEAT)
- Feedline Heat Transfer Code (FDLINE)

A description of these computer codes is provided in the following paragraphs.

3.1 APSDS Code

This code sizes the propulsion system to a fixed volume or fixed total impulse constraint. Sizing to a fixed pod volume constraint is accomplished through use of an iteration loop within the code. To start, propellant tank volumes are calculated based on an assumed total impulse requirement. The calculated total tank volumes (fuel and oxidizer) are then compared to the total available tank volume within the pod. If the calculated volume is out of tolerance a revised total impulse estimate is made, and tank volumes are recalculated. To ensure rapid convergence a secant numerical analysis technique is used to estimate a new total impulse requirement. A simplified flow diagram for the fixed volume analysis is shown in Figure 5. After the propellant tank volume is determined, the program calculates the system pressure budget and total system weight. Table VII identifies the system components that are modeled in the APSDS code and Table VIII shows example output for a LOX/ethanol system with common OMS-aft RCS propellant tanks. A brief description of major system component models--tanks, accumulators, feedlines, and engines--is provided below.

3.1.1 Propellant Tanks - The cryogenic propellant tank model is shown in Figure 6. Options for tank shape, material, and insulation are available depending on the propellant and system type. The tank shapes employed for Phase I were:

- OMS tanks--cylindrical with oblate spheroid end domes
- RCS tanks--spherical
- Common OMS/RCS tanks--cylindrical with oblate spheriod end domes.

Aluminum, 2219-T87, was assumed for the LOX tank, while either 2219-T87 aluminum or 6AL-4V titanium was assumed for the fuel tank (whichever was lighter). The

ORIGINAL PAGE IS
OF POOR QUALITY

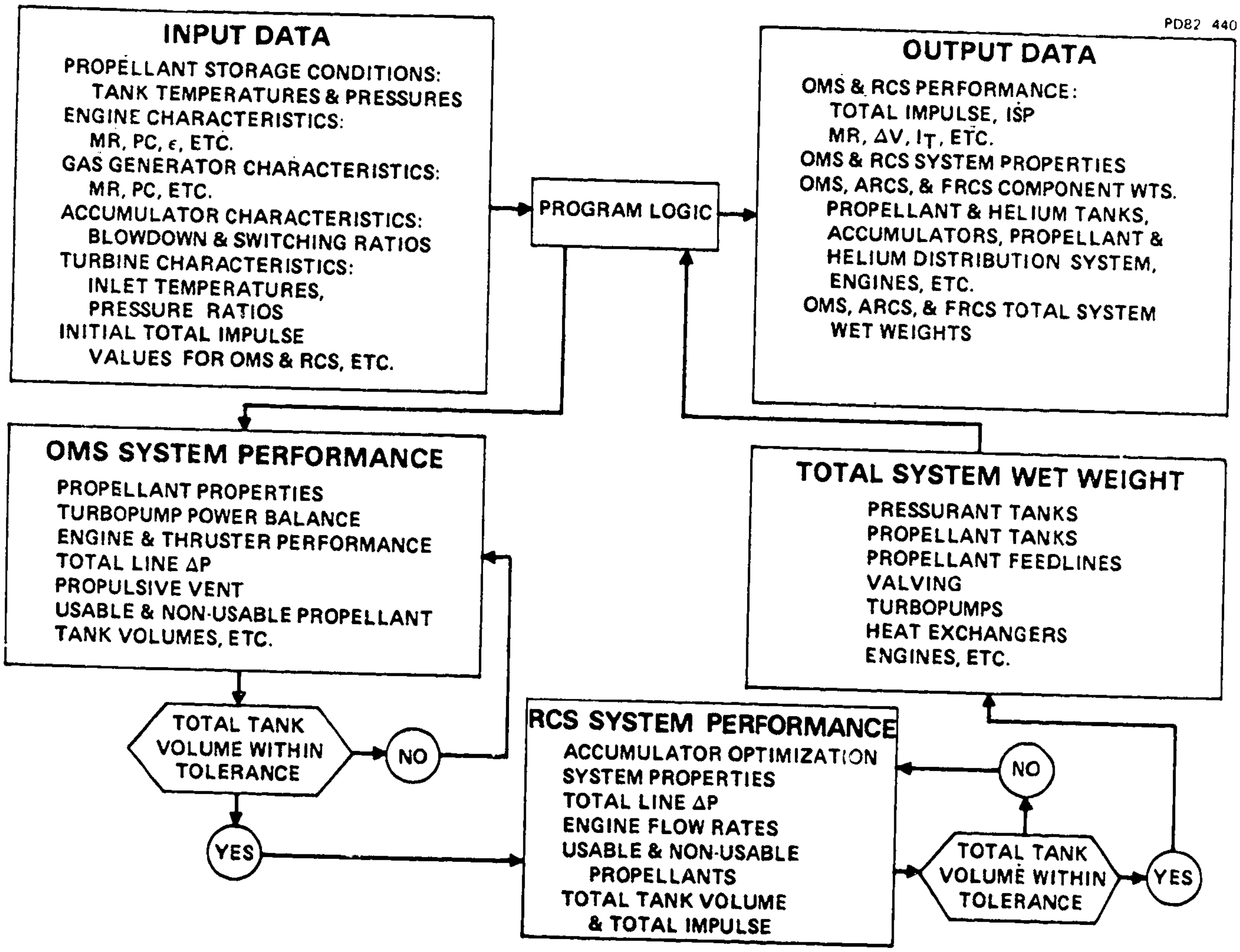


FIGURE 5 APSDS FLOW DIAGRAM FOR FIXED VOLUME ANALYSIS

TABLE VII

SYSTEM COMPONENTS IN APSDS COMPUTER CODE

- Pressurant tanks
  - metallic (monolithic)
  - composite
- Propellant tanks (insulated and non-insulated) — aluminum and titanium
  - spherical
  - cylindrical
  - conical
- Accumulators (insulated and non-insulated) — aluminum and titanium
  - spherical
  - cylindrical
- Feed system components
  - pressure regulators
  - check valves
  - bust disk/relief valves
  - manual valves
  - solenoid valves
  - cryogenic valves
- Propellant feedlines — aluminum and stainless steel
  - insulated
  - non-insulated
- OMS engine (regen-cooled)
  - pump fed
  - pressure fed
- RCS thruster (film-cooled)

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE VIII
EXAMPLE SYSTEM WEIGHT SUMMARY FROM APSDS COMPUTER CODE

APS SUMMARY/POD
COMMON OMS/RCS LOX/ETHANOL(NBP)
INTEGRATED FRCS/APS

PERFORMANCE

• OMS SYSTEM		• OMS ENGINE			
FSYS, LBF	= 6090.00	F, LBF	= 10000.0		
IT LBF-SEC	= .3340E+07	PC, PSIA	= 800.0		
ISP, LBF-SEC/LBM	= 344.10	ISP, LBF-SEC/LBM	= 349.0		
O/F	= 1.75	O/F	= 1.80		
		AE/AT	= 240.0		
• RCS SYSTEM		**• RCS PRIMARY ENGINE**		**• RCS VERNIER ENGINE**	
FSYS, LBF	= 6090.00	F, LBF	= 870.0	F, LBF	= 25.0
IT LBF-SEC	= .1290E+07	PC, PSIA	= 250.0	PC, PSIA	= 250.0
ISP, LBF-SEC/LBM	= 234.52	ISP, LBF-SEC/LBM	= 301.0	ISP, LBF-SEC/LBM	= 225.8
O/F	= 1.32	O/F	= 1.41	O/F	= 1.80
		AE/AT	= 47.0	AE/AT	= 43.0

WEIGHT, LBM

	OX	FUEL	TOTAL
• SYSTEM WET WEIGHT	-	-	18966.48
• USFABLE PROPELLANT	9302.66	5905.30	15207.96
- TANKED PROP	8890.98	5607.37	14498.34
- SUMP TANK PROP	411.69	297.93	709.61
• NON-USEABLE PROPELLANT	574.73	345.39	920.11
- TANK BOIL-OFF	55.34	0.00	55.34
- LINE BOIL-OFF	0.00	0.00	0.00
- PROP TANK LIQ/VAP RESID	228.39	121.54	349.94
- APS ACCUMULATOR PROP	165.33	59.46	224.79
- LINE PROPELLANT	7.29	22.08	29.37
- HALF CROSS-FEED PROP	7.85	7.64	15.49
- ARCS INTERCON LINE PROP	.35	1.73	2.08
- SUMP TANK LIQ/VAP RESID	9.97	6.13	16.10
- FRCS INTERCON LINE PROP	9.01	50.99	60.00
- FRCS ACCUMULATOR PROP	88.93	59.46	148.39
- FWD RCS LINE PROP	2.26	16.34	18.61
• HELIUM	-	-	10.02
• SYSTEM DRY WEIGHT	-	-	2828.39
- PROPELLANT TANKS	327.88	199.21	527.09
- APS ACCUMULATORS	159.58	44.94	204.53
- PROPELLANT DISTRIBUTION	50.63	100.45	151.07
- HELIUM TANKS	43.07	-	43.07
- HELIUM DISTRIBUTION	-	-	48.14
- ENGINES	-	-	938.20
- GG VENT	22.65	25.35	47.99
- TPA+GG	117.74	88.51	206.25
- HEAT EXCHANGERS	21.14	0.00	21.14
- HEAT EXCHANGER GG	31.65	0.00	31.65
- ONE-HALF CROSS FEED	16.54	23.45	39.99
- ARCS INTERCONNECT LINE	12.97	18.53	31.49
- ENTRY SUMP TANK	46.74	33.75	80.50
- FRCS INTERCON LINE	39.22	99.40	138.62
- FRCS ACCUMULATORS	122.92	44.94	167.87
- FRCS LINE	43.73	77.07	120.80

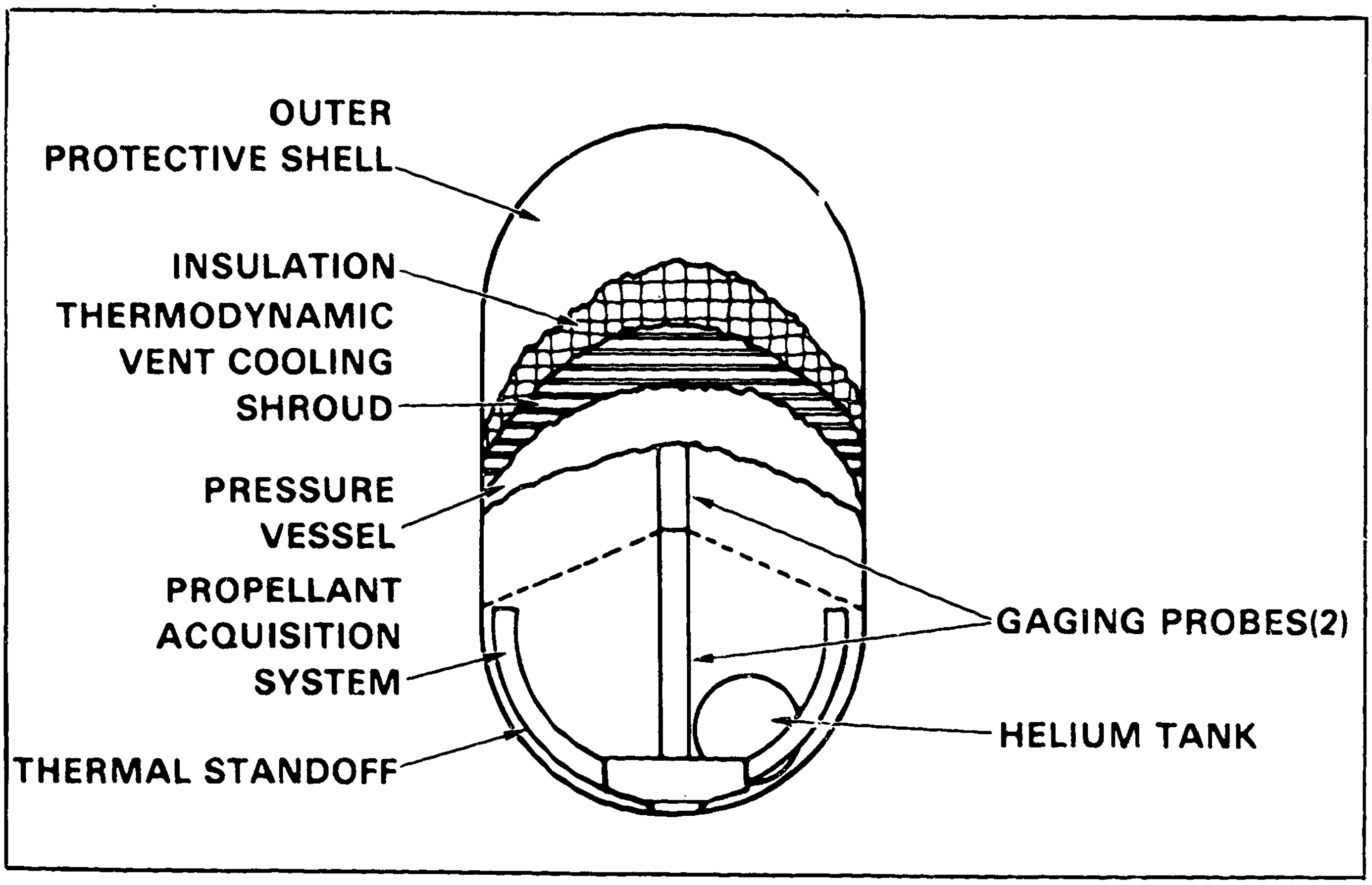


FIGURE 6 CRYOGENIC PROPELLANT TANK MODEL

pressure vessel was sized for the total required propellant volume, including allowances for vent losses, tank residuals (liquid and vapor), and a 5% ullage volume. Pressure vessel wall thickness was calculated—applying the material ultimate stress and the maximum operating pressure (tank relief pressure) with a factor of safety of 1.5. Minimum gage wall thicknesses were specified by NASA to be 0.03 in. for aluminum and 0.02 in. for titanium. The calculated pressure vessel weight includes a non-optimum factor to account for bosses, gage variations, support attachments, and weldments. The cooling shroud (thermodynamic vent system), insulation, and outer shell weights were calculated based on the tank surface area, while the acquisition system weight was based on the current OMS and RCS designs. OMS gaging probe weights were calculated as a function of tank length. A tank support structure weight was also calculated based on the total tank weight and loaded propellant weight. An example computer output weight summary for common OMS-aft RCS propellant tanks (LOX and ethanol) is shown in Table IX.

3.1.2 Accumulators - The RCS accumulator has three basic functions in a pump fed system: to provide propellant to the gas generator during the pump start transient, to provide impulsive propellant to the RCS thrusters during the mission, and to provide an ullage volume for propellant thermal expansion due to line heating. The OMS accumulator has one primary function--to supply propellant to the OMS gas generator during engine startup. As such its volume is much less than the RCS accumulator.

The accumulator operates in a blowdown mode as shown in Figure 7. Initially, the accumulator is charged to a maximum pressure. It is then allowed to blowdown to a switching pressure, at which time the turbopump assembly is activated. During the pump start transient, the accumulator supplies propellant to the gas generators and the pressure decays further to a minimum pressure. The accumulator is then supplied with propellant from the turbopump and recharged to the maximum pressure. In Phase I the RCS accumulator was sized to provide 50 recharge cycles per mission.

Accumulator weights are calculated in a manner similar to the propellant tanks but do not include a cooling shroud or gaging system. An example weight summary for the RCS accumulators is presented in Table X. This example is for a hybrid RCS in which the thrusters are supplied with gaseous O_2 and liquid ethanol at ambient temperature.

TABLE IX
EXAMPLE APSDS OUTPUT -- PROPELLANT TANKS

APS PROPELLANT TANKAGE MODEL

COMPONENT		(AL) OXIDIZER SIDE	(AL) FUEL SIDE
PRESSURE VESSEL	-	80.75	77.03
COOLING SHROUD	-	10.83	0.00
INSULATION	-	52.01	0.00
OUTER SHELL	-	36.00	0.00
AQUISITION SYSTEM	-	69.48	64.45
HELIUM TANK	-	40.44	-
HELIUM TANK SUPPORT STRUCTURE	-	2.62	-
PROPELLANT TANK SUPPORT STRUCTURE	-	78.81	57.73
TOTAL		370.94	199.21

TOTAL PROPELLANT TANKAGE DRY WEIGHT - 570.15 LBS PER POD

PROPELLANT TANK VOLUME : OX SIDE - 137.24 CUB FT
FUEL SIDE - 122.62 CUB FT

PROPELLANT TANK DIAMETER : OX SIDE - 4.12 FT
FUEL SIDE - 3.89 FT

PROPELLANT TANK PRESSURE : OX SIDE - 35.00 PSIA
FUEL SIDE - 35.00 PSIA

PROP TANK RELIEF PRESSURE: OX SIDE - 48.94 PSIA
FUEL SIDE - 45.90 PSIA

HELIUM TANK VOLUME - 1.80 CUB FT

HELIUM TANK DIAMETER - 1.51 FT

ORIGINAL PAGE IS
OF POOR QUALITY

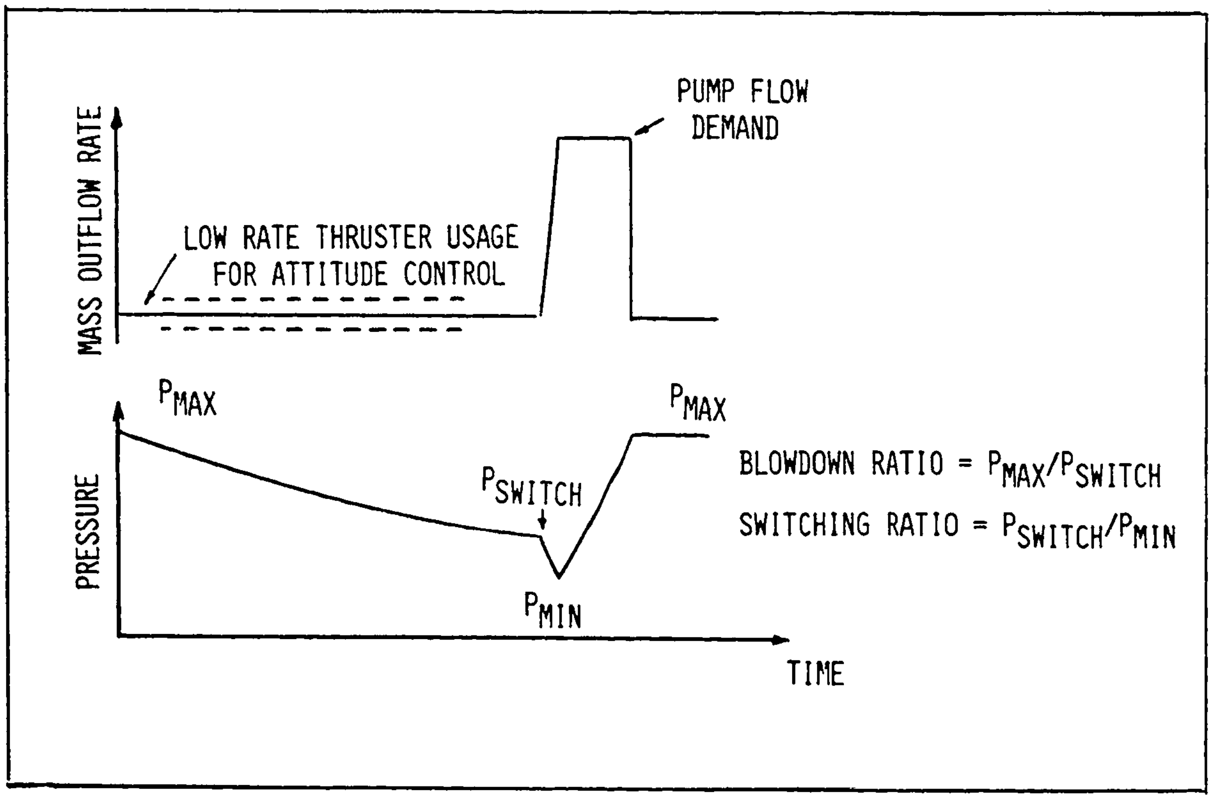


FIGURE 7 RCS ACCUMULATOR OPERATION

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE X
EXAMPLE APSDS OUTPUT -- RCS ACCUMULATORS

APS ACCUMULATOR WEIGHT PER POD

COMPONENT		(GAS) OXIDIZER SIDE	(LIQ) FUEL SIDE
PRESSURE VESSEL	-	88.31	35.98
INSULATION	-	0.00	0.00
FIBERGLAS SHROUD	-	0.00	2.47
AQUISITION SYSTEM	-	0.00	2.39
REGS AND VALVES	-	28.08	0.00
SUPPORT STRUCTURE	-	6.53	4.10
TOTAL		122.92	44.94
WEIGHT OF PROPELLANT IN ACCUMULATOR	-	88.93	59.46

TOTAL ACCUMULATOR WET WEIGHT 316.26 LBS PER POD

ACCUMULATOR VOLUME : OX SIDE - 14.69 CUB FT
FUEL SIDE - 2.47 CUB FT

ACCUMULATOR DIAMETER : OX SIDE - 3.04 FT
FUEL SIDE - 1.68 FT

3.1.3 Feedlines - In Phase I, vacuum jacketed feedlines were modeled for cryogenic propellant feed while non-insulated lines were modeled for ambient temperature propellant feed. The line lengths were based on the current OMS-RCS line routings, and each line segment was sized by iteratively solving the Darcy pressure drop and Colebrook friction factor equations. The feedline weights were determined based on the use of 2219-T87 aluminum with a minimum gage thickness of 0.028 in. The cryogenic feedline model is illustrated in Figure 8 and includes weights for multi-layer insulation, vacuum jacketing, and linear/angular compensation joints. Feedline support weights were also calculated based on the feedline weight and weight of propellant contained in the feedline. A typical computer output summary is shown in Table XI for a cryogenic RCS LOX feedline. This summary includes the weights for feedline isolation valves.

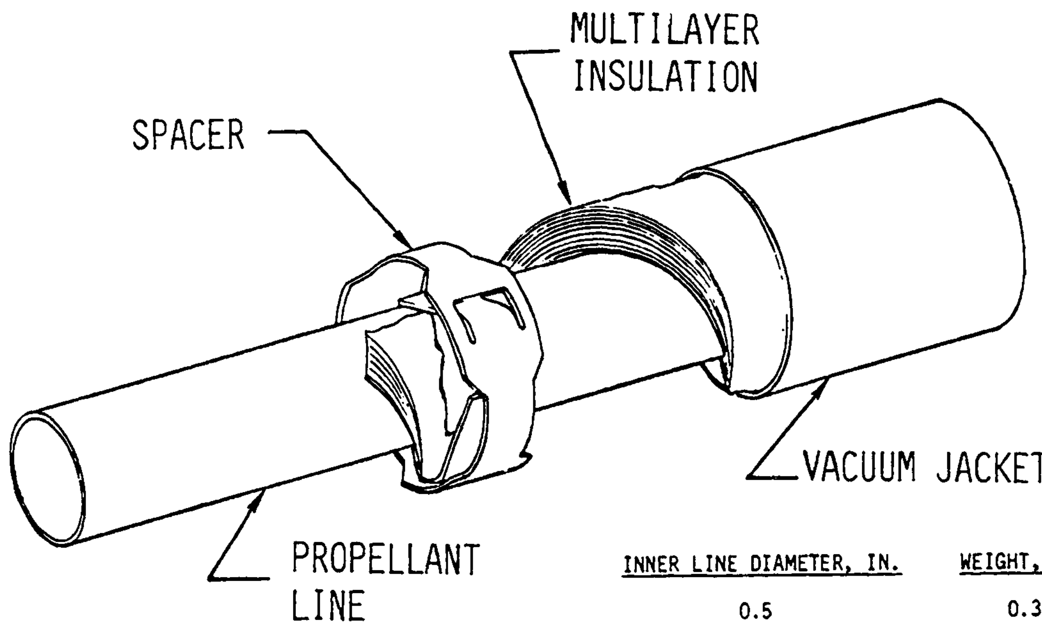
3.1.4 Engines - Engine system component weight and performance data were developed by ALRC and were provided in Volume II--Parts A and B of Reference (1). Included in the engine system are the turbopumps, gas generators, thrust chamber assemblies, and valving. The OMS engine was assumed to be fuel regen-cooled, while the RCS thruster was assumed to be film-cooled. OMS engine and RCS thruster lengths and diameters were constrained to their current values.

3.2 TKHEAT Code

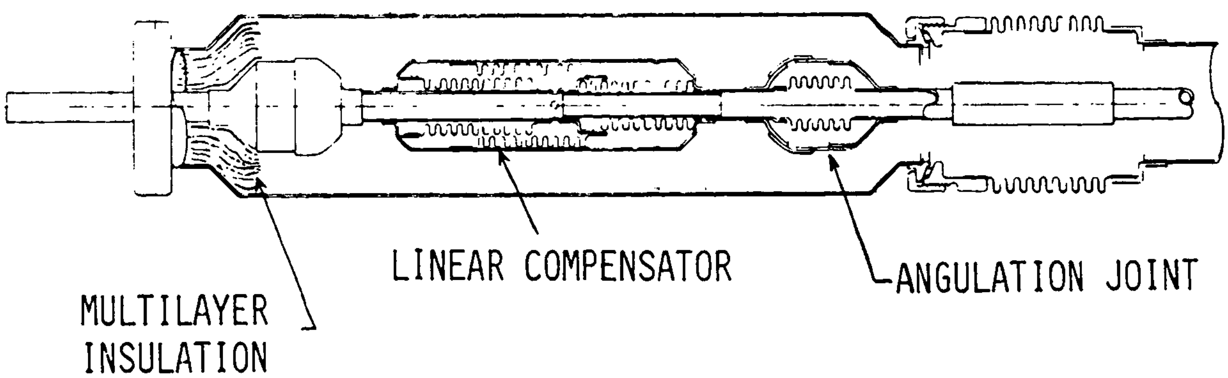
This code was developed to determine the thermodynamic response of cryogenic propellant tanks and accumulators during representative orbital mission duty cycles. The basic cryogenic tank model (Figure 6) consists of a pressure vessel, insulation system, an optional thermodynamic vent system, and optional outer cover. The insulation system can be a single component or a composite type system, i.e., foam and multi-layer insulation.

The operation of the thermodynamic vent system (TVS) is shown in Figure 9. In this system propellant is vented to maintain acceptable tank pressure and temperature levels. Vent propellant is withdrawn from the tank in a liquid phase through the propellant acquisition assembly. After throttling to a lower pressure and temperature it is passed through a tank heat exchanger where it is vaporized by heat entering the tank. This TVS concept eliminates the propellant positioning

ORIGINAL PAGE IS
OF POOR QUALITY



INNER LINE DIAMETER, IN.	WEIGHT, LB/FT
0.5	0.36
1.5	0.54
2.5	1.00



INNER LINE DIA., IN.	COMPENSATOR TOTAL WEIGHT, LB
.5	3.7 LBS
1.0	3.8 LBS
1.5	4.0 LBS

FIGURE 8 CRYOGENIC PROPELLANT FEEDLINE MODEL

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE XI
EXAMPLE APSDS OUTPUT -- RCS LOX FEEDLINE

RCS OXIDIZER SIDE PROPELLANT FEEDLINE MODEL (PER POD)

LINE NO.	NO. OF LNS	DESIGN THRUST (LBS)	LEN (IN)	DI (IN)	IN LINE THICK (IN)	TUB WT (LBS)	ANG JNT WT (LBS)	LIN CMP WT (LBS)	VALVE WT (LBS)
1	1	6090.0	128.30	1.727	.028	1.988	.679	.684	-
2	1	4350.0	8.50	1.517	.028	.116	-	-	4.315
3	1	4350.0	4.80	1.517	.028	.065	-	-	4.315
4	1	4350.0	8.50	1.517	.028	.116	-	-	4.315
5	1	4350.0	4.60	1.517	.028	.063	.588	.021	-
6	1	4350.0	16.50	1.517	.028	.225	.588	.076	-
7	1	4350.0	7.10	1.517	.028	.097	.588	.033	-
8	1	2610.0	14.40	1.246	.028	.161	-	-	-
9	1	2610.0	5.00	1.246	.028	.056	-	-	-
10	1	2610.0	2.50	1.246	.028	.028	-	-	-
11	1	2610.0	6.00	1.246	.028	.067	-	-	-
12	1	25.0	142.00	.243	.028	.309	.086	.269	-
13	1	2610.0	78.80	1.246	.028	.881	.475	.300	3.290
14	1	870.0	54.30	.816	.028	.398	-	-	-
15	1	870.0	33.10	.816	.028	.242	-	-	-
16	1	870.0	35.30	.816	.028	.259	-	-	-
17	1	2610.0	90.10	1.246	.028	1.007	.475	.344	3.290
18	1	870.0	12.00	.816	.028	.088	-	-	-
19	1	870.0	31.10	.816	.028	.228	-	-	-
20	1	870.0	21.80	.816	.028	.160	-	-	-
21	1	2610.0	84.90	1.246	.028	.949	.475	.324	3.290
22	1	870.0	11.50	.816	.028	.084	-	-	-
23	1	870.0	28.00	.816	.028	.205	-	-	-
24	1	870.0	28.60	.816	.028	.209	-	-	-
25	1	2610.0	51.40	1.246	.028	.575	.475	.196	3.290
26	1	870.0	10.80	.816	.028	.079	-	-	-
27	1	870.0	32.90	.816	.028	.241	-	-	-
28	1	870.0	23.90	.816	.028	.175	-	-	-
					TOTAL	9.069	4.430	2.247	26.104

TOTAL LINE DRY WEIGHT - 41.85 LBS
TOTAL PROPELLANT IN LINES - 2.26 LBS
TOTAL LINE SUPPORT WEIGHT - 1.88 LBS

LINE DELTA-P/L - 1.00 PSI/FT

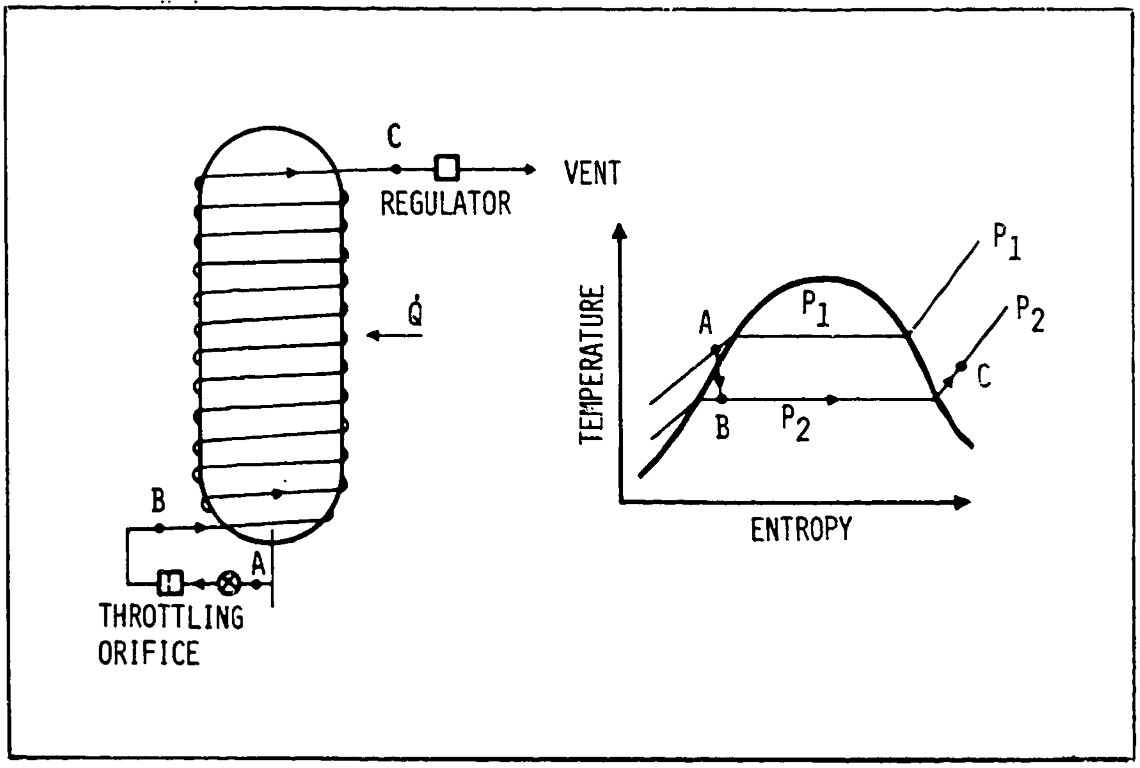


FIGURE 9 THERMODYNAMIC VENT SYSTEM CONCEPT

problems associated with vapor phase tank venting and reduces the heat flux into the tank. The TKHEAT code can evaluate the relative effectiveness of TVS heat exchanger lines mounted directly on the pressure vessel or on a cooling shroud that surrounds but is displaced from the pressure vessel.

The tank thermal model is illustrated in Figure 10 for an installation within the Orbiter aft pod. The steady state one-dimensional heat transfer equations are solved using an implicit finite difference technique. The surface boundary condition is obtained by calculating the net solar flux entering the thermal tiles at surface 1 or by specifying vehicle skin internal temperature at surface 2. A uniform state approximation is applied to the fluid within the propellant tank. The fluid inside the tank can be single or multi-phase, homogeneous (propellant only), or heterogeneous (propellant and pressurant gas).

Engine, vent and gas pressurization valve operations are modeled to calculate the thermodynamic response of fluid within the tank. Fluid pressure and temperature response are determined by solving the unsteady flow forms of the conservation of mass and the first law of thermodynamics using an implicit finite difference technique. A simplified flow diagram for the TKHEAT code is provided in Figure 11.

To validate the code computed results were compared with prior experimental data obtained on an MDAC-STL prototype cryogenic tank using liquid nitrogen as the test fluid. The tank was spherical in shape, had a diameter of 39 in., and was constructed of Inconel 718. The insulation system consisted of 2 in. of foam and 2 in. of aluminized mylar multi-layer insulation (MLI). The tank also employed a thermodynamic vent system. As shown in Figure 12, test data obtained from this tank compare very well with analytic predictions using the TKHEAT code.

The TKHEAT code was used to evaluate propellant tank heating and venting during typical OMS/RCS missions. Example LOX tank results for an OMS 30 day mission are presented in Figure 13. LOX tank venting initiates when the tank total pressure reaches 60 psia and terminates when the total pressure decays to 57 psia. The total LOX vent loss is just over 200 lb.

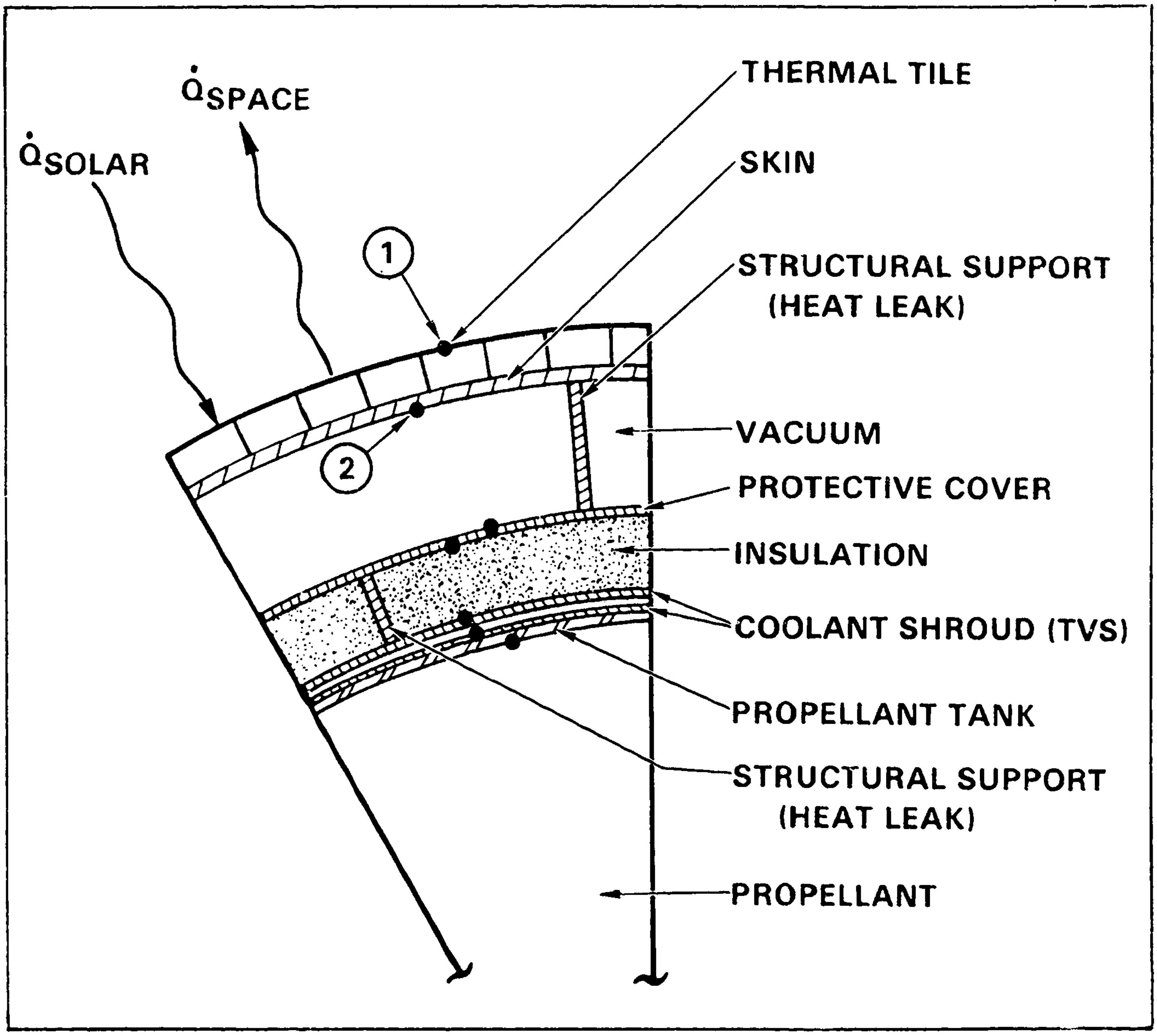


FIGURE 10 TANK THERMAL MODEL

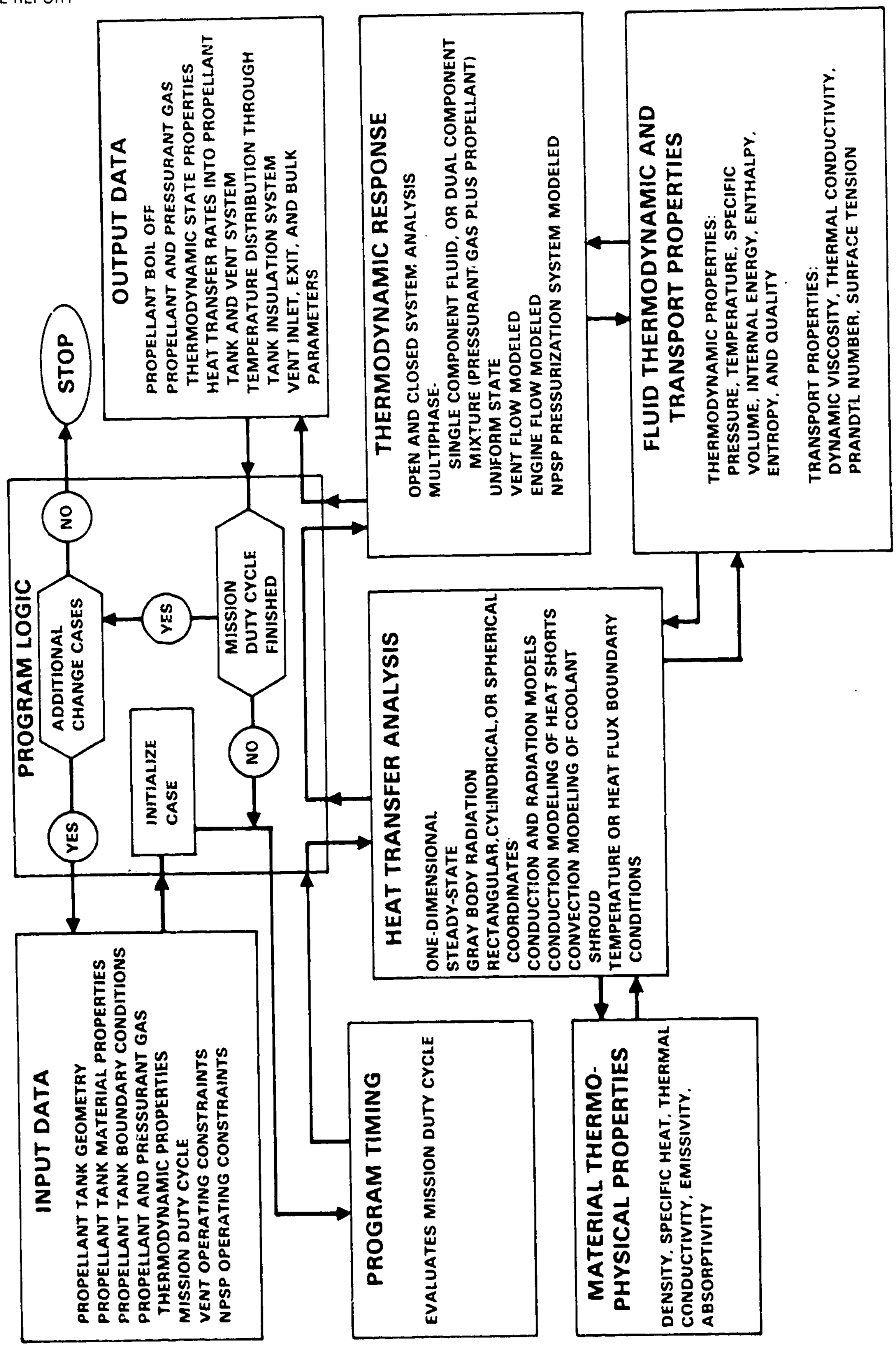


FIGURE 11 TKHEAT FLOW DIAGRAM

ORIGINAL PAGE IS
OF POOR QUALITY

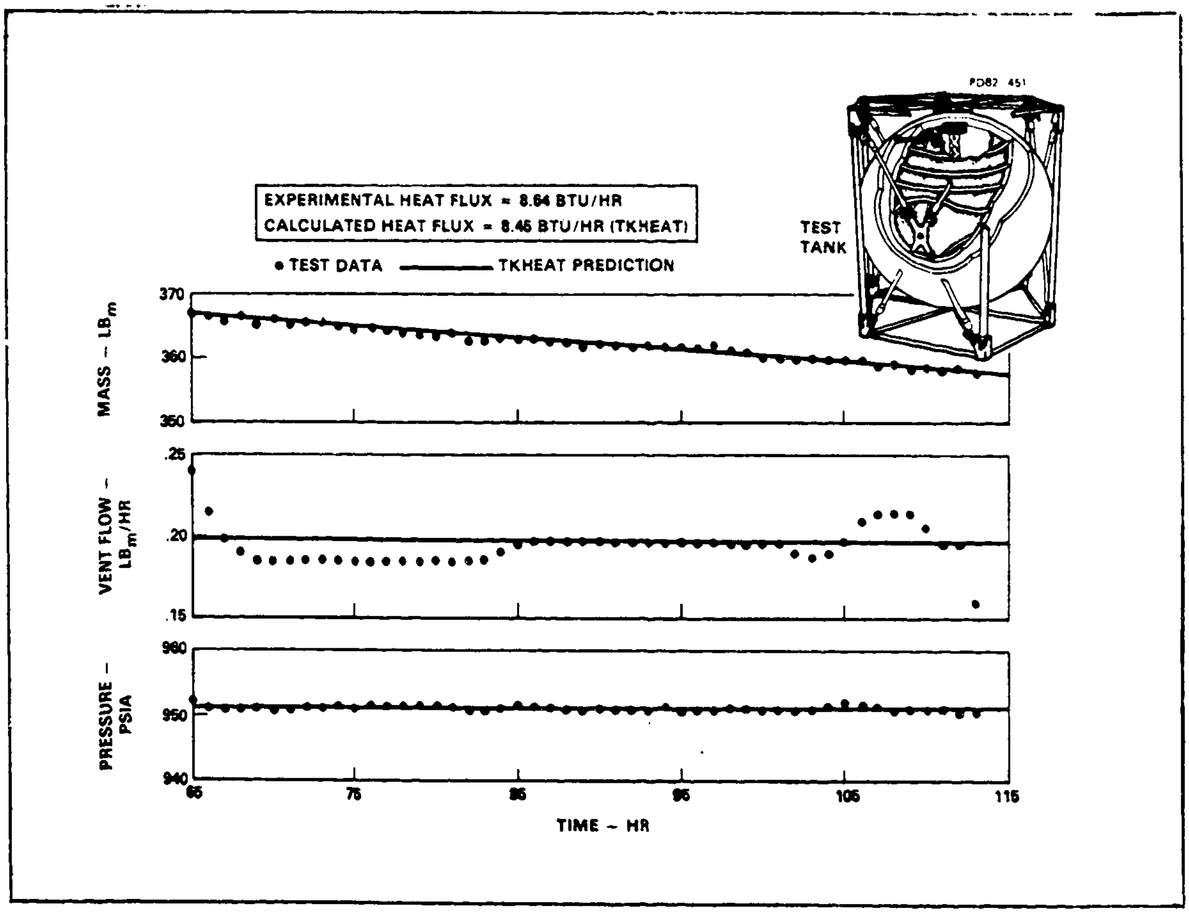


FIGURE 12 COMPARISON OF TKHEAT CODE WITH TEST DATA

- INITIAL LOX LOAD ~ 9350 LB_M
- RELIEF PRESSURE = 60 PSIA

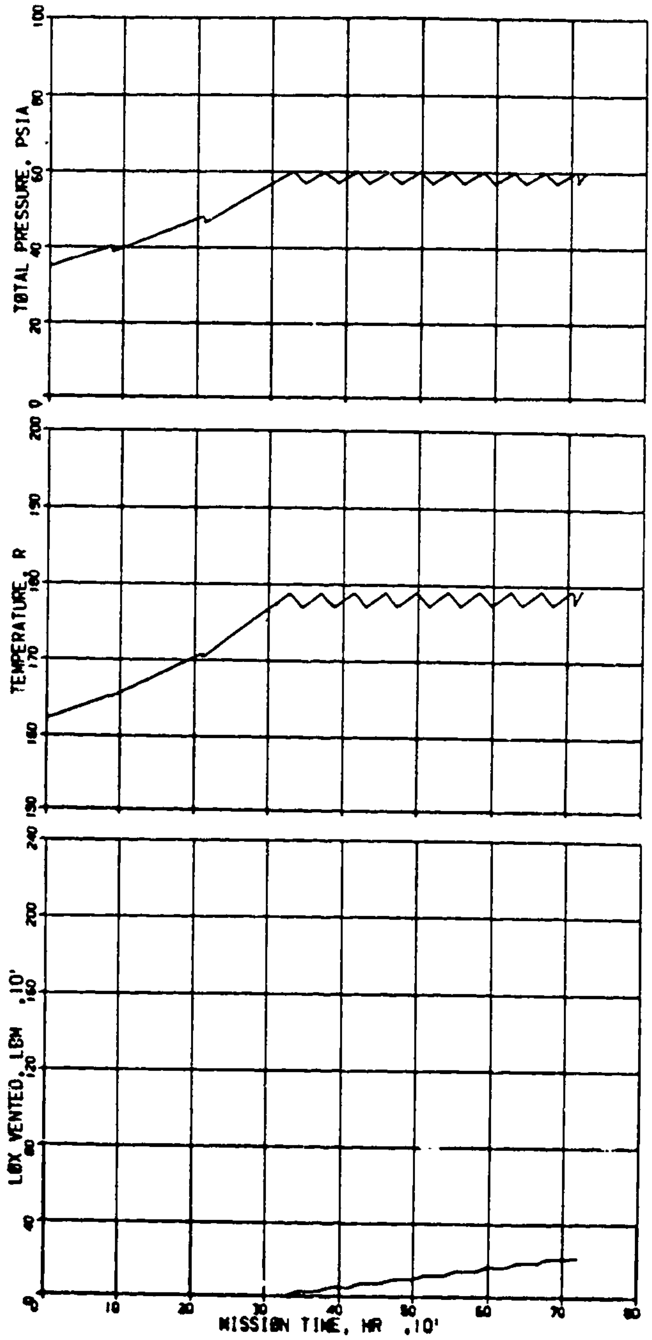


FIGURE 13 EXAMPLE TKHEAT COMPUTATIONS FOR OMS LOX TANK

3.3 FDLINE Code

This code was developed to determine the thermal response of propellant feedlines during orbital mission duty cycles.

The propellant thermal response is computed by first dividing the feedline into segments as illustrated in Figure 14. The conservation of mass and energy equations for each segment are solved simultaneously by an implicit finite difference method for each time step. A two-dimensional transient heat transfer analysis of the feedline segments is performed. Heat transfer is by conduction through the insulation, along the feedline, and through structural members (such as line supports). The outer surface insulation temperature and heat leak source temperatures are fixed boundary conditions. Heat soakback from the engines into the feedlines is computed by specifying a thrust chamber injector head temperature and valve thermal isolation resistance. The propellant in the feedline is modeled as a single or multiphase, homogeneous fluid. A simplified flow diagram for the FDLINE code is presented in Figure 15.

The FDLINE code was used to compute LOX feedline temperature response during representative RCS mission duty cycles. The mission duty cycle is broken down into two distinct modes of operation--primary thruster firings and vernier thruster firings. Each primary thruster firing (~150 per mission) is modeled as a discrete pulse, whereas the vernier firings (~15,000 per mission) are modeled as a continuous burn at low flowrate.

Example LOX temperature profiles for a 30 day RCS mission are shown in Figure 16. In this example, all the RCS propellant is expended through a single primary manifold feeding all the primary and vernier thrusters necessary for Orbiter three-axis attitude control. The feedline insulation for this example consists of one inch of aluminized mylar multi-layer insulation (MLI). Despite a wide range of accumulator LOX temperatures (160 to 200°R), acceptable feedline temperatures are achieved throughout the mission.

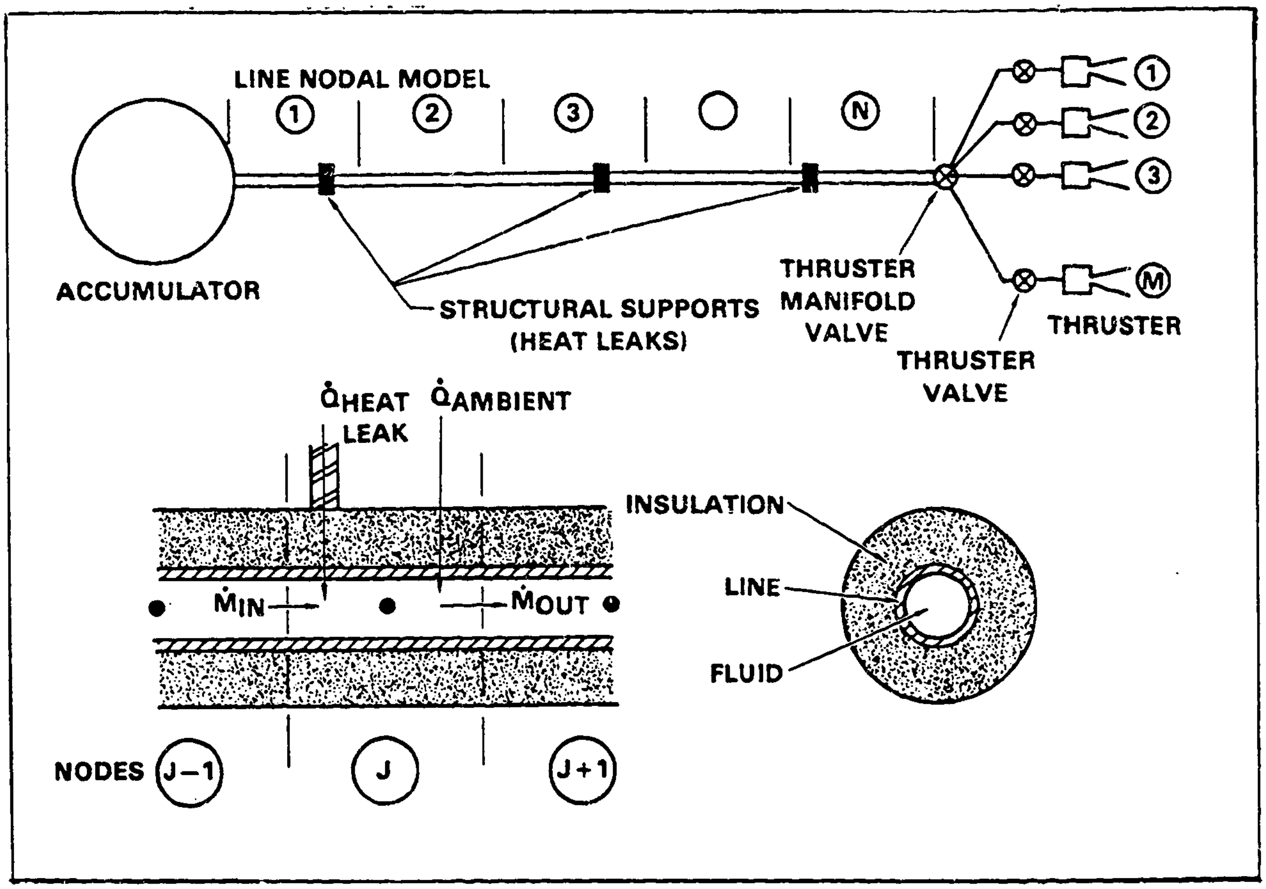


FIGURE 14 FEEDLINE THERMAL MODEL

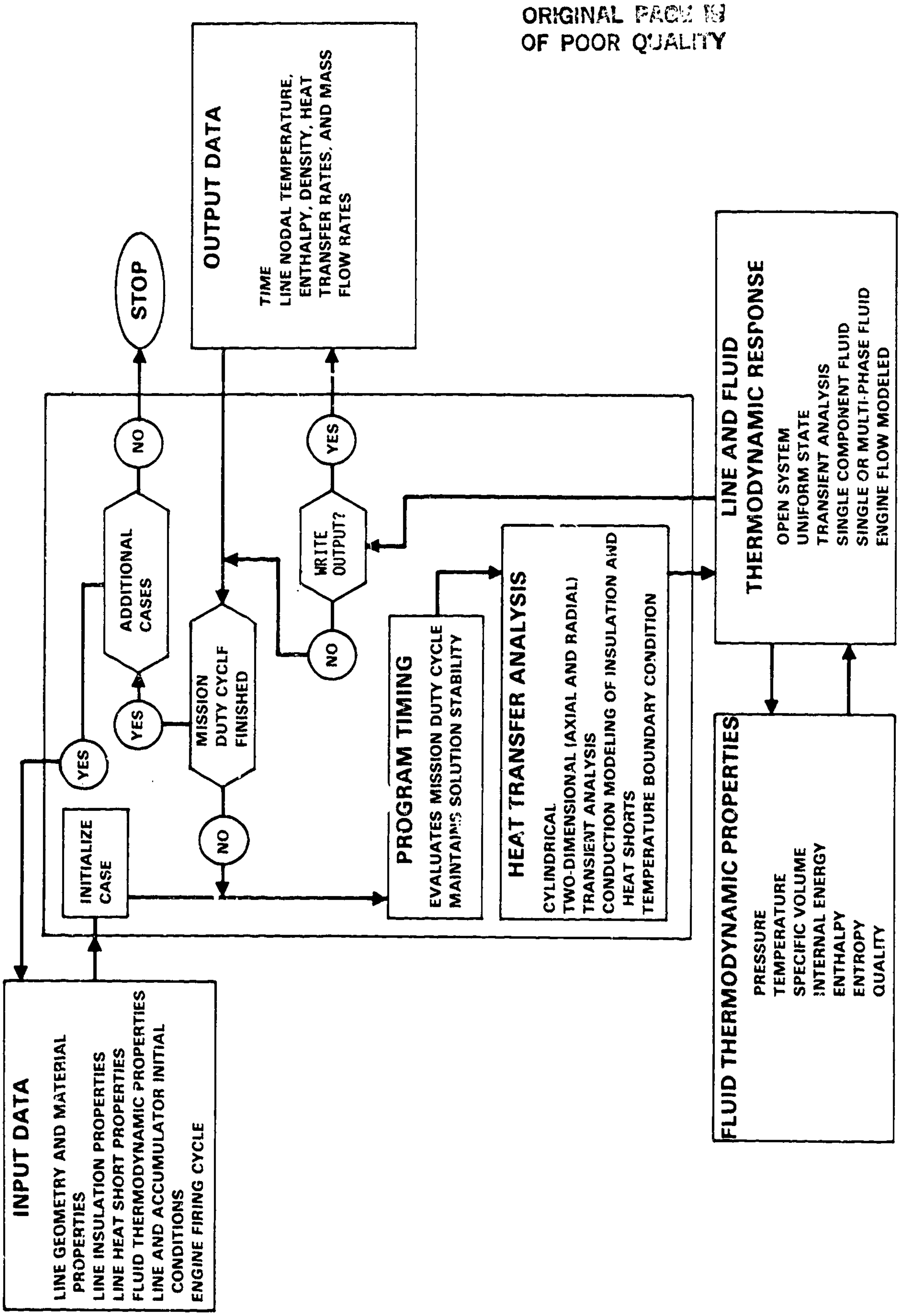


FIGURE 15 FDLINE FLOW DIAGRAM

ORIGINAL PAGE IS
OF POOR QUALITY

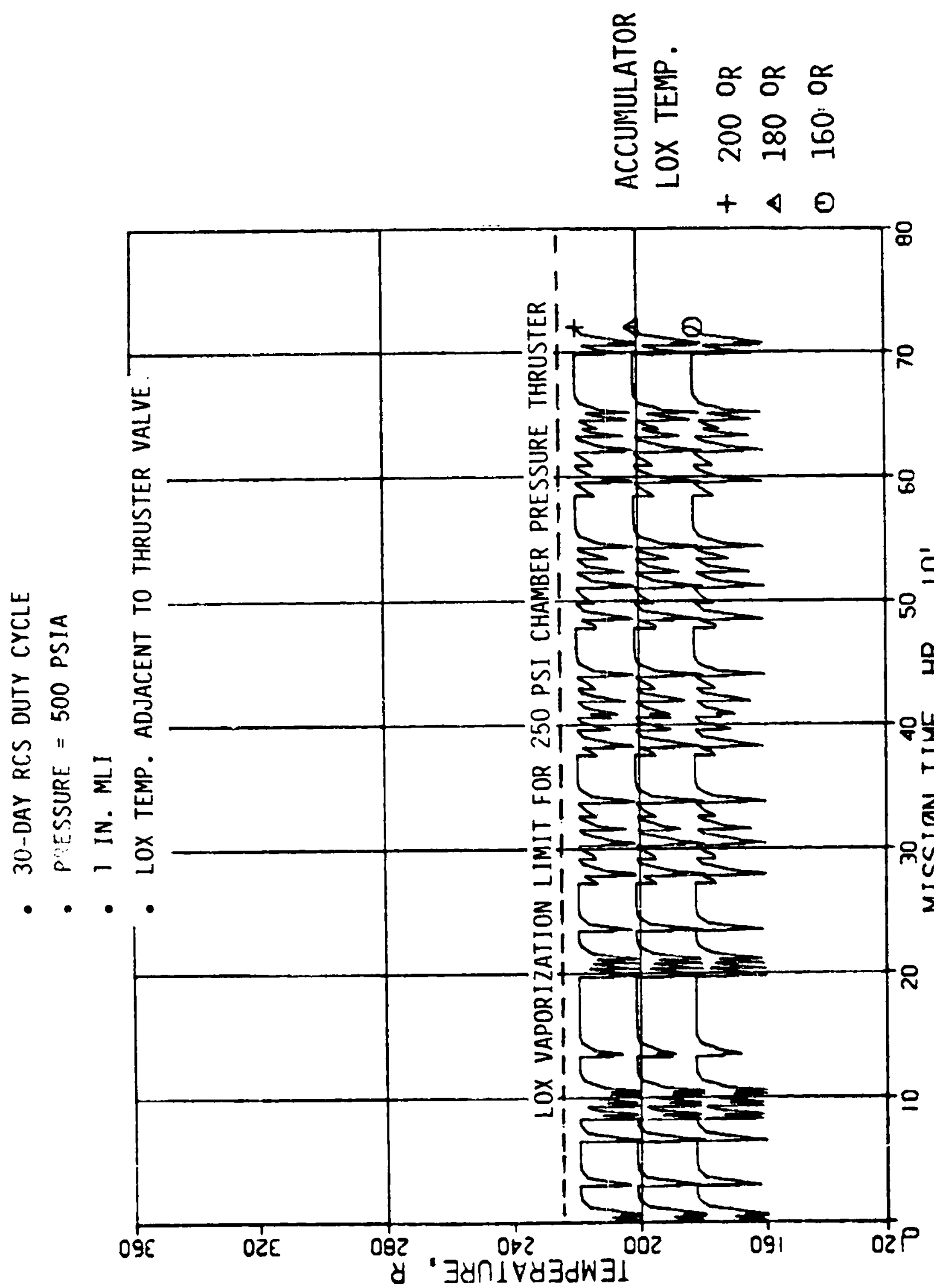


FIGURE 16 EXAMPLE FDLINE COMPUTATIONS FOR RCS LOX FEEDLINE

4.0 TASK I.3 -- PHASE I SYSTEM EVALUATIONS

The system design options established in Task I.1 (Table V) were evaluated in this task. The required system weight and performance data were generated using the APSDS computer code with engine system models supplied by ALRC. Computer output summaries for each system concept were presented in Volume II--Part C of Reference (1). The following paragraphs present the results and conclusions from these evaluations.

4.1 Pump Versus Pressure Feed

As discussed in Section 2.2.1, this option was evaluated for both the OMS and RCS, as well as, all four fuel candidates.

4.1.1 OMS - As shown in Figure 17, the pressure fed LOX/HC OMS is similar to the current OMS with exception that the helium bottle is stored inside the LOX tank. The pump fed LOX/HC OMS schematic is shown in Figure 18 and incorporates the component redundancy necessary to meet the fail operational-fail safe reliability requirement of the current OMS. The pumps are powered by gas generator driven turbines, and pump NPSP is provided by a small helium pressurization system. During startup the gas generators are supplied with propellants from small liquid accumulators that operate in a blowdown mode. As in the current OMS the engine is fuel regeneratively cooled, and a separate nitrogen supply is used for engine valve actuation. LOX and methane propellants are fed to the engine at cryogenic temperatures, and the feedlines are vented following each burn.

Even though the bulk density-specific impulse product for the LOX/HC propellants is less than for the current storable propellant combination (N_2O_4/MMH) the LOX/HC OMS provided an opportunity for improved propulsion system packaging. The reason for this can be seen by referring back to Figure 1 which shows propulsion system packaging for the current system. By storing the helium bottle inside the LOX tank the required helium volume is reduced as a result of the low storage temperature (165°R), and the propellant tanks can be extended 11.5 inches aft. The corresponding increase in available propellant tank volume

• SEE SCHEMATIC NOMENCLATURE OF FIGURES 2 & 3

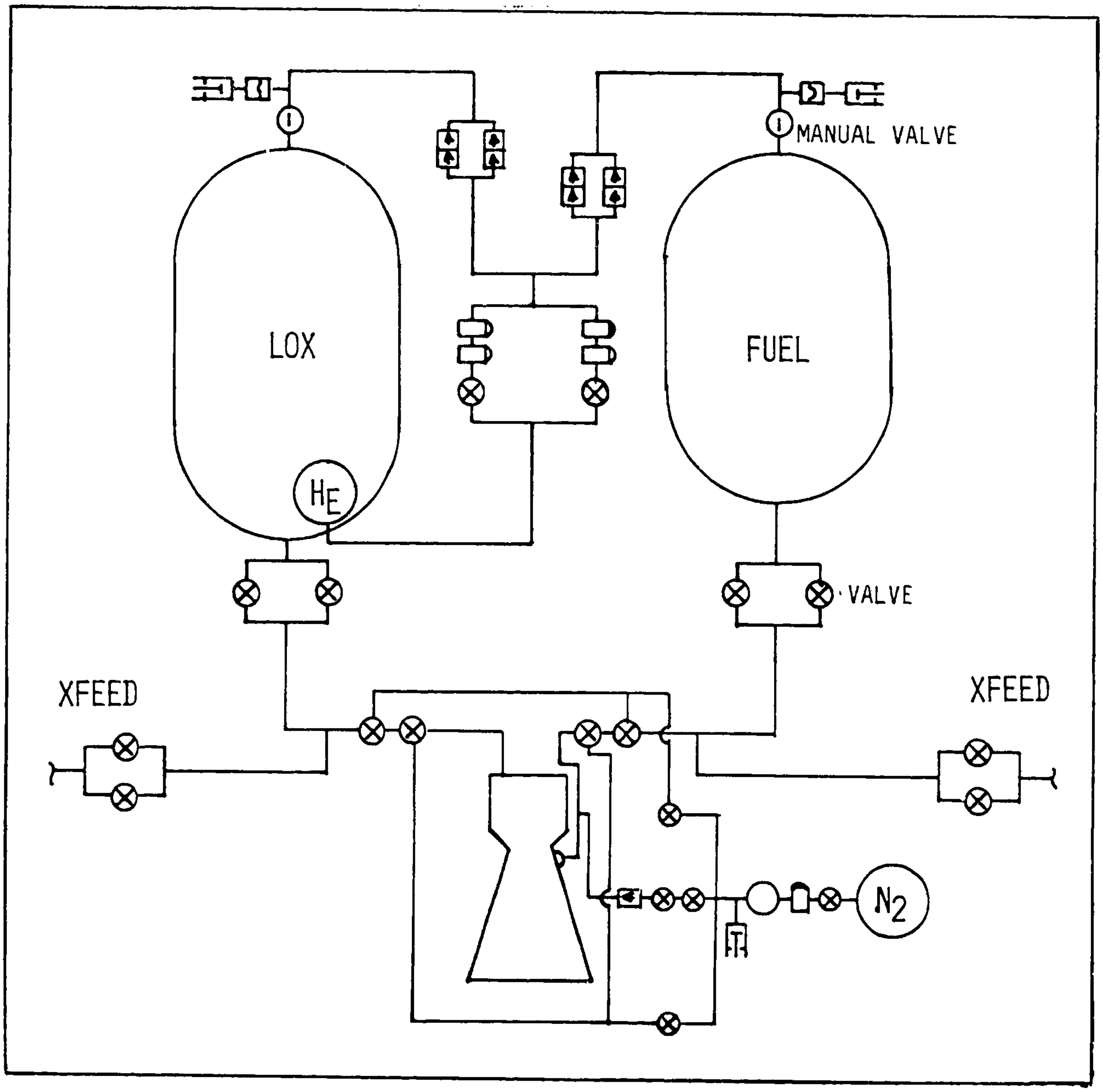


FIGURE 17 PRESSURE FED OMS SCHEMATIC

ORIGINAL PAGE IS
OF POOR QUALITY

• SEE SCHEMATIC NOMENCLATURE OF FIGURES 2 & 3

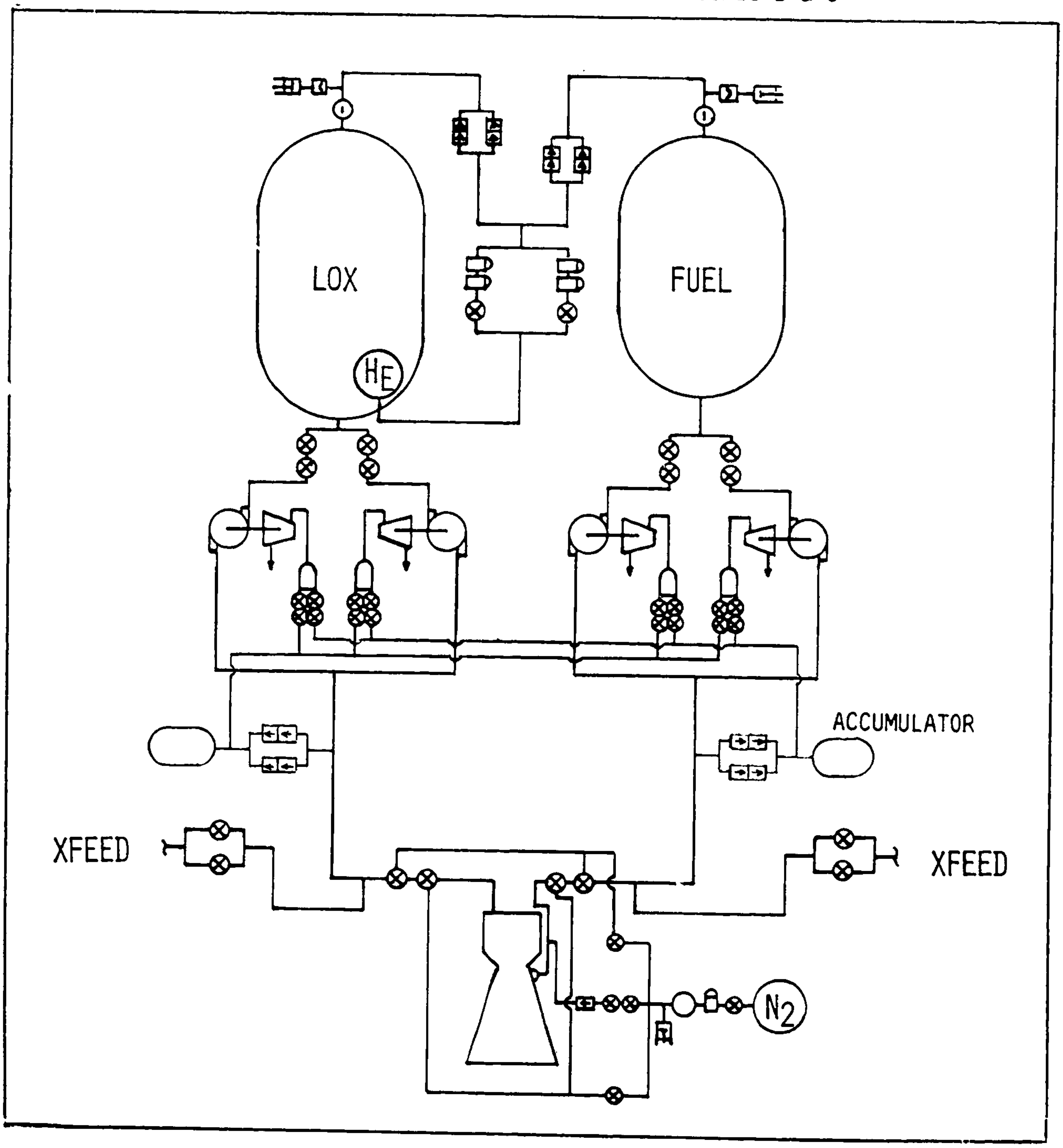


FIGURE 18 PUMP FED OMS SCHEMATIC

compensates for the lower bulk density of the LOX/HC propellants. The benefit is most pronounced for the pump fed systems which have substantially lower helium mass requirements for tank pressurization.

Based on the sensitivity data of Figure 19 for LOX/propane, an OMS chamber pressure of 800 psia was baselined for the pump fed systems in Phase I to maximize performance (ΔV capability) and minimize weight. A chamber pressure of 100 psia was selected for the pressure fed system based on prior experience.

The pump and pressure fed systems are compared in Figure 20 for all four fuel candidates. Three criteria are used in the comparison; OMS ΔV capability, OMS wet weight, and OMS dry weight. To compare OMS ΔV capability the aft pod volume was fixed at the current value. To compare wet and dry weights the ΔV capability was set equal to the current OMS value of 500 ft/sec per pod. (The dashed line in each comparison represents the capability of the current OMS.) From the comparisons of Figure 20 it is seen that the pump-fed OMS offers overriding advantages in terms of weight and performance. This is the result of the higher engine specific impulse that can be achieved with the pump fed systems. For example, the LOX/propane pump fed engine I_{SP} is 363 lbf-sec/lbm (with a nozzle area ratio of 240), while the pressure fed engine I_{SP} is only 324 lbf-sec/lbm (with a nozzle area ratio of 44). As discussed in Section 2.3 the overall engine envelope is constrained to the same dimensions as the current OMS engine. Also, from Figure 20, it is seen that ethanol offers the highest OMS ΔV capability and lowest system dry weight. This is because the LOX/ethanol combination offers the highest bulk density-specific impulse product of the candidate propellants. Although LOX/methane provides the lowest system weight (highest payload capability) for a fixed ΔV requirement, the LOX/ethanol system would be less costly since cryogenic tankage is required for the LOX side of the system, only. On the basis of these comparisons the pump fed OMS was basedlined for Phase II. For both aft pods the pump fed OMS offers a 3000-4000 lb weight advantage over the pressure fed system.

4.1.2 <u>RCS</u> - Schematics for the pressure and pump fed aft-RCS are shown in Figures 21 and 22, respectively. The forward-RCS is similar but incorporates two additional primary thrusters. Both schematics incorporate the same component

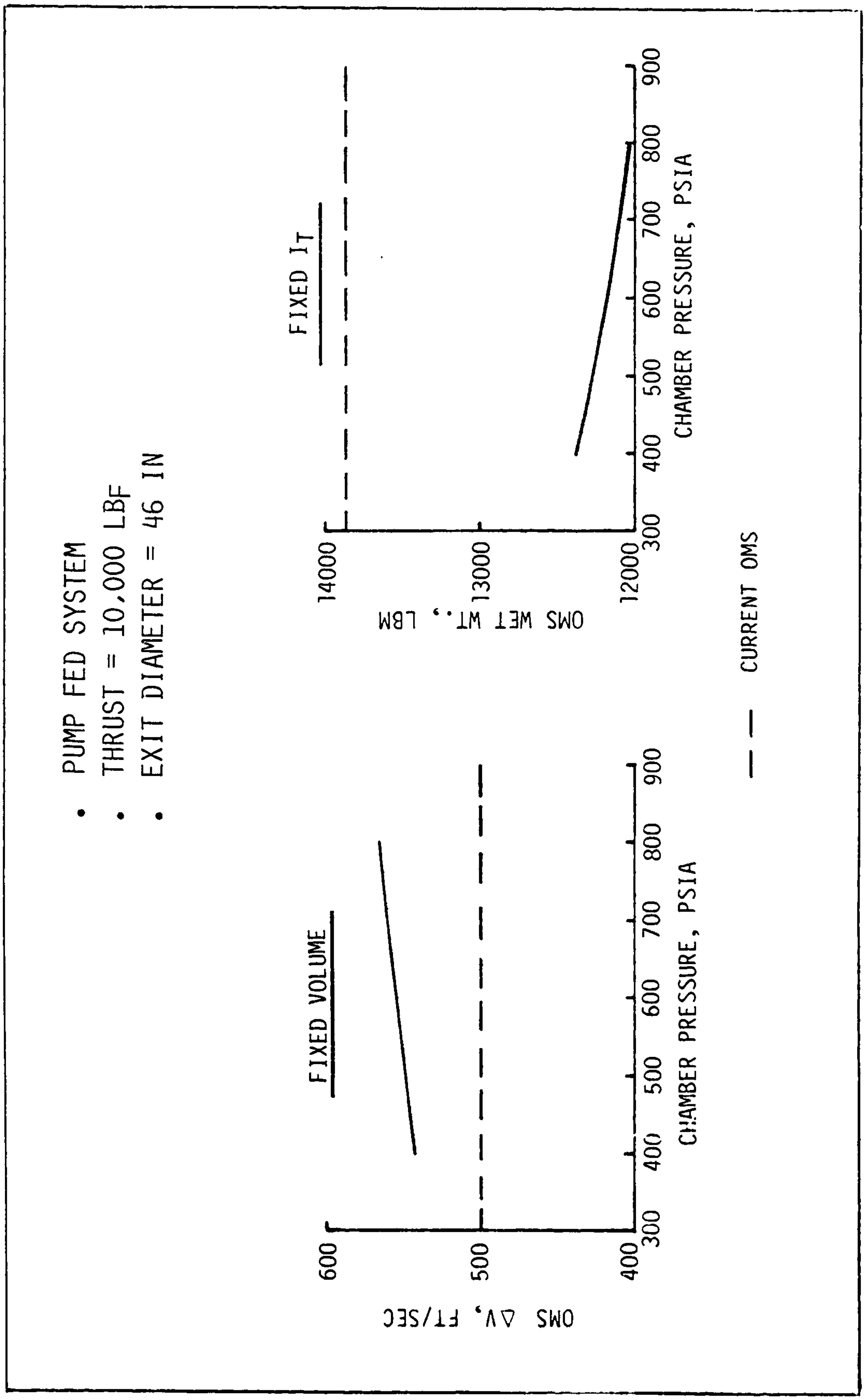


FIGURE 19 PUMP FED OMS P_C SENSITIVITY

ORIGINAL PAGE IS
OF POOR QUALITY

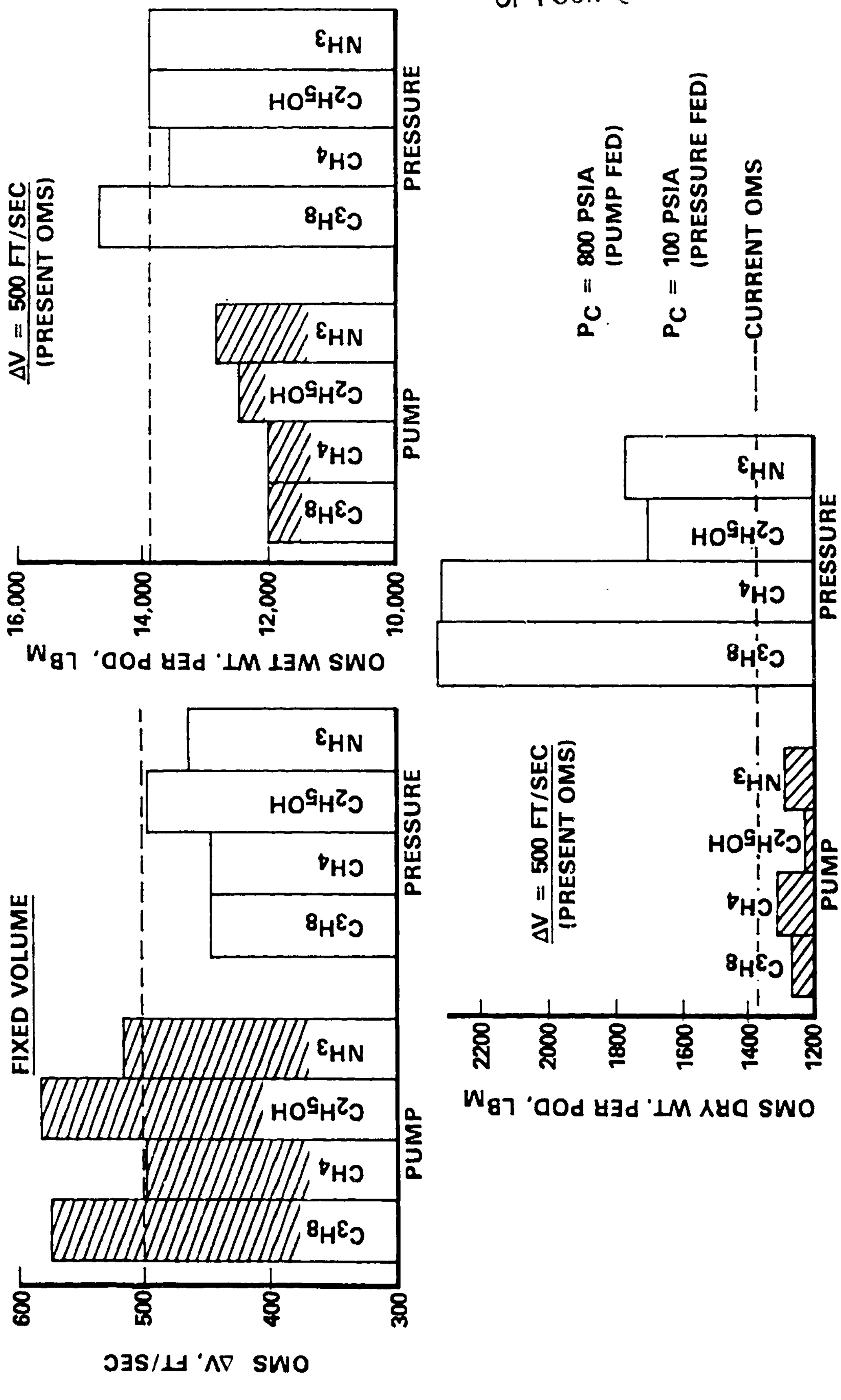


FIGURE 20 PUMP AND PRESSURE FED OMS COMPARISONS

• SEE SCHEMATIC NOMENCLATURE OF FIGURES 2 & 3

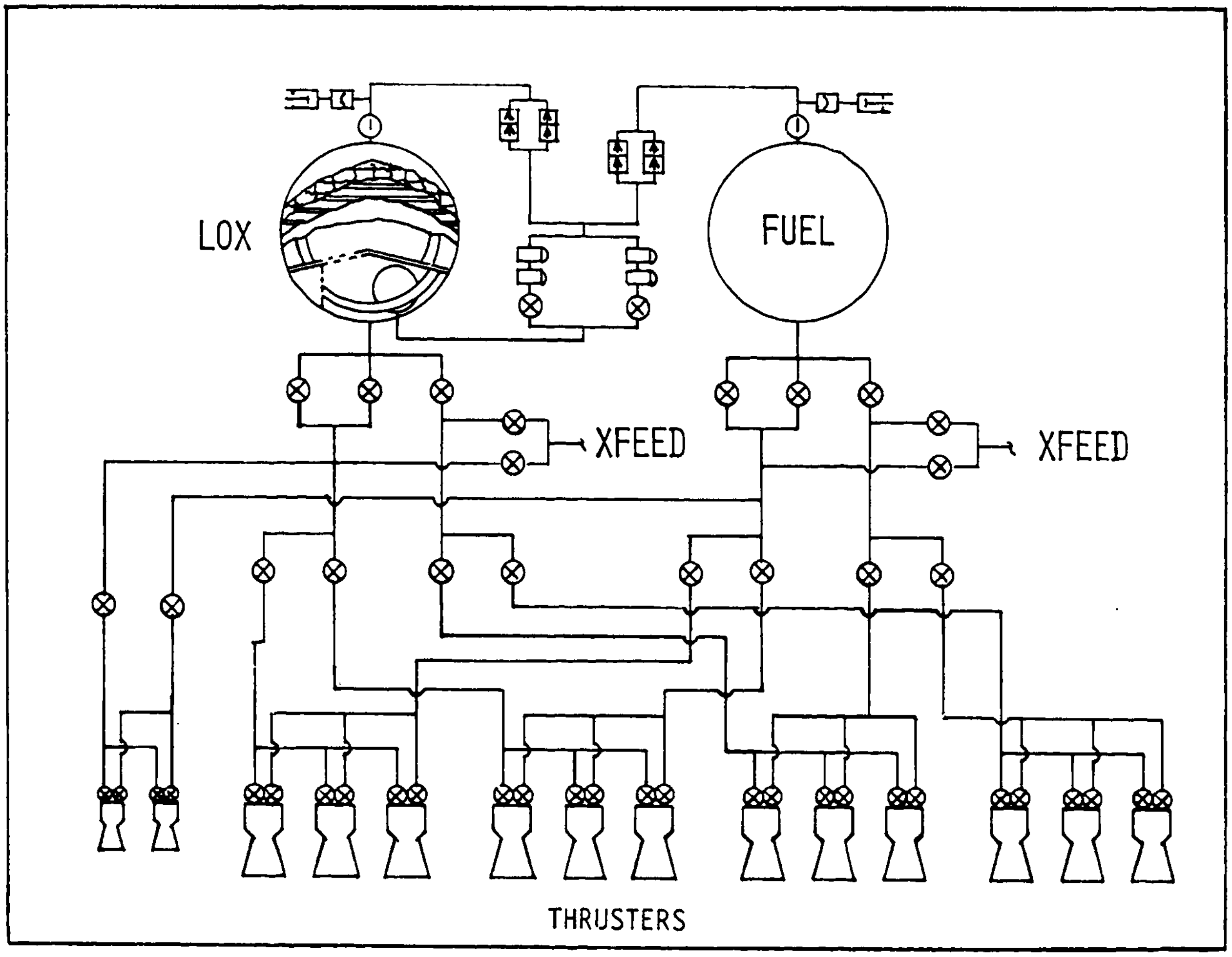


FIGURE 21 PRESSURE FED RCS SCHEMATIC

• SEE SCHEMATIC NOMENCLATURE OF FIGURES 2 & 3

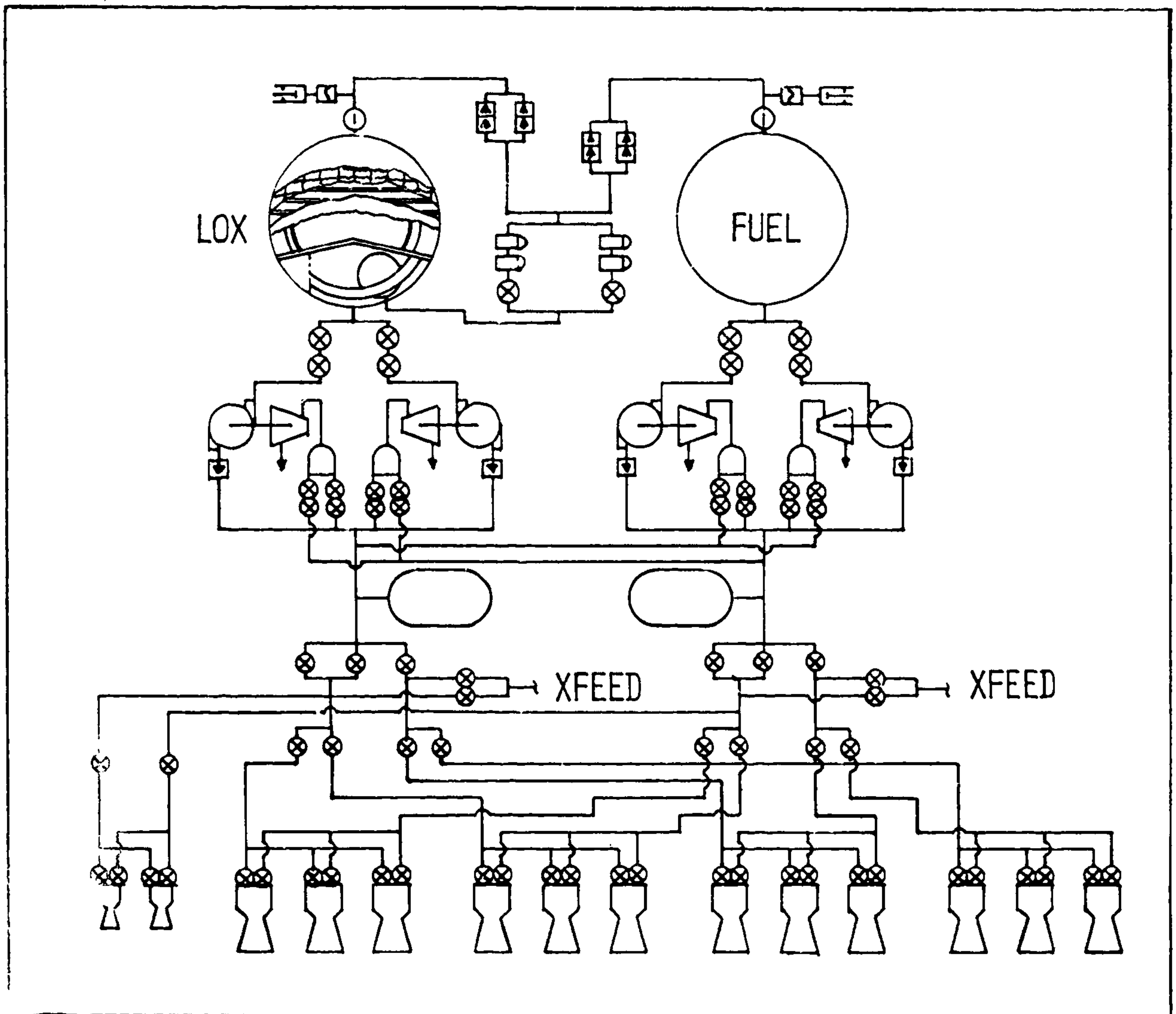


FIGURE 22 PUMP FED RCS SCHEMATIC

redundancy as the current RCS and assume liquid propellant delivery to the thrusters. As such, the LOX and methane feed systems employ insulated feedlines and accumulators. (Vacuum jacketed feedlines incorporating multi-layer insulation were baselined for these evaluations.) The pump fed RCS (Figure 22) employs OMS-type turbopumps to preclude the necessity for a second turbopump development program. System specific impulse calculations in the APSDS computer code account for I_{SP} penalties associated with the use of the OMS turbopumps and for penalties associated with pulse mode operation of the RCS thrusters. As discussed in Section 3.1.2 the accumulators of Figure 22 operate in blowdown mode while supplying impulsive propellant to the RCS thrusters. They were sized to limit the number of turbopump cycles to 50 per mission.

A comparison of pump and pressure fed RCS is presented in Figure 23 for all four fuel candidates. Similar to the OMS three criteria are used in the comparison; percent total impulse capability, wet weight, and dry weight. (100% total impulse capability corresponds to the capability of the current earth storable RCS, and the dashed lines show the wet and dry weights of the current RCS.) As shown in Figure 23, neither the pump nor pressure fed systems are able to meet the total impulse capability of the current system when constrained to the same RCS tank volume as the current aft pod. This is because of the lower bulk density-specific impulse product of the LOX/HC propellants. When sized to a fixed total impulse requirement the pump fed systems are heavier as a result of their lower system specific impulse. The lower specific impulse is due to turbine vent loss penalties. When sized to a fixed volume requirement the pump fed systems generally provide higher total impulse capability. This is due to lower system mixture ratios which permit more efficient propellant packaging within the pod. As in the case of the OMS, the LOX/ethanol propellant combination provides the highest ΔV capability and lowest dry weight.

The comparisons of Figure 23 were performed for a RCS thruster chamber pressure of 150 psia. The performance and weight sensitivities of the pump and pressure fed systems to chamber pressure are presented in Figure 24 for LOX/propane. These data show that the near optimum chamber pressures are 300 and 100 psia for the pump and pressure fed systems, respectively. When compared at their near optimum chamber pressures it is seen that the pump and pressure fed

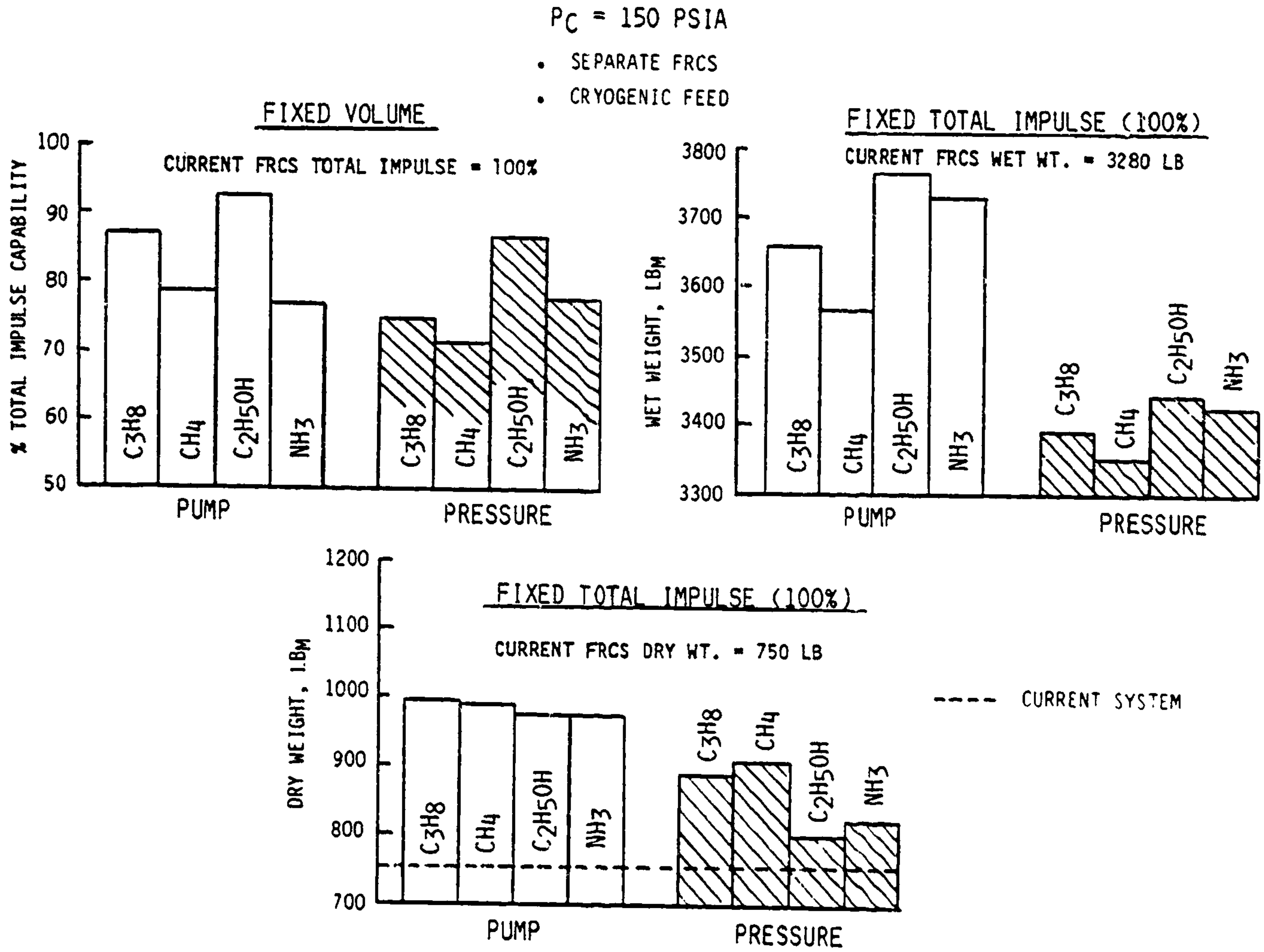


FIGURE 23 PUMP AND PRESSURE FED RCS COMPARISONS

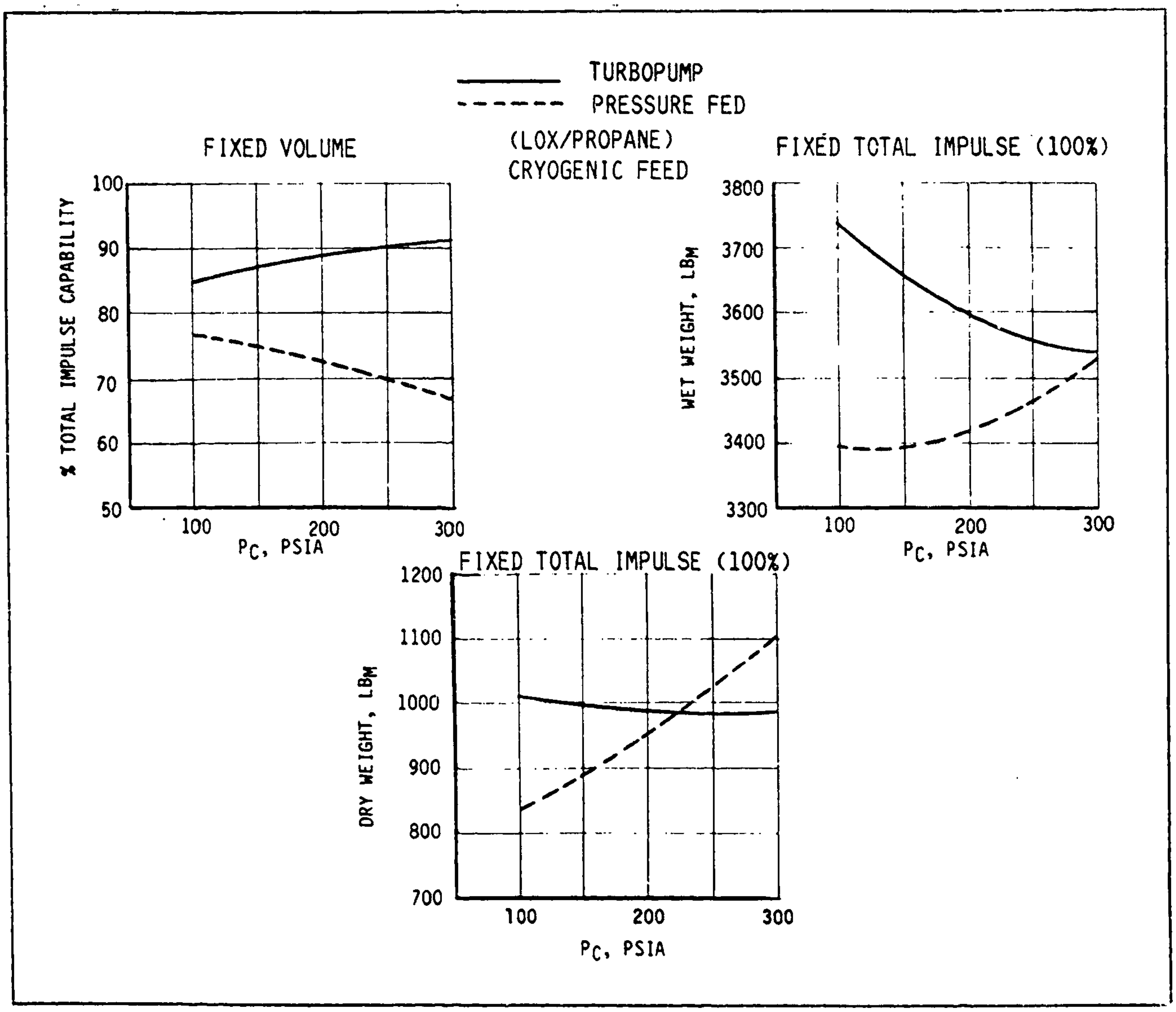


FIGURE 24 RCS P_C SENSITIVITY (PUMP AND PRESSURE FED SYSTEMS)

systems are more competitive in terms of weight and performance than at 150 psia. Because of the competitiveness of the two systems the pump versus pressure fed option was selected for further evaluation in Phase II. Also, it was decided to consider electric RCS pumps in order to increase system performance and decrease feed system complexity.

4.2 NBP Versus Subcooled Fuel Storage

As discussed in Section 2.2.2, propane has a low freezing point and can be stored at LOX temperatures with a 25% increase in density. This increased density offers the potential for increased ΔV capability. Initial evaluations showed that only a limited OMS ΔV advantage could be achieved with subcooled propane storage because of the constraint of equal fuel and oxidizer tank lengths (Table VI). Because of the high LOX/propane mixture ratio requirement the OMS LOX tank was near its maximum allowable diameter. Therefore, even though the propane volume could be reduced with subcooling, the oxidizer tank diameter could not be increased sufficiently to provide enhanced ΔV capability. As a result an alternate design approach was considered in which the pod aft bulkhead was divided to allow lengthening the LOX tank. To accommodate the longer LOX tank the O_2 turbomachinery and accumulators were relocated to the fuel side of the pod as shown in Figure 25. Figure 26 compares the OMS ΔV capabilities for NBP and subcooled propane storage and shows a substantial ΔV improvement with the extended LOX tank. This ΔV enhancement must be balanced against the increased thermal control complexity associated with subcooled propane storage (cryogenic fuel tank as well as oxidizer tank) and the restricted access to the accumulators and turbopumps for maintenance as a result of the compact packaging on the fuel side of the pod.

4.3 Cryogenic Versus Ambient Temperature RCS Propellant Feed

As discussed in Section 2.2.3 ambient temperature propellant feed eliminates the need for insulation on the RCS accumulators and feedlines but reduces overall system performance as a result of I_{sp} penalties associated with propellant thermal conditioning. As shown in Figure 27 the ambient temperature feed system for the LOX/ethanol, LOX/propane, and LOX/ammonia RCS is a hybrid concept in which gaseous

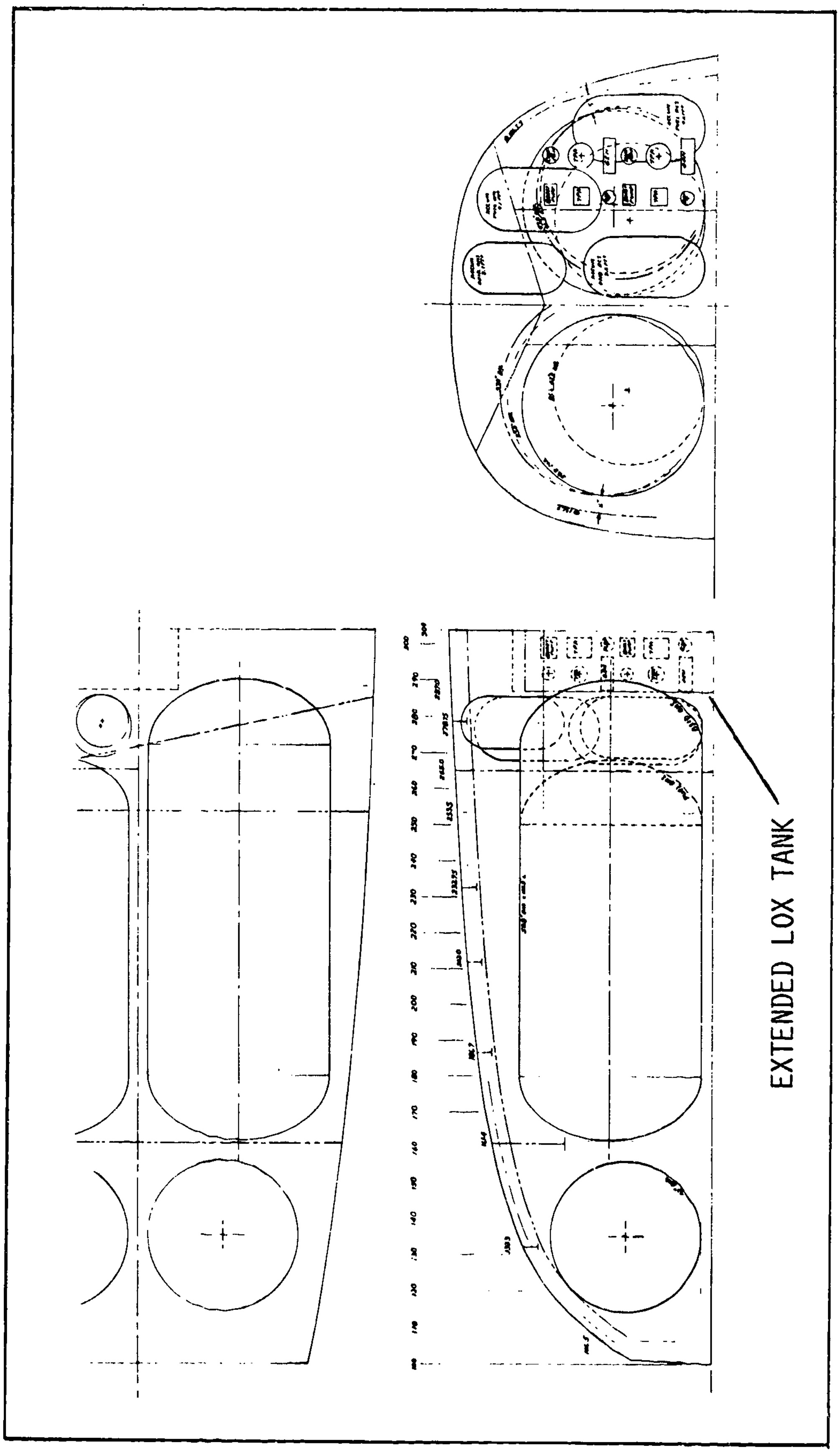


FIGURE 25 POD LAYOUT SKETCH FOR SUBCOOLED PROPANE STORAGE

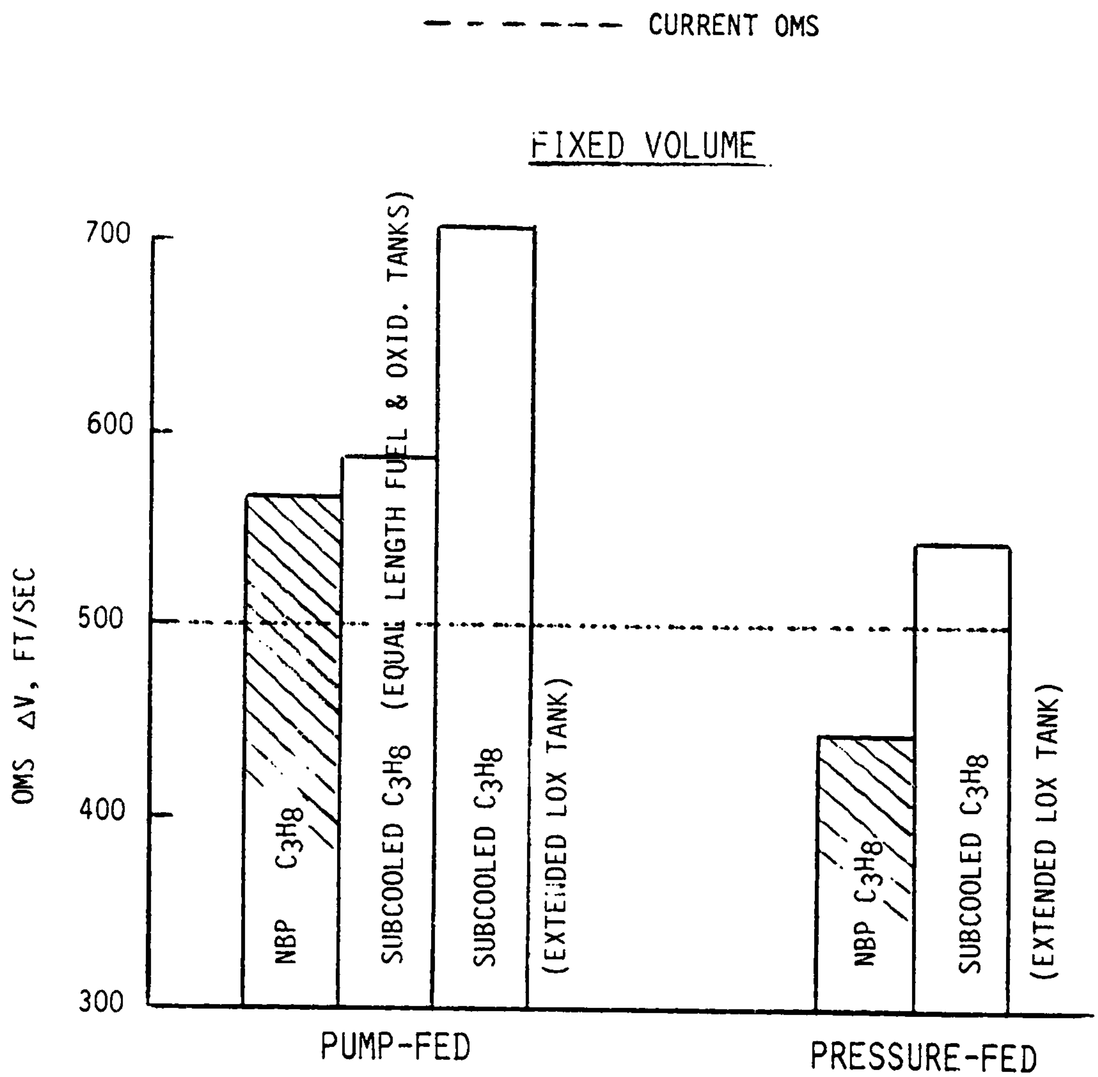


FIGURE 26 OMS ΔV COMPARISON FOR NBP AND SUBCOOLED PROPANE STORAGE

• SEE SCHEMATIC NOMENCLATURE OF FIGURES 2 & 3

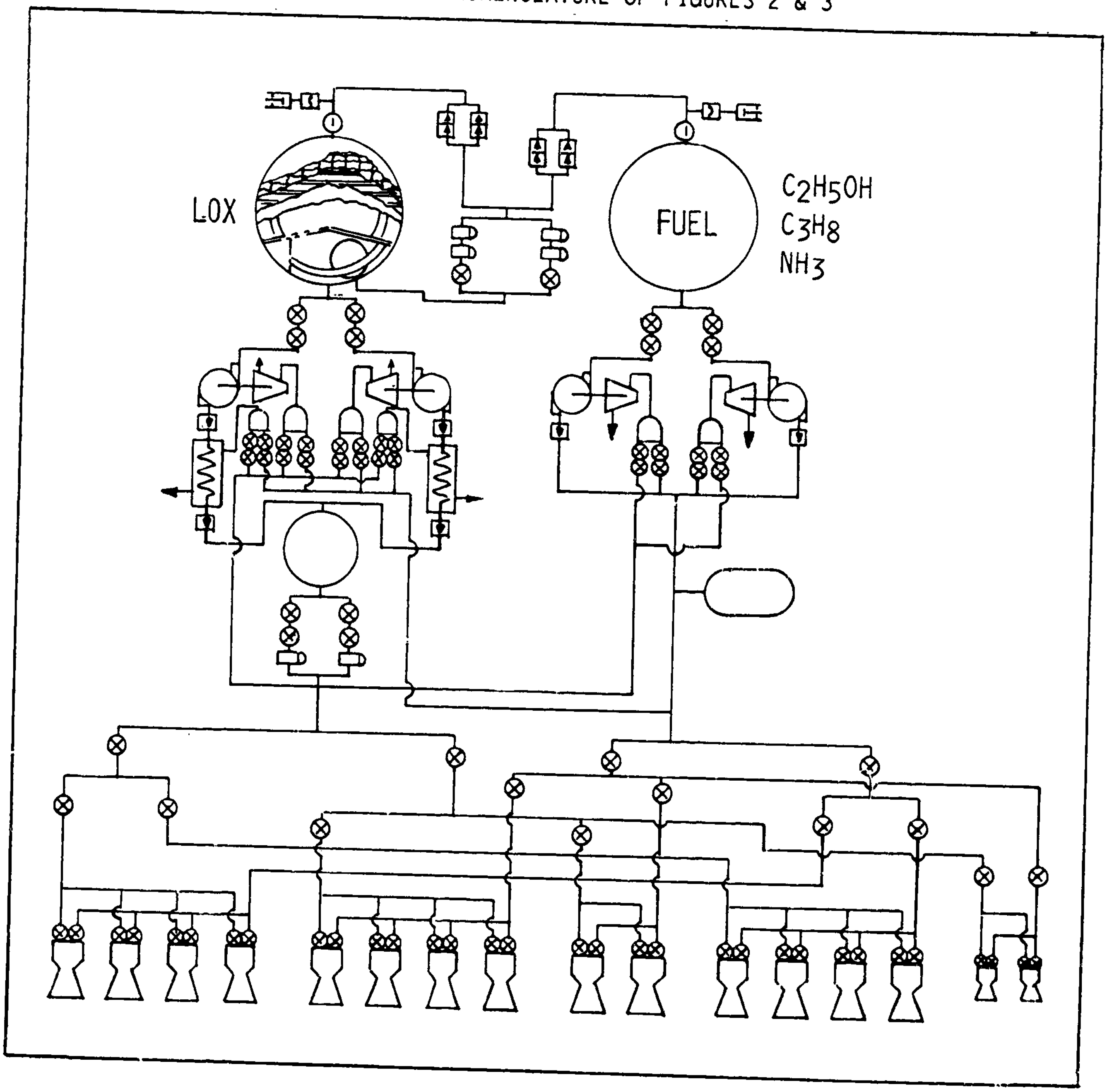


FIGURE 27 AMBIENT PROPELLANT TEMPERATURE FEED RCS SCHEMATIC (GASEOUS O_2/LIQUID FUEL)

oxygen and liquid fuel are delivered to the thrusters. Oxygen thermal conditioning is achieved in a tube-in-shell heat exchanger in which the hot side is supplied with combustion products from a separate gas generator assembly. The use of a separate gas generator allows independent development of the heat exchanger and turbopump assemblies. In the LOX/methane ambient temperature RCS feed system both oxygen and fuel are thermally conditioned to a gaseous state as shown in Figure 28. The performance and weight sensitivities of the gas/liquid and gas/gas ambient temperature feed systems to RCS chamber pressure are presented in Figure 29. As shown, the near optimum RCS chamber pressure for both systems is 250 psia.

The cryogenic and ambient propellant temperature RCS feed systems are compared in Figure 30 in terms of weight and performance. As shown, the ambient temperature feed systems are heavier and provide lower total impulse capability as a result of I_{SP} penalties associated with propellant thermal conditioning. The I_{SP} penalties are greatest for the LOX/methane system because of the requirement to thermally condition both the oxidizer and fuel. The LOX/ethanol RCS is the most attractive ambient temperature feed system because of its higher total impulse capability. The thermal conditioning energy requirement is lower for the LOX/ethanol RCS as a result of its lower thruster mixture ratio (1.4 for LOX/ethanol as compared to 2.2 for LOX/propane and 2.4 for LOX/methane). Because of this LOX/ethanol ambient temperature RCS feed systems were selected for further evaluation in Phase II. In addition it was decided to consider passive O_2 thermal conditioning approaches to improve system performance and reduce weight.

4.4 Common Versus Separate OMS/RCS Tanks

Common propellant tanks were evaluated for the OMS and aft RCS, as well as the OMS, aft RCS, and forward RCS, in order to increase propellant utilization flexibility and reduce the number of system components.

4.4.1 Common OMS-Aft RCS Propellant Tanks - A schematic for an OMS-aft RCS with common propellant tanks is presented in Figure 31. The entry sumps, which are located just downstream of the main propellant tanks, are sized to provide propellants to the aft RCS thrusters during the entry phase of the mission. They are filled to capacity prior to launch and remain full during the orbital phase.

• SEE SCHEMATIC NOMENCLATURE OF FIGURES 2 & 3

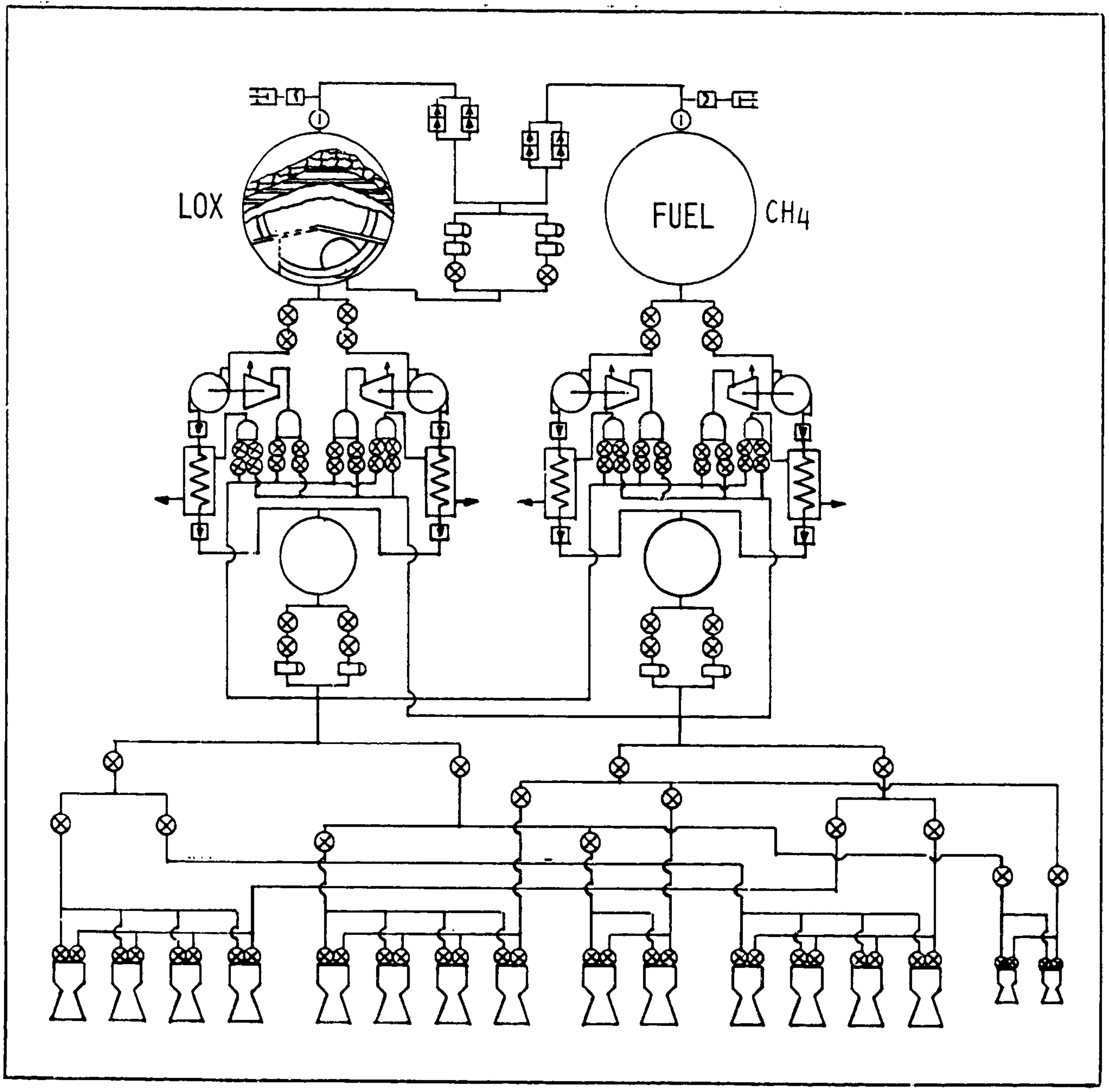


FIGURE 28 AMBIENT PROPELLANT TEMPERATURE FEED RCS SCHEMATIC (GASEOUS O_2/GASEOUS FUEL)

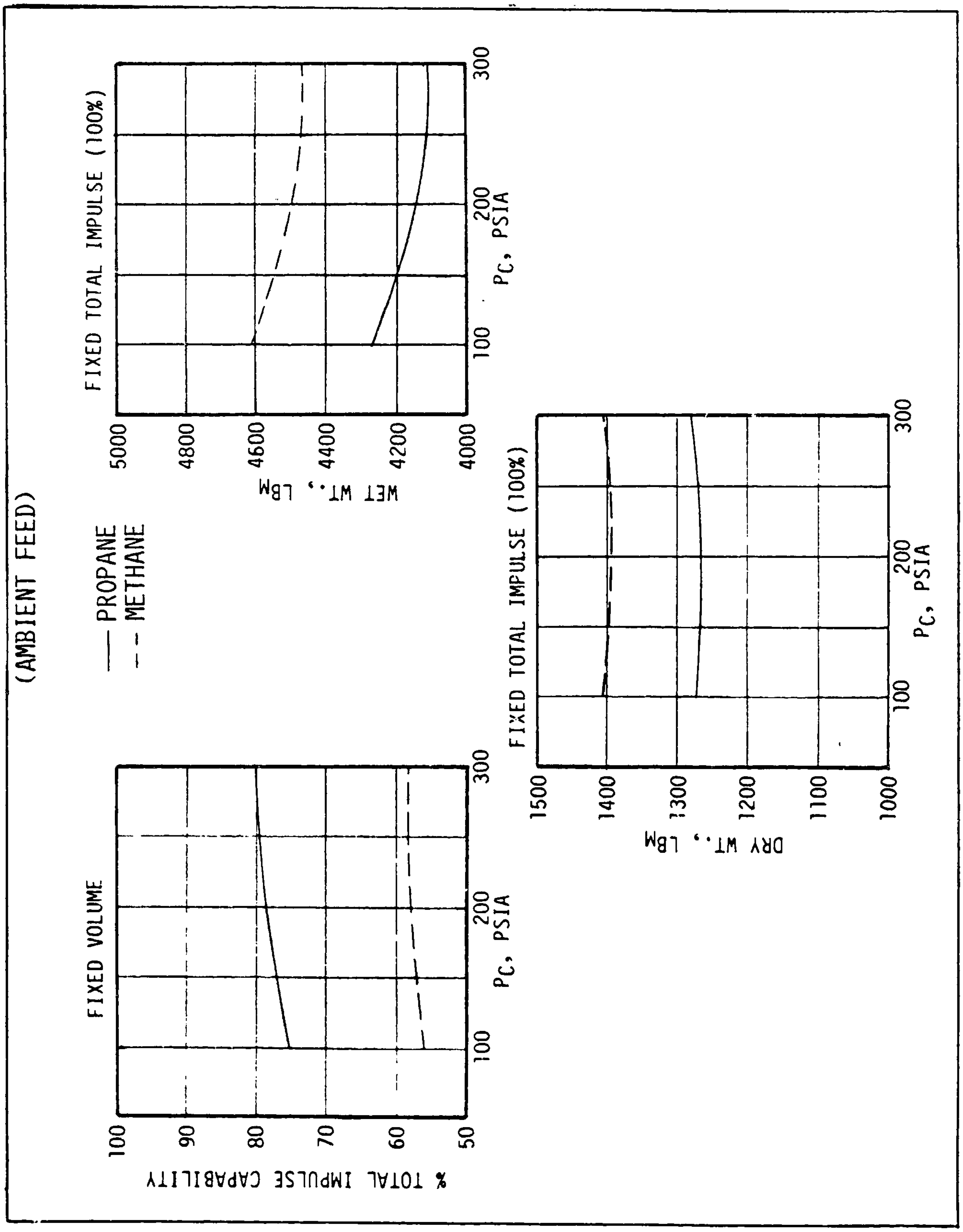


FIGURE 29 RCS P_C SENSITIVITY (AMBIENT PROPELLANT TEMPERATURE FEED)

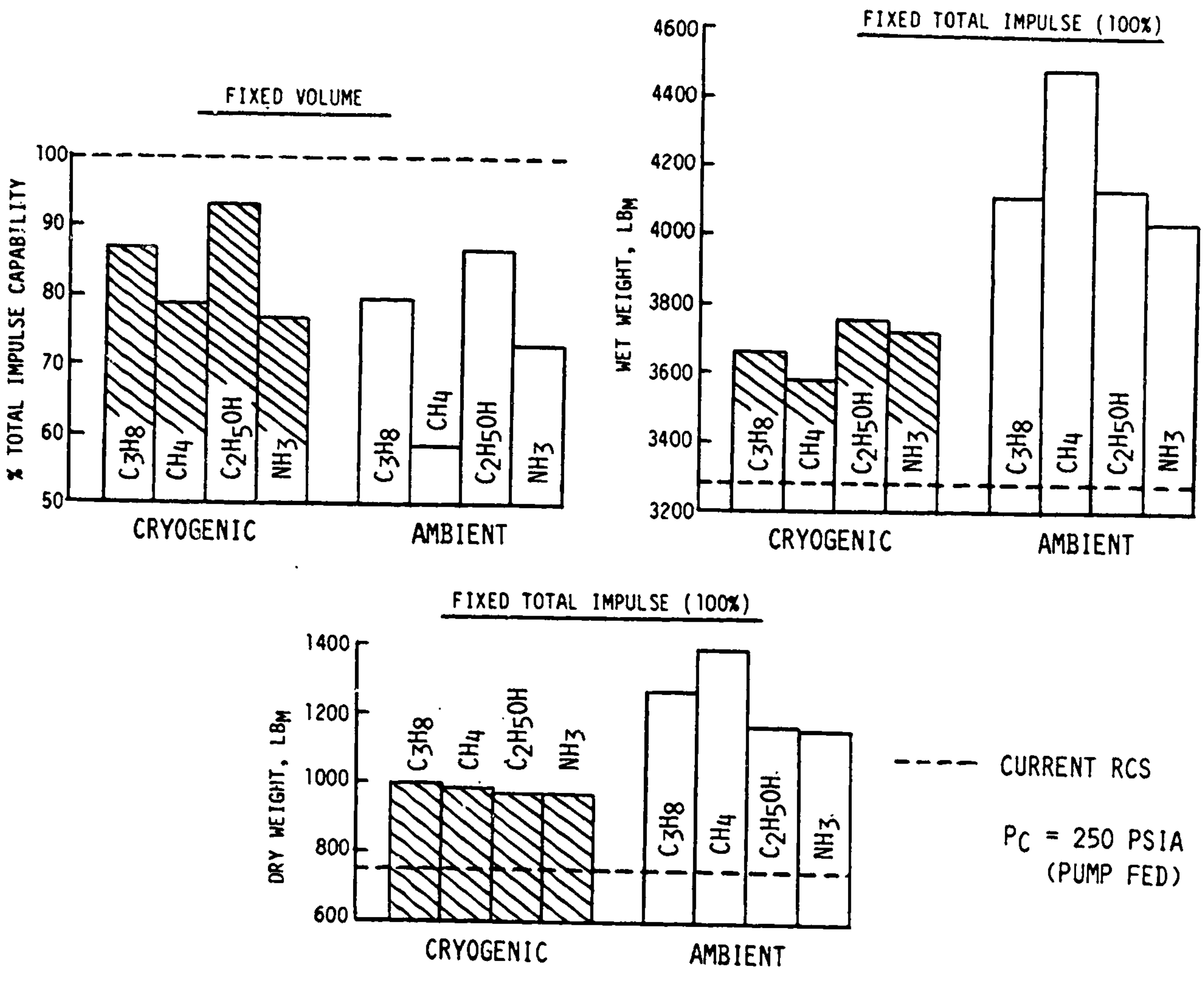


FIGURE 30 COMPARISON OF CRYOGENIC AND AMBIENT TEMPERATURE PROPELLANT FEED RCS

- SEE SCHEMATIC NOMENCLATURE OF FIGURES 2 & 3

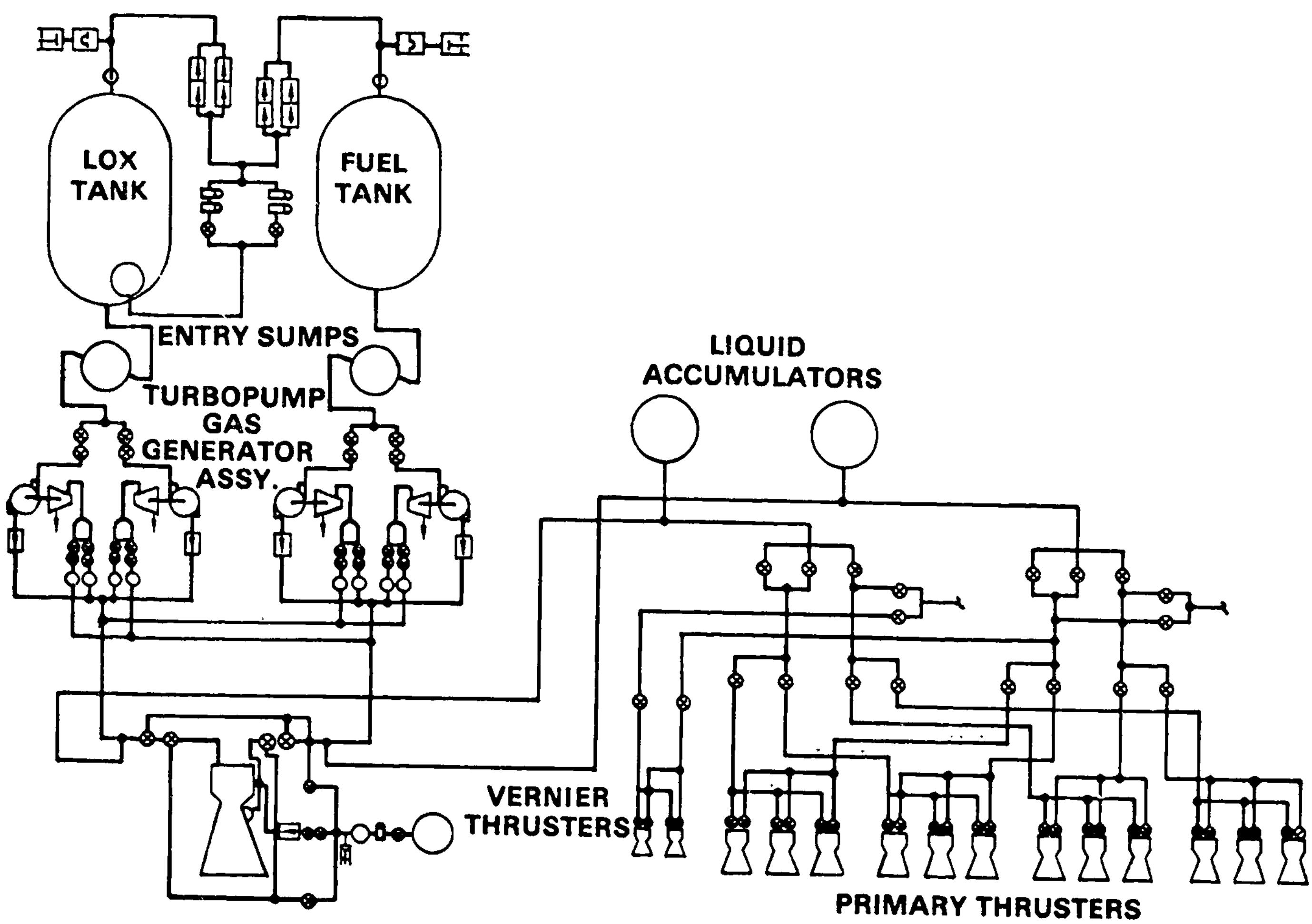


FIGURE 31 SCHEMATIC FOR OMS-AFT RCS WITH COMMON PROPELLANT TANKS

Weight and performance comparisons for the OMS/aft RCS with common and separate propellant tanks are shown in Figure 32. The most significant advantage of common tanks is the ability to provide ~100% of the current aft RCS total impulse requirement while still exceeding the OMS ΔV capability of the current storable system. The low volumetric mixture ratio for the common LOX/ethanol system permits efficient propellant tank packaging within the pod and affords the highest ΔV-total impulse capability of the candidate propellants. The common systems also provide a substantial reduction in wet and dry weights. Because of these advantages common OMS-aft RCS tanks were baselined for the Phase II evaluations.

4.4.2 Common OMS, Aft RCS, and Forward RCS Propellant Tanks - To evaluate common propellant tanks for the OMS, aft RCS, and forward RCS, a feedline model was developed for interconnecting the forward and aft pods (Figure 4). Propellant is transferred through this feedline from common tanks in the aft pod to RCS accumulators in the nose pod. The advantage of this approach is increased propellant usage flexibility. The disadvantage is the loss in propellant storage volume in the nose pod and the complexity of installing the interconnecting feedline.

Comparisons of separate and interconnected forward and aft propulsion systems are presented in Figure 33 for all four fuel candidates. (A turbopump, cryogenic propellant delivery system was assumed for the comparisons.) Because of the loss of propellant volume in the nose module the OMS ΔV capability is substantially reduced for the integrated systems. Only the LOX/ethanol system provides an OMS ΔV in excess of the current capability. As such, it was decided to consider conical propellant tank shapes in Phase II as a means of increasing propellant volume capability for the interconnected forward and aft propulsion systems.

4.5 Tank Insulation Options

Foam, fiberous, and multi-layer (MLI) insulation concepts were evaluated for separate OMS, separate RCS, and common OMS-aft RCS tanks. The intent of these evaluations was not to develop a detailed insulation system design but to determine the feasibility of candidate insulation materials. The LOX tank was selected for these evaluations since LOX has the lowest storage temperature and lowest heat of

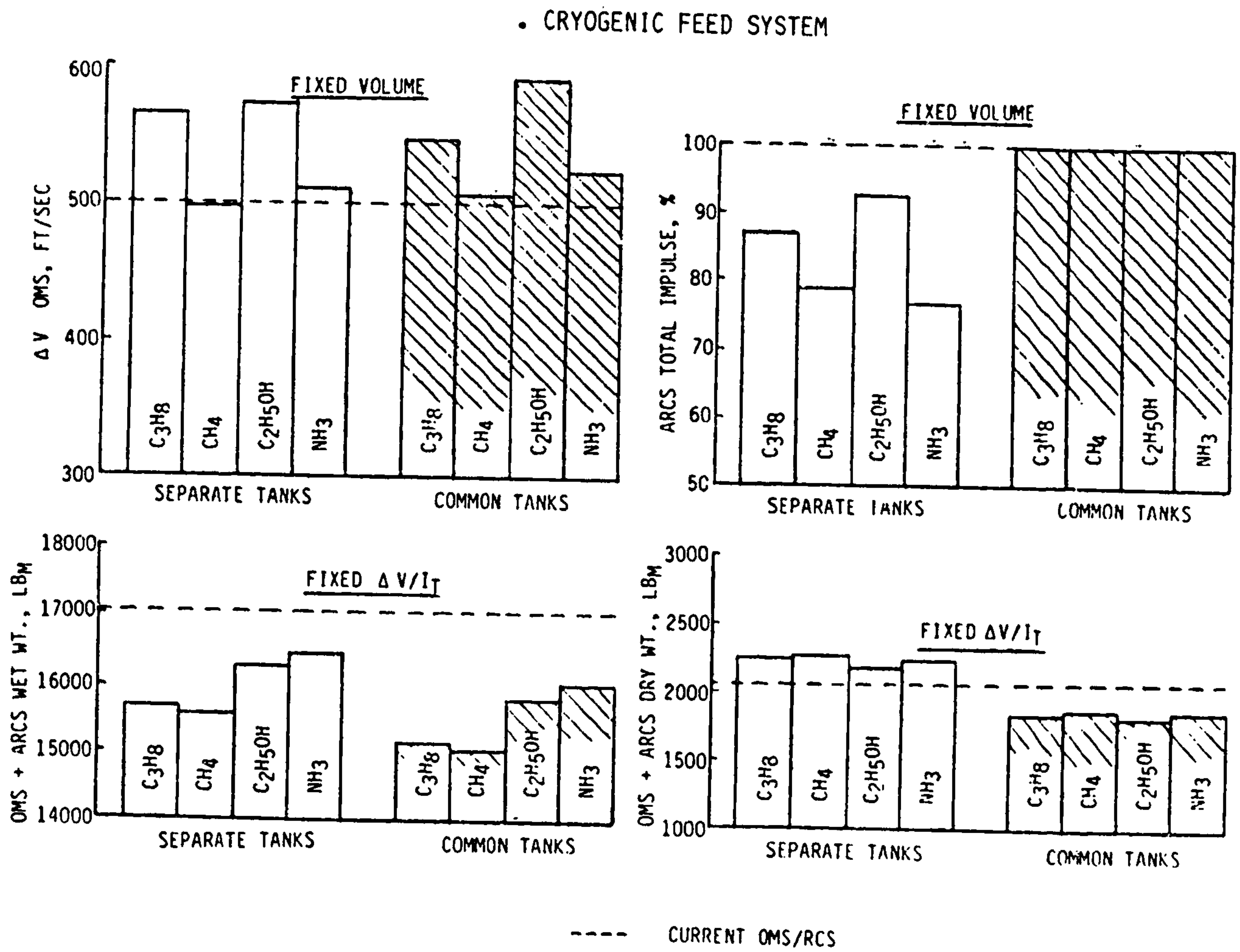


FIGURE 32 COMPARISON OF OMS-AFT RCS WITH COMMON AND SEPARATE PROPELLANT TANKS

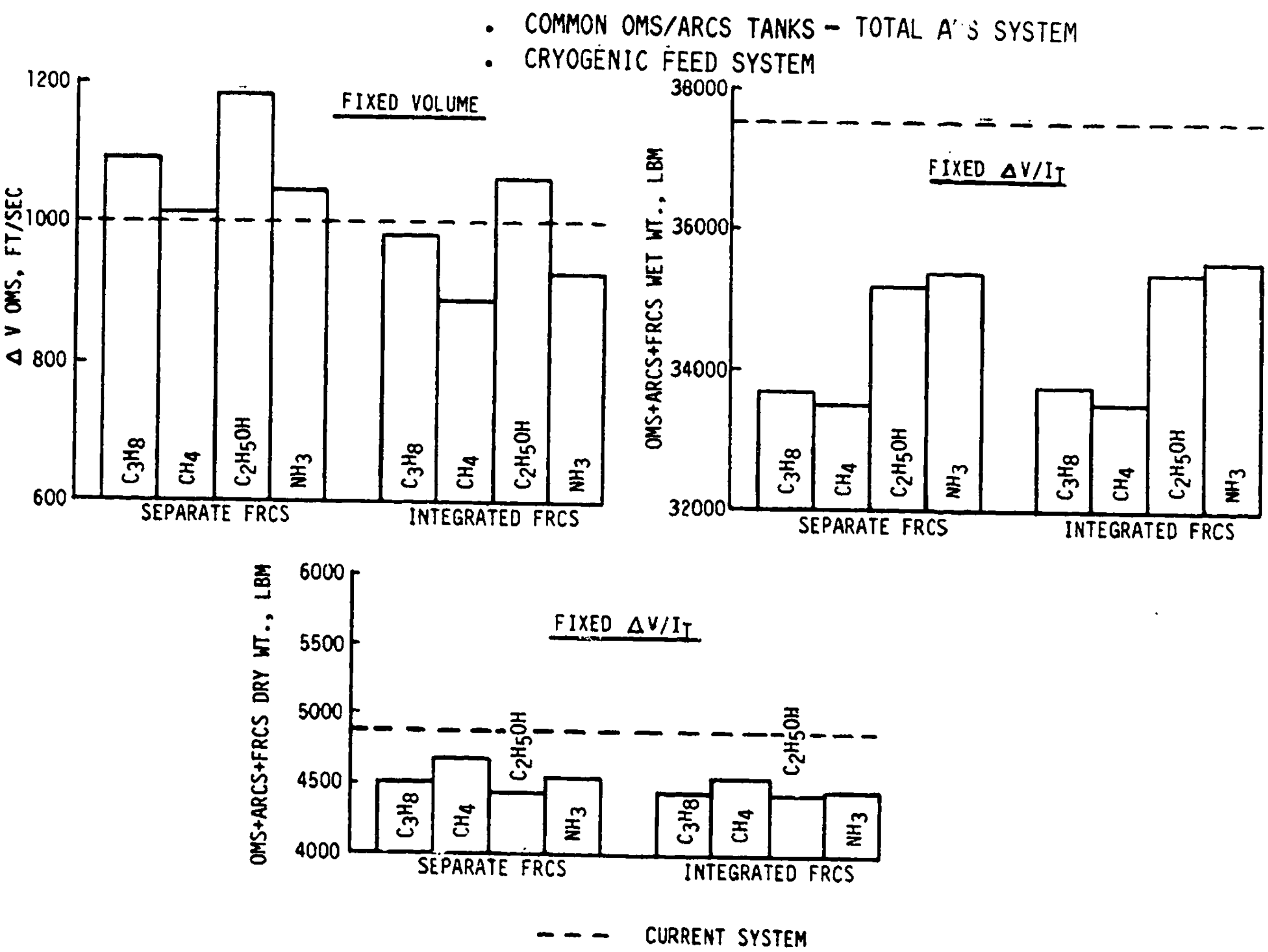


FIGURE 33 COMPARISON OF SEPARATE AND INTERCONNECTED FORWARD AND AFT PROPULSION SYSTEMS

vaporization compared to the other propellants. The evaluations were performed using the TKHEAT code described in Section 3.2 applying representative OMS-RCS engine firing cycles for a 30-day mission.

The properties for the candidate insulation materials are shown in Table XII. The MLI exhibits the lowest vacuum thermal conductivity but requires a vacuum cover (dewar-type tank) to prevent moisture degradation. The TG-15000 silica fiber insulation is an attractive material because it is easier to handle and install than MLI and is not susceptable to moisture degradation (does not require a vacuum cover). TG-15000 insulation is currently employed on the aft pod internal moldline. Its disadvantage is a higher vacuum thermal conductivity compared to MLI.

The measure of tank insulation effectiveness is the propellant boil-off (vent) loss that occurs as a result of environmental heating during the mission. Thirty-day LOX vent losses for the three candidate insulation materials are compared in Figures 34 through 36 for a separate OMS tank, separate RCS tank, and common OMS-aft RCS tank. As shown, vent losses with foam insulation are excessive, whereas, vent losses with both MLI and TG-15000 are considered acceptable. The MLI provides the lowest vent loss as a result of its low vacuum thermal conductivity. It is noteworthy that the common OMS-aft RCS tank provides a lower vent loss than the combined totals for separate OMS and RCS tanks. On the basis of these evaluations both MLI and TG-15000 were selected for further evaluation in Phase II.

4.6 Feedline Insulation Options

Because of the poor vacuum performance of foam insulation only MLI and TG-15000 insulation were evaluated for cryogenic RCS feedlines. The evaluations were performed using the FDLINE code described in Section 3.3 applying representative RCS thruster firing cycles for 7 and 30-day missions.

Initially evaluations were performed for the current RCS manifold arrangement in which the propellant usage is divided among four primary thruster manifolds and one vernier thruster manifold. The results are shown in Figure 37 where LOX temperature at the thruster valve inlet (for one primary thruster manifold) is

TABLE XII

PROPERTIES OF CANDIDATE INSULATION MATERIALS

INSULATION MATERIAL	AMBIENT (1) THERMAL (3) CONDUCTIVITY BTU/(HR-FT-°R)	EVACUATED (2) THERMAL (3) CONDUCTIVITY BTU/(HR-FT-°R)	HEAT CAPACITY (3) BTU/(LBM-°R)	DENSITY LBM/FT^3
TG-15000 FIBROUS INSULATION(4)	0.0123	0.00075	0.2	2.0
NRC-2 SINGLY ALUMINIZED MYLAR MLI (50 LAYERS/IN) WITH 5% PERFORATION	0.05	0.000038	0.27	1.14

(1) GROUND HOLD CONDITIONS, PRESSURE = 14.7 PSIA.
(2) ORBIT CONDITIONS, PRESSURE = VACUUM
(3) PROPERTIES EVALUATED AT A MEAN TEMPERATURE OF 180°R.
(4) TG-15000 INSULATION IS EMPLOYED ON THE ORBITER APS POD INTERNAL SURFACE.

• INITIAL LOX LOAD ~ 9350 LB_M

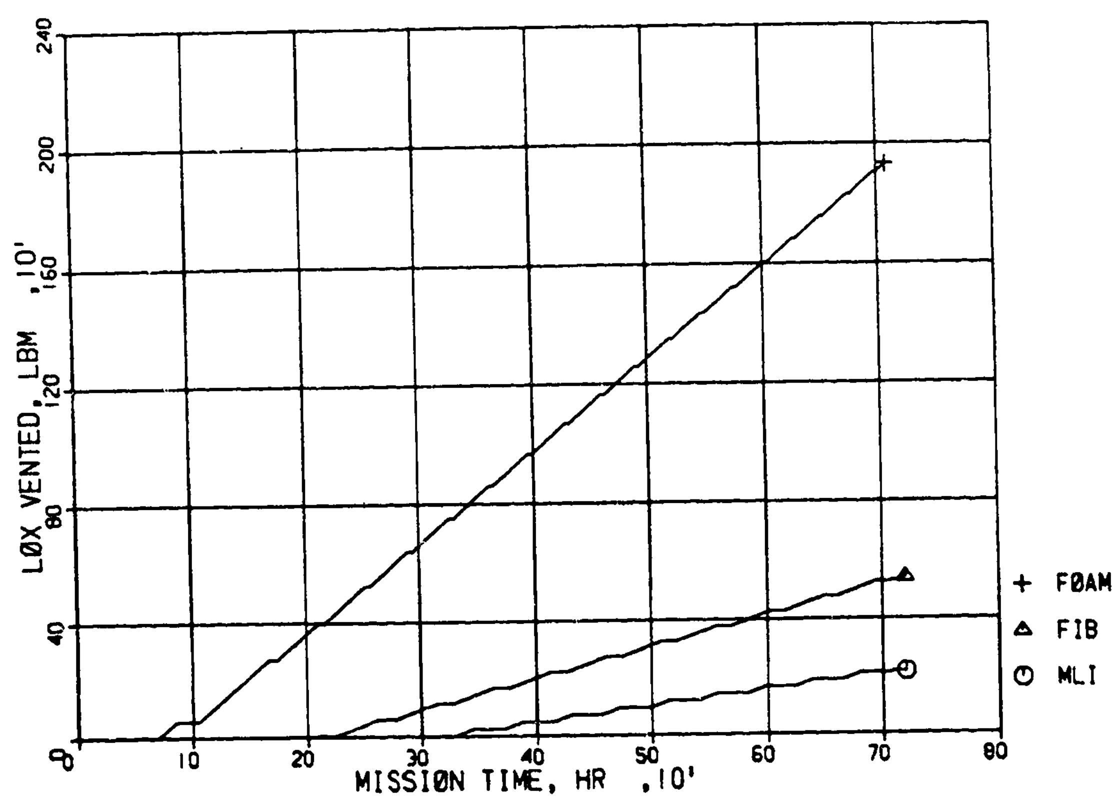


FIGURE 34 OMS LOX TANK INSULATION COMPARISONS

• INITIAL LOX LOAD ~ 1650 LB_M

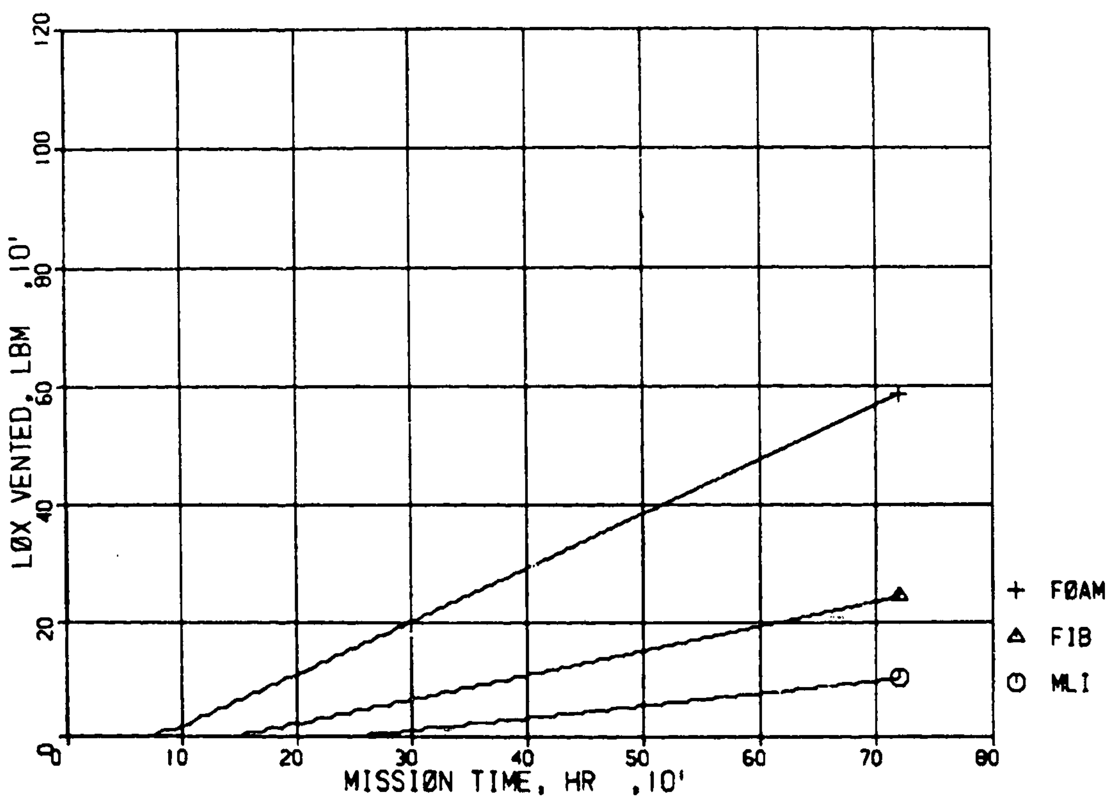


FIGURE 35 RCS LOX TANK INSULATION COMPARISONS

• INITIAL LOX LOAD ~11,000 LB_M

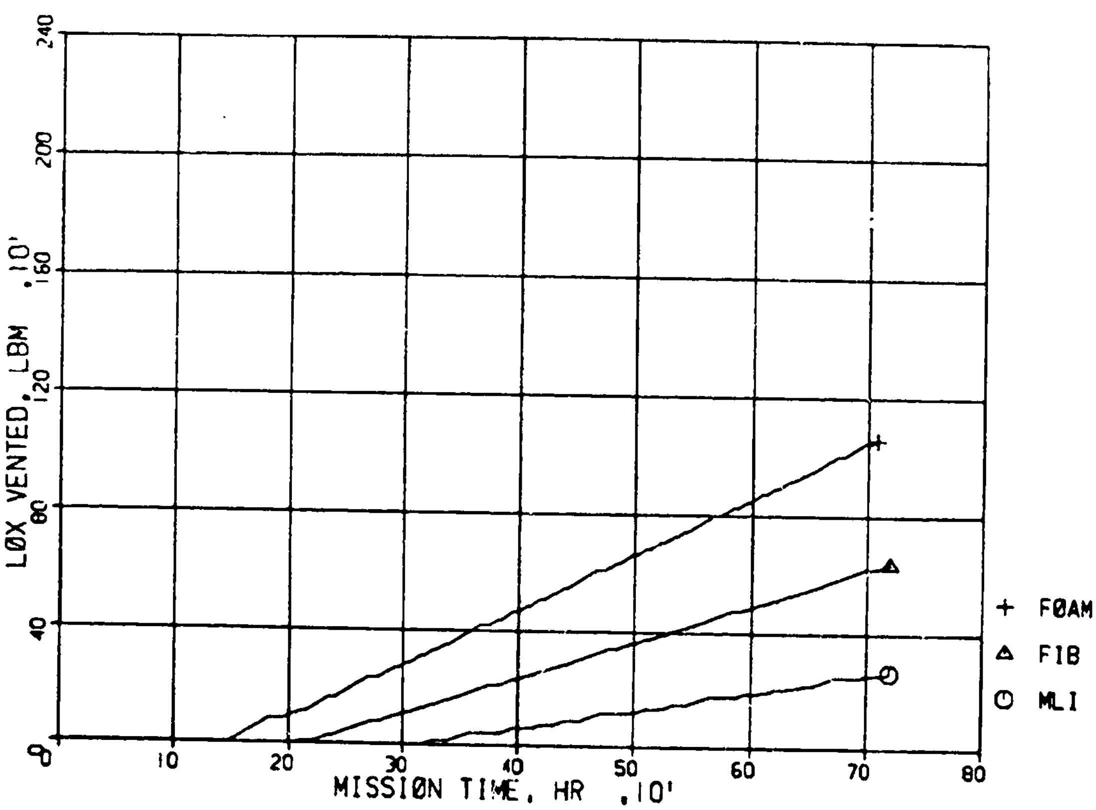


FIGURE 36 COMMON OMS-RCS LOX TANK INSULATION COMPARISONS

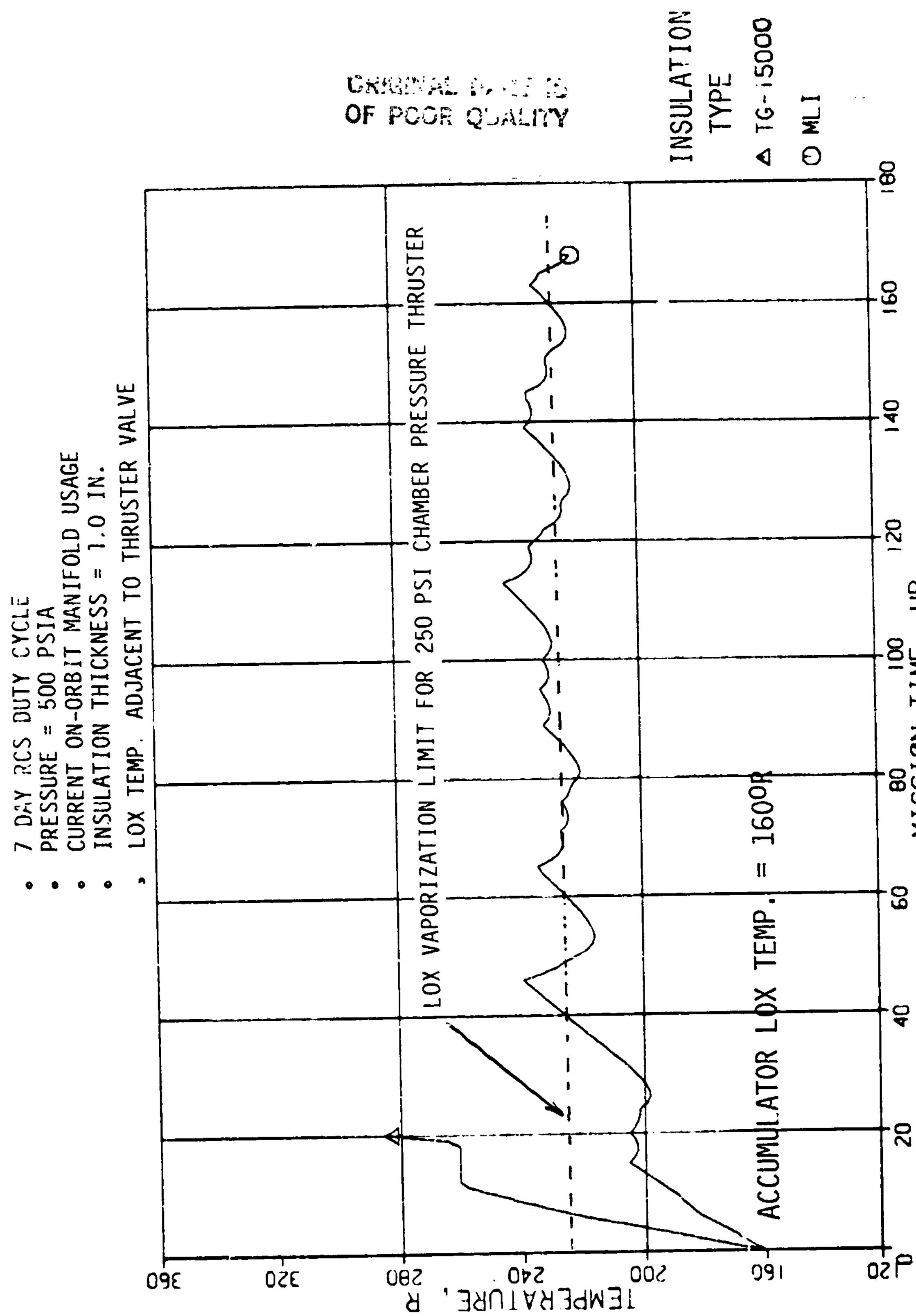


FIGURE 37 RCS FEEDLINE INSULATION PERFORMANCE WITH CURRENT MANIFOLD ARRANGEMENT

plotted as a function of mission time for both MLI and TG-15000 insulation. The plot shows that the LOX vaporization limit is exceeded for both insulation materials. (The vaporization limit corresponds to the temperature at which vaporization will occur in the injector for a 250 psia chamber pressure thruster.)

Since lower LOX feedline temperatures can be achieved with higher LOX usage rates, this analysis was repeated for a re-configured manifold arrangement in which all the RCS propellant is consumed through a single thruster manifold having the required number of primary and vernier thrusters for Orbiter three-axis attitude control. (Should a thruster failure occur with this manifold arrangement--i.e., failed open thruster valve--the primary manifold would be isolated and a back-up manifold activated.) A LOX temperature history for this reconfigured manifold arrangement is presented in Figure 38 for a 7-day RCS mission. This plot is for the LOX temperature adjacent to the thruster valve, which is the warmest point in the feedline. As shown by this example one-inch of TG-15000 insulation provides acceptable LOX feedline temperatures throughout the mission. As a result the reconfigured manifold arrangement was baselined for all subsequent feedline thermal analyses.

A summary plot of maximum LOX feedline temperatures as a function of usage rate and accumulator temperature is presented in Figure 39 for TG-15000 insulation. At the usage rate associated with a 7-day mission the LOX vaporization limit is exceeded for the 200°R accumulator temperature. For the low usage rate associated with a 30-day mission the LOX vaporization limit is exceeded for all three accumulator temperatures. On the basis of these results it was concluded that the TG-15000 insulation provides inadequate thermal protection for the RCS LOX feedlines. Similar data is presented in Figure 40 for one-inch of MLI. Even for the low usage rate associated with a 30 day mission LOX temperatures are maintained below the vaporization limit for a wide range in accumulator temperature (160 to 200°R). Based on these analyses it was concluded that a vacuum-jacketed MLI system is required to maintain acceptable temperatures in the RCS LOX feedlines.

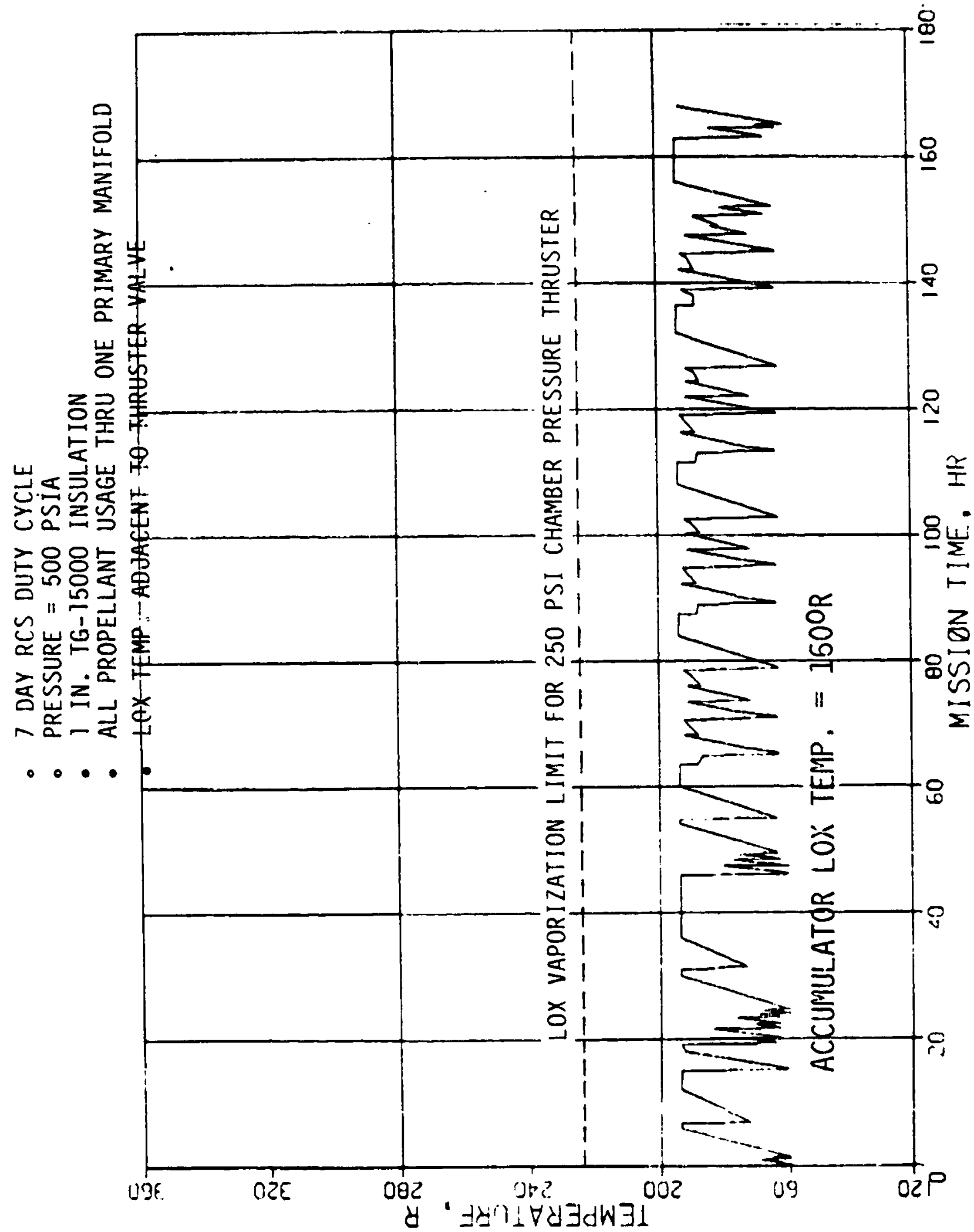


FIGURE 38 TG-15000 INSULATION PERFORMANCE WITH RE-CONFIGURED MANIFOLD ARRANGEMENT

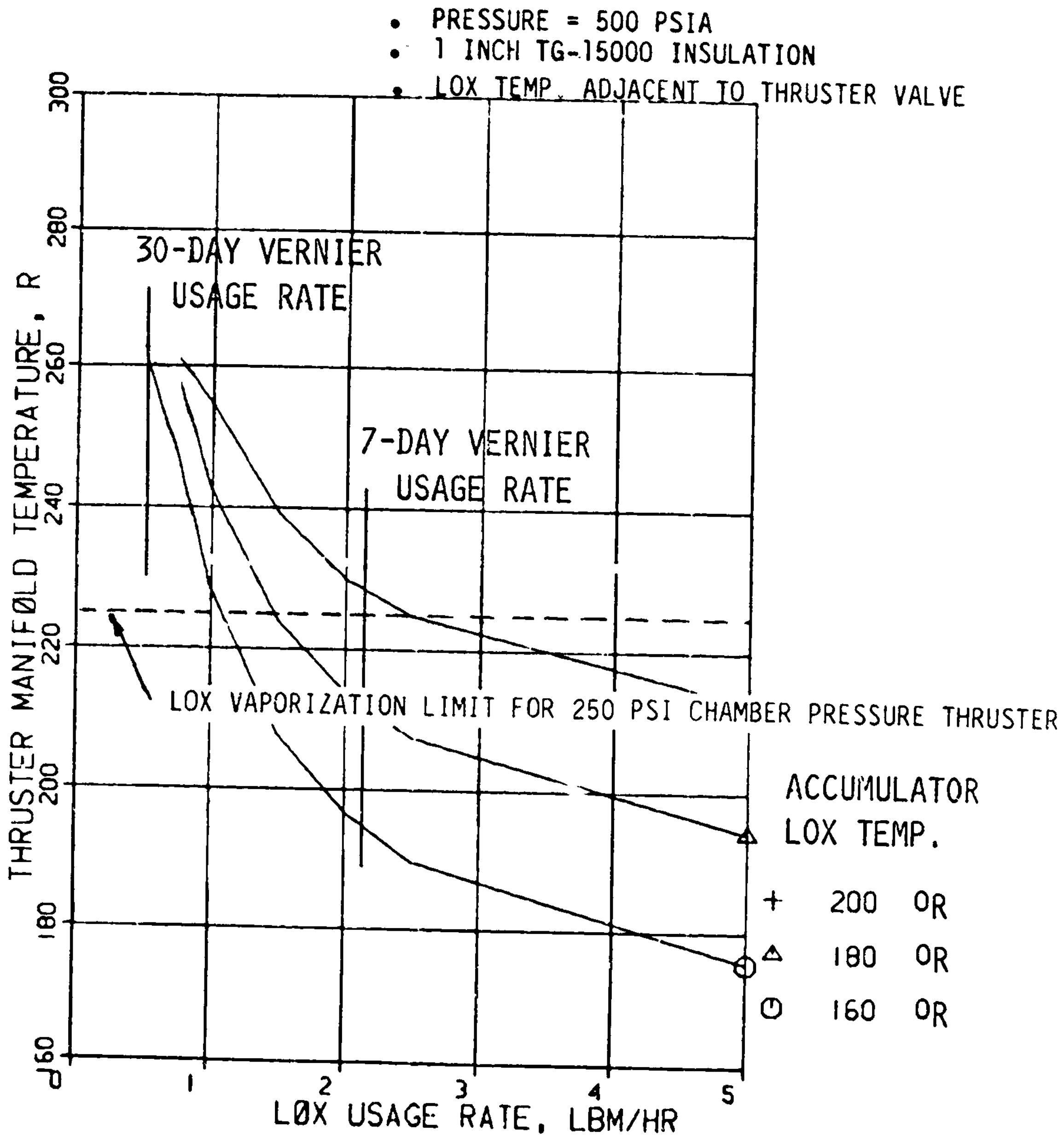


FIGURE 39 EFFECT OF LOX USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (TG-15000 INSULATION)

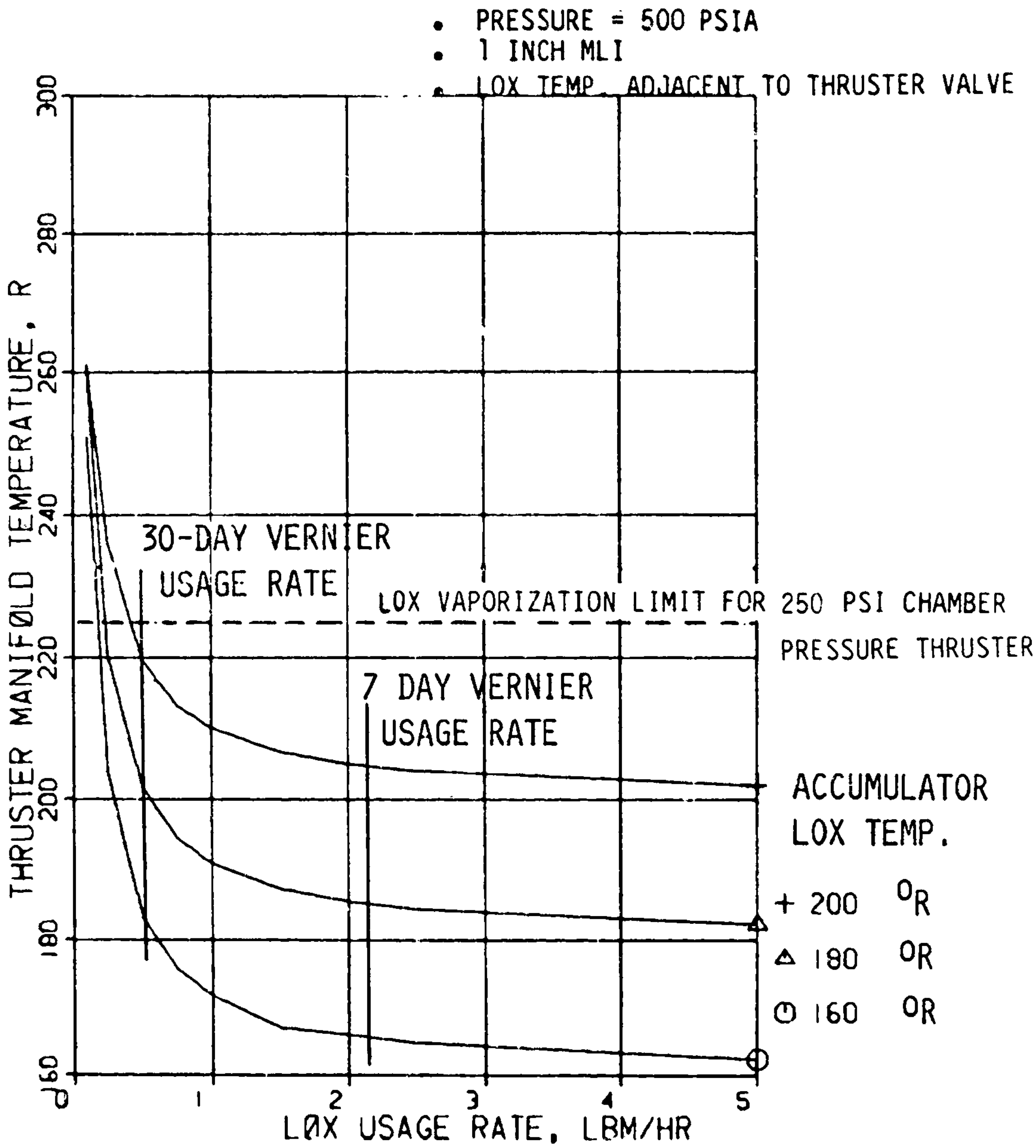


FIGURE 40 EFFECT OF LOX USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (MLI)

5.0 TASK II.1--PHASE II GROUNDRULES

The results from the Phase I effort, described above, formed the groundrules for the Phase II effort. These results are summarized below.

On the basis of the Phase I evaluations, two fuel candidates were selected for Phase II--ethanol and methane. Ethanol is a storable fuel with a vapor pressure slightly higher than MMH, while methane is a cryogenic fuel. Both are non-coking and offer high performance capability. LOX/ethanol affords the highest total impulse capability for systems constrained to the current pod volume because of its higher bulk density-specific impulse product. LOX/methane affords the lowest system wet weight (highest payload capability) for systems sized to a fixed total impulse requirement because of its high engine specific impulse (I_{SP}).

A pump fed OMS was baselined for Phase II because it offers overriding weight and performance advantages compared to a pressure fed system. A gas generator cycle engine was selected for LOX/ethanol, whereas an expander cycle engine was selected for LOX/methane. (The expander cycle allows higher I_{SP} for the LOX/methane OMS engine.) In addition, a single turbine drive for both the fuel and oxidizer pumps was selected to reduce the number of components and provide low engine system weight.

Pump and pressure fed feed system options were more competitive in terms of weight and performance for the RCS than for the OMS because of the lower RCS total impulse requirement. As a result, both pump and pressure fed RCS were selected for further evaluation in Phase II. However, battery powered electric pumps were baselined for the pump fed RCS to eliminate the I_{SP} penalty associated with turbopumps and to reduce the number of feed system components.

Common OMS/ARCS propellant tanks were baselined for Phase II because they offer improved propellant packaging in the aft pods (higher OMS ΔV and RCS total impulse), reduce feed system weight, and provide greater flexibility in the utilization of OMS/ARCS propellants compared to separate propellant tanks. Because of these advantages fully integrated tankage systems for the OMS, ARCS, and

FRCS were selected for further evaluation in Phase II considering the use of conical propellant tanks for improved aft pod packaging.

A cryogenic RCS feed system was baselined for LOX/methane, however, an ambient propellant temperature RCS feed system was baselined for LOX/ethanol because of the lower energy requirement for thermal conditioning. (Only one propellant--LOX--must be thermally conditioned--in the LOX/ethanol RCS.) The advantage of the ambient temperature RCS feed system is the elimination of insulation and thermal control requirements except for the storage tanks and pumps. Furthermore, because of the low mixture ratio (1.4) for the LOX/ethanol RCS thrusters, it was felt that passive heat exchanger approaches (without the use of fuel rich hot gas O_2 heat exchangers) would be feasible for thermally conditioning the RCS oxygen flow. As such, two passive thermal conditioning approaches for the LOX/ethanol RCS were selected for Phase II evaluation. The first employs an ethanol feedline heat exchanger for gasifying the oxygen flow while the second employs an ethanol tank heat exchanger. In the first concept (Figure 41), the fuel flow is pre-heated using a hot gas heat exchanger, and then the heated fuel flow is used to vaporize the O_2 in a passive feedline heat exchanger. In the second concept (Figure 42), the oxygen flow is circulated through a heat exchanger coiled around the outside of the ethanol tank where it absorbs heat from the tank wall, the environment, and the ethanol within the tank.

The final concept variable selected for Phase II evaluation was the choice of insulation materials for the cryogenic LOX/methane tanks and RCS feedlines. On the basis of the Phase I results for LOX, two types of insulation materials--aluminized mylar multi-layer insulation and TG-15000 silica fiber insulation--were selected for further evaluation in Phase II.

In accordance with the above discussion the Phase II groundrules are summarized in Table XIII. The system design requirements and constraints for component weight and sizing, which are similar to those established in Phase I, are summarized in Table XIV. One notable change to the Phase I component weight and sizing groundrules was that the minimum gage for tank and accumulator wall thickness was increased to 0.060 inch because of the concern that the Phase I values of 0.030 inch for aluminum vessels and 0.020 inch for titanium vessels were very susceptible to handling damage.

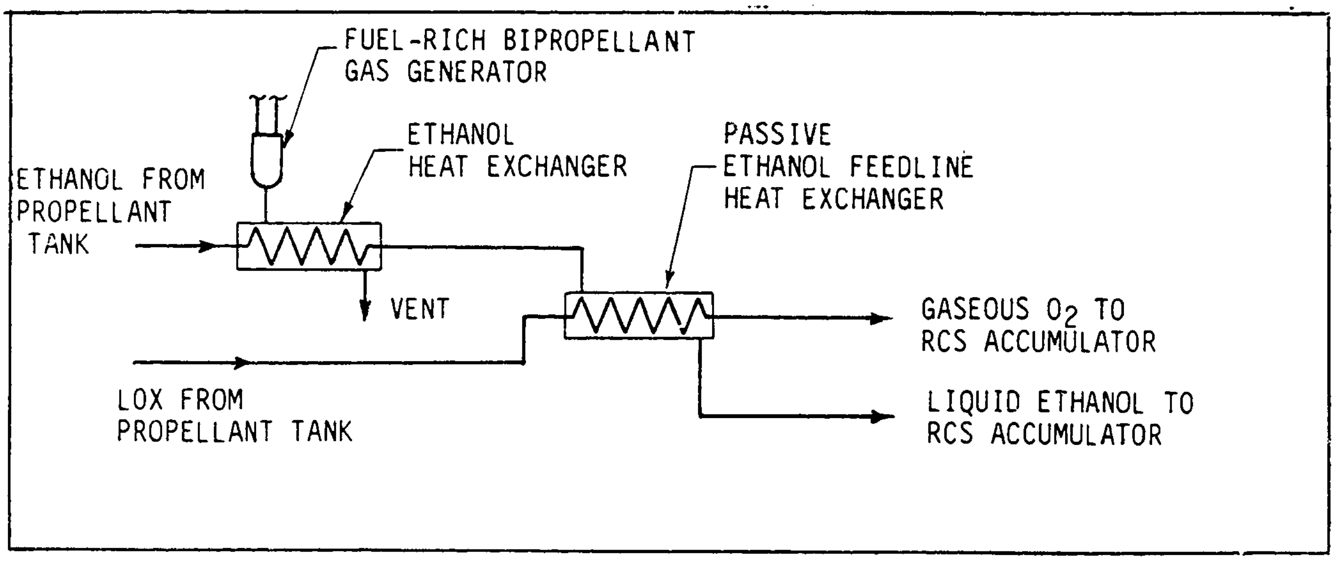


FIGURE 41 PASSIVE ETHANOL FEEDLINE O_2 HEAT EXCHANGER CONCEPT

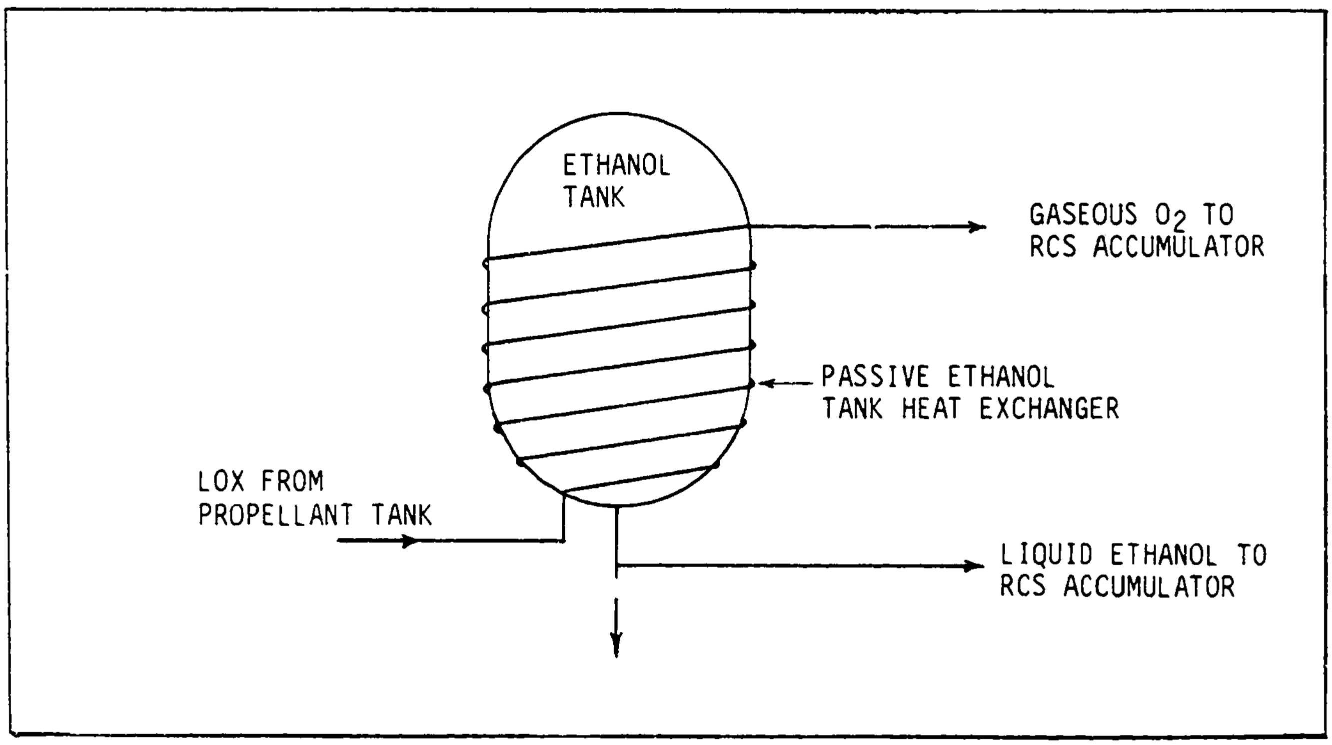


FIGURE 42 PASSIVE ETHANOL TANK O_2 HEAT EXCHANGER CONCEPT

TABLE XIII

PHASE II GROUNDRULES SUMMARY

I. Fuels:
- ethanol
- methane

II. Baseline Feed System Constraints
- pump-fed OMS
  - single turbine drive for both fuel and oxidizer pumps
  - gas generator cycle for LOX/ethanol
  - expander cycle for LOX/methane
- common propellant tanks for OMS/ARCS
- cryogenic propellant tanks for OMS (LOX and methane)
- cyrogenic propellant feed for LOX/methane RCS
- ambient temperature propellant feed for LOX/ethanol RCS
  - ethanol: liquid phase
  - oxygen: gas phase

III. Feed System Options to be Evaluated
- propellant tank insulation options for LOX and methane
  - aluminized mylar multi-layer insulation (MLI)
  - TG-15000 silica fiber insulation
- RCS feedline insulation options for LOX and methane
  - aluminized mylar MLI
  - TG-15000 silica fiber insulation
- turbopump versus electric pump-fed RCS (LOX/ethanol)
- passive O_2 thermal conditioning options for LOX/ethanol RCS
  - ethanol feedline heat exchanger
  - ethanol tank heat exchanger
- pump versus pressure fed FRCS (LOX/methane)
- separate versus common FRCS/aft propulsion tanks (LOX/ethanol)
- conventional versus conical aft propulsion tanks (LOX/ethanol)

TABLE XIV

PHASE II DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

I. Helium Pressurization System

- common helium supply for fuel and oxidizer tanks
- current OMS/RCS line lengths
- ling Mach number = 0.1 (Maximum)
- real gas effects
- solubility effects
- propellant vapor pressure effects
- line material: 304L stainless steel (SS)
- polytropic exponent = 1.0 (helium bottle inside LOX tank)
- regulator pressure ratio = 0.7 (outlet/minimum inlet)
- tank shape: spherical
- tank material: 2219-T87 aluminum (Al)
- storage pressure: 3000 psia
- ultimate factor of safety for helium tank = 1.5

II. Propellant Tanks

- propellant dumped overboard during an abort
- tank volume determination
  - impulsive propellant volume
  - 2% liquid residuals by volume
  - 98% vapor residuals by volume
  - tank boil-off loss (LOX and methane)
  - OMS feedline chilldown/vent los (LOX and methane)
  - 5% ullage volume at storage temperature
- Common OMS/ARCS tank shape
  - cylindrical with oblate spheriod end domes, or
  - conical with oblate spheriod end domes
- Common OMS/ARCS tanks are constrained to equal lengths to permit attachment to common aft pod bulkhead
- FRCS tank and entry sump shape: spherical

TABLE XIV (Continued)
PHASE II DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

- materials
  - LOX: 2219-T87 Al
  - fuel: 2219-T87 Al or 6Al-4V titanium (Ti) (whichever is lighter)
- minimum gage thickness: 0.06 in.
- ultimate factor of safety = 1.5
- insulation options (LOX and methane)
  - aluminized mylar MLI with thermodynamic vent system
  - TG-15000 silica fiber insulation with thermodynamic vent system
- propellant acquisition: surface tension screens
- OMS propellant gaging: capacitance probes
- RCS propellant gaging: P-V-T

III. RCS Accumulators

- sized to provide Shuttle External Tank separation impulse without resupply
- shape: spherical
- blowdown accumulator operation (isentropic blowdown process)
- materials
  - LOX: 2219-T87 Al
  - fuel: 2219-T87 Al or 6Al-4V Ti (whichever is lighter)
- minimum gage thickness: 0.06 in.
- ulitmate factor of safety = 1.5
- insulation options (LOX and methane)
  - aluminized mylar MLI without vent
  - TG-15000 silica fiber insulation without vent
- propellant acquisition for liquid accumulators: surface tension screens

IV. Propellant Feedlines

- current OMS/RCS line lengths
- pressure drop criteria:
  - 0.5 psi/ft for pressure-fed system
  - 1.0 psi/ft for pump-fed system

TABLE XIV (Continued)

PHASE II DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

- Darcy friction factor
- isenthalpic expansion process
- material: 2219-T87 Al
- minimum gage = 0.028 in.
- ultimate factor of safety:
  - 4.0 for diameters < 1.5 in.
  - 1.5 for diameters ≥ 1.5 in.
- linear and angular compensation joints
- insulation options for RCS feedlines (LOX and methane)
  - aluminized mylar MLI
  - TG-15000 silica fiber insulation

V. Gas Generator Exhaust Vent Line

- line Mach number = 0.3 (maximum)
- Fanno line analysis
- line length: 20 ft
- exhaust nozzle area ratio = 2.0
- propulsive vent for OMS; nonpropulsive vent for RCS
- line material: 304L SS
- minimum gage and ultimate factor of safety: same as feedlines

6.0 TASK II.2--PHASE II COMPONENT CHARACTERIZATION

The three computer codes described in Section 3.0 were used to perform the system evaluations of Task II.3. Changes that were made to support the Phase II effort are described below.

6.1 APSDS Code

This code sizes the overall propulsion system (OMS and RCS) to a fixed pod volume or fixed total impulse constraint. It was changed in Phase II to include revised performance and weight models for the OMS and RCS engines and new models for battery powered electric motor pumps for RCS propellant feed.

6.1.1 OMS and RCS Engine Models - The data for the OMS and RCS engine models were developed by ALRC and are provided in the appendicies of Reference (2). Engine lengths and diameters were constrained to the current values. The OMS engine was based on fuel regenerative cooling and a single turbine for driving both the fuel and oxidizer pumps. A gas generator cycle was selected for LOX/ethanol while an expander cycle was selected for LOX/methane to provide maximum performance. In the expander cycle, gaseous methane leaving the engine cooling jacket is used to drive the turbine. The methane exiting the turbine is then routed directly to the engine injector to avoid the vent loss associated with the gas generator cycle.

LOX/ethanol OMS engine specific impulse (I_{SP}) is shown in Figure 43 as a function of chamber pressure (P_C) for both zirconium-copper (Zr-Cu) and nickel (Ni) chambers. The decrease in I_{SP} with chamber pressure for the Ni chamber is the result of high supplementary film cooling losses. Supplementary film cooling is not required in the Zr-Cu chambers up to a chamber pressure of 600 psia, and only 0.7% film cooling is required at 800 psia. Because of its high performance capability a Zr-Cu chamber was baselined for the OMS engine.

Similar parametric data for the LOX/methane OMS engine was not developed since an energy balance could not be achieved with the expander cycle at chamber pressures greater than 400 psia. (At the higher chamber pressures there is insufficient thermal energy transferred to the methane in the cooling jacket to

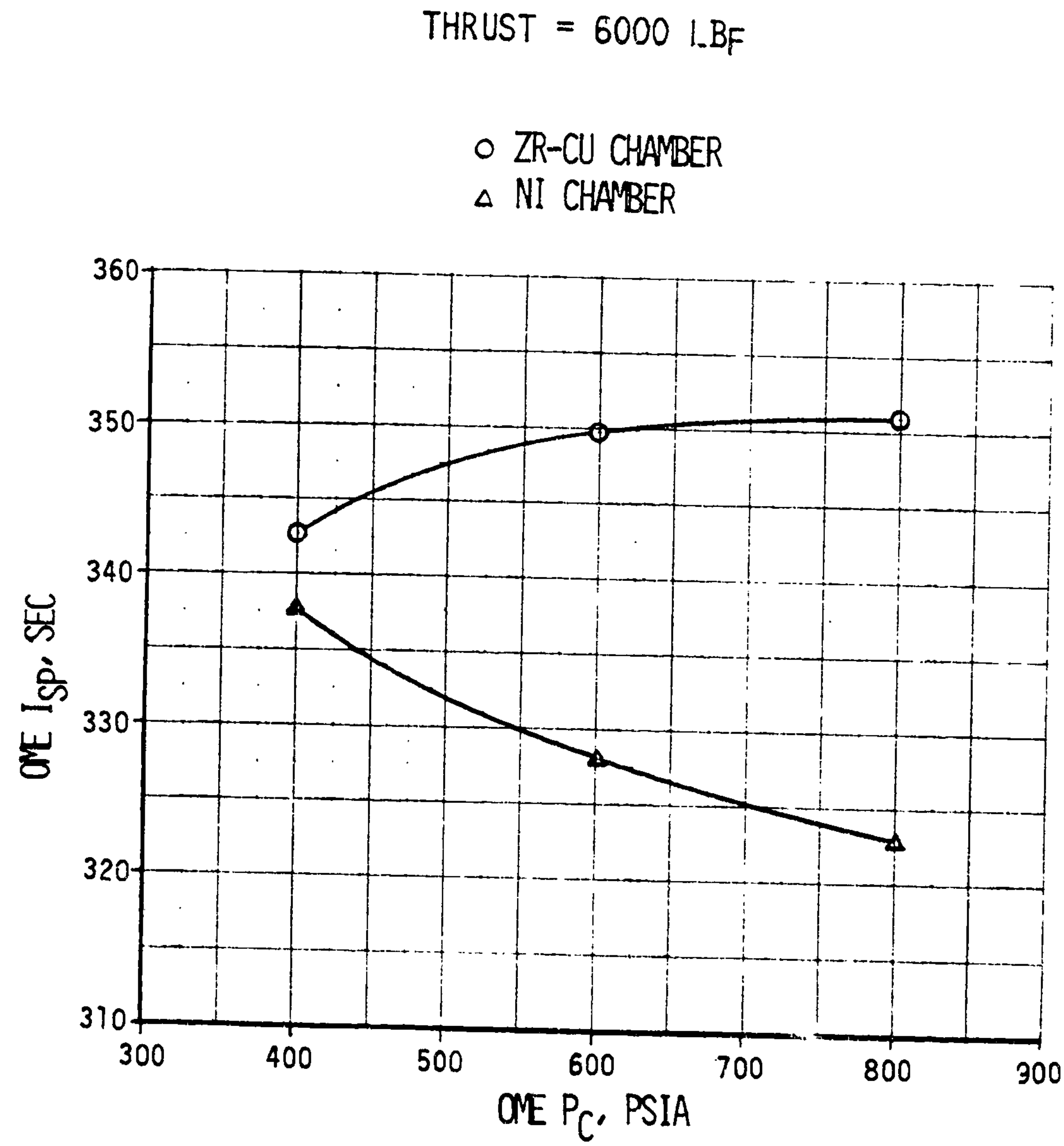


FIGURE 43 LOX/ETHANOL OMS ENGINE SPECIFIC IMPULSE

C-2

drive the turbine.) As a result a chamber pressure of 400 psia was baselined for the LOX/methane OMS engine, providing a specific impulse of 364 seconds for a Zr-Cu chamber. Despite the lower chamber pressure capability with the expander cycle the LOX/methane OMS engine specific impulse is substantially higher than that achieved with the LOX/ethanol gas generator cycle engine.

RCS engine specific impulse as a function of chamber pressure is presented in Figures 44 and 45 for LOX/ethanol and LOX/methane, respectively. These data are based on film-cooled Zr-Cu chambers. The 550 lb-thrust chambers have a higher I_{SP} than the 870 lb-thrust chambers because of the fixed envelope constraint which permits a larger nozzle (higher expansion ratio) for the lower thrust level.

6.1.2 Electric Motor and Pump Weights - Electric motor operated RCS pump weights were also generated by ALRC (see Reference (2) appendicies) for incorporation into the APSDS code. The electric motor weights were based on an alternating current design to provide minimum weight. The total weights for the motor and pump are presented in Figures 46 through 48 for LOX, methane, and ethanol, respectively. As shown, weights were developed as a function of flow rate and discharge pressure. The power demand for these pumps was based on the shaft horsepower requirements and a pump efficiency of 90%. The corresponding battery weights for meeting the RCS total impulse requirement are shown in Figure 49 for both silver-zinc (Ag-Zn) and lithium (Li) batteries. These weights were developed by NASA-JSC. The lithium batteries require new technology development but were baselined for the study because of their low weight.

6.2 TKHEAT Code

The TKHEAT code determines the thermodynamic response of propellant contained in storage tanks or accumulators during representative orbital mission duty cycles. The code was changed in Phase II to include the capability to analyze methane and to provide a subroutine for evaluating a passive ethanol tank O_2 heat exchanger.

The ethanol tank O_2 heat exchanger model is shown in Figure 50. The O_2 heat exchanger line is coiled around the outside wall of the ethanol tank where it

ORIGINAL PAGE IS
OF POOR QUALITY

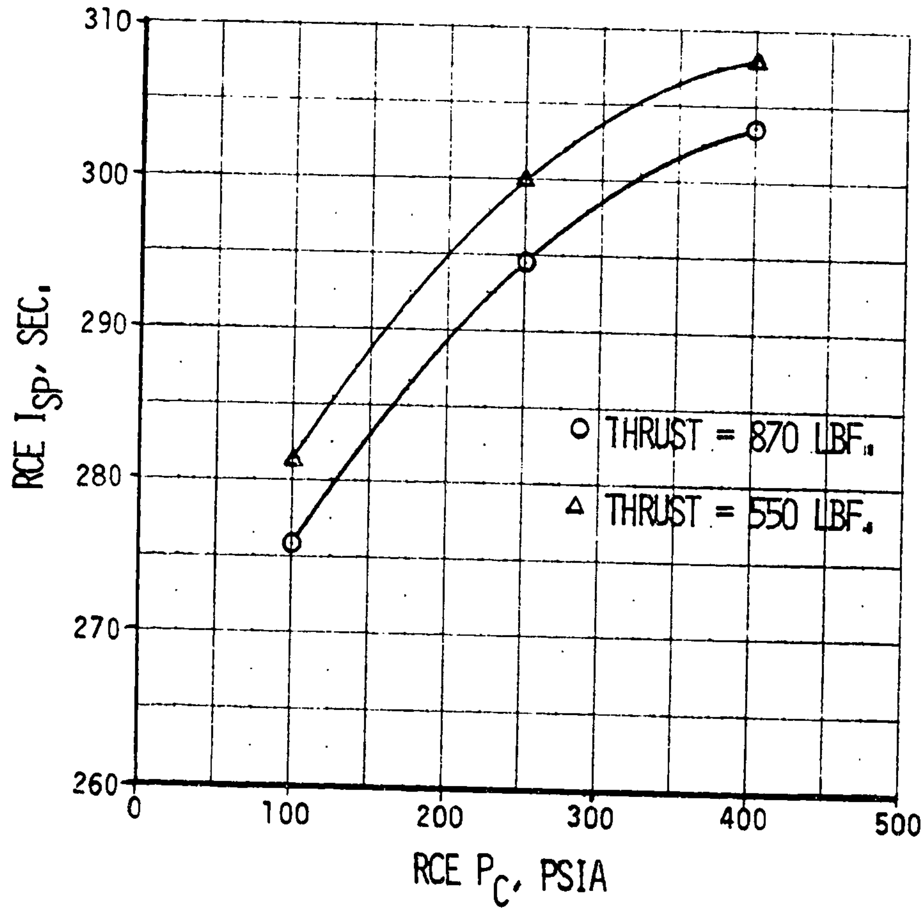


FIGURE 44 LOX/ETHANOL RCS ENGINE SPECIFIC IMPULSE

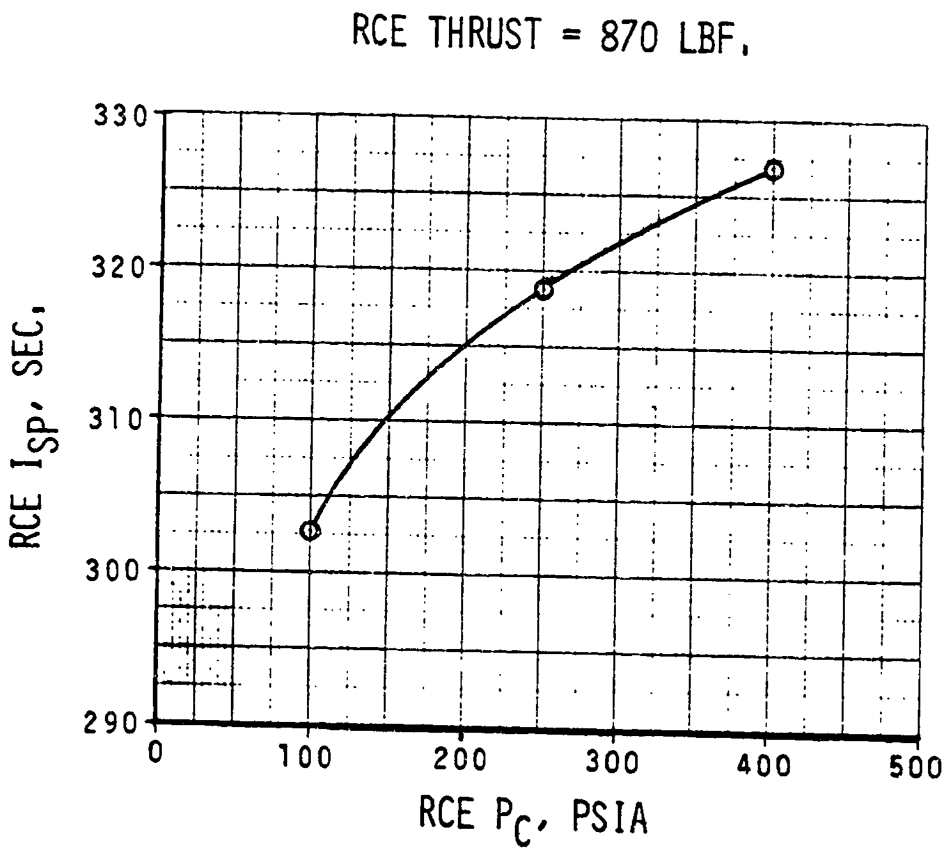


FIGURE 45 LOX/METHANE RCS ENGINE SPECIFIC IMPULSE

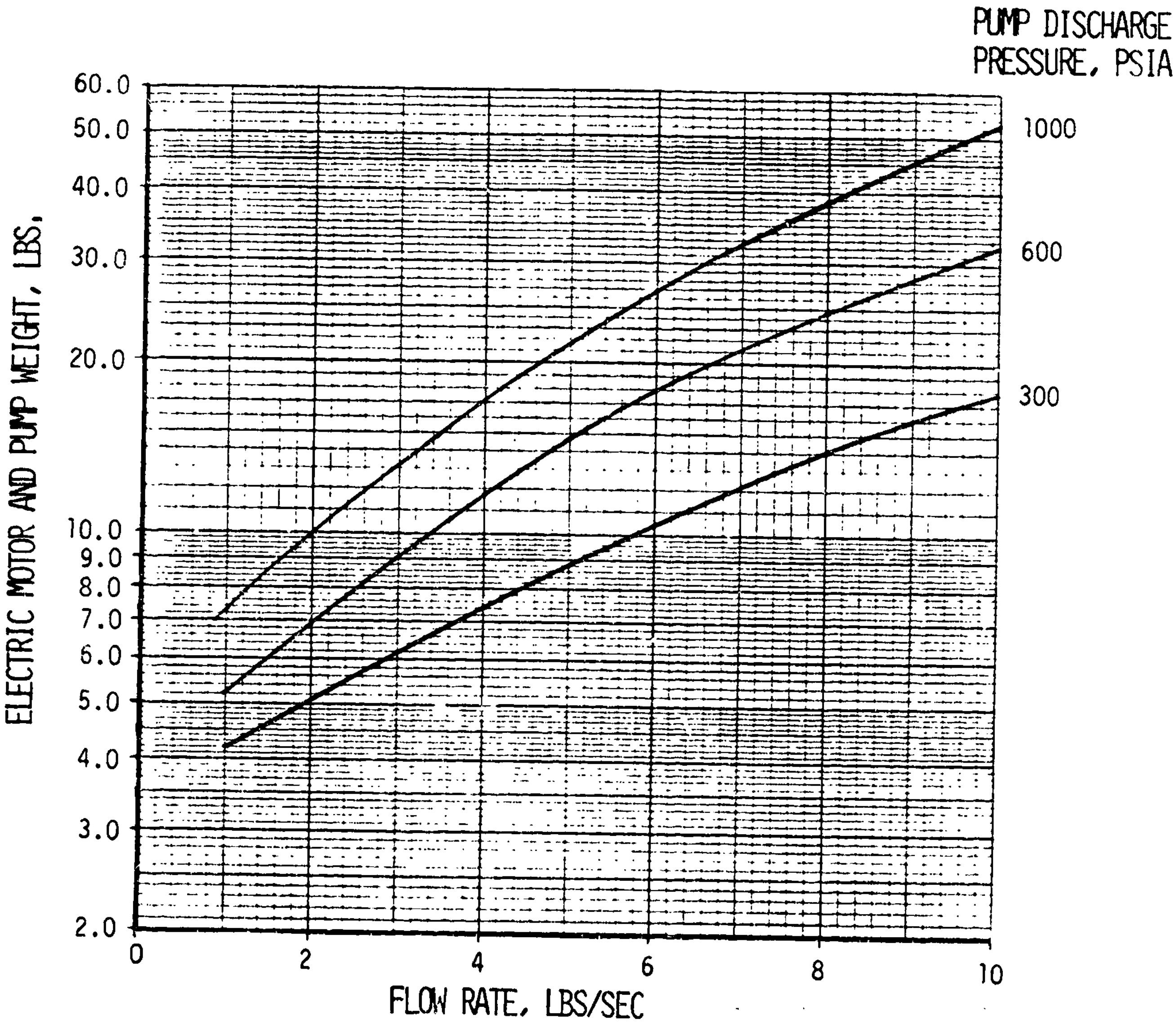


FIGURE 46 LOX ELECTRIC MOTOR AND PUMP WEIGHT

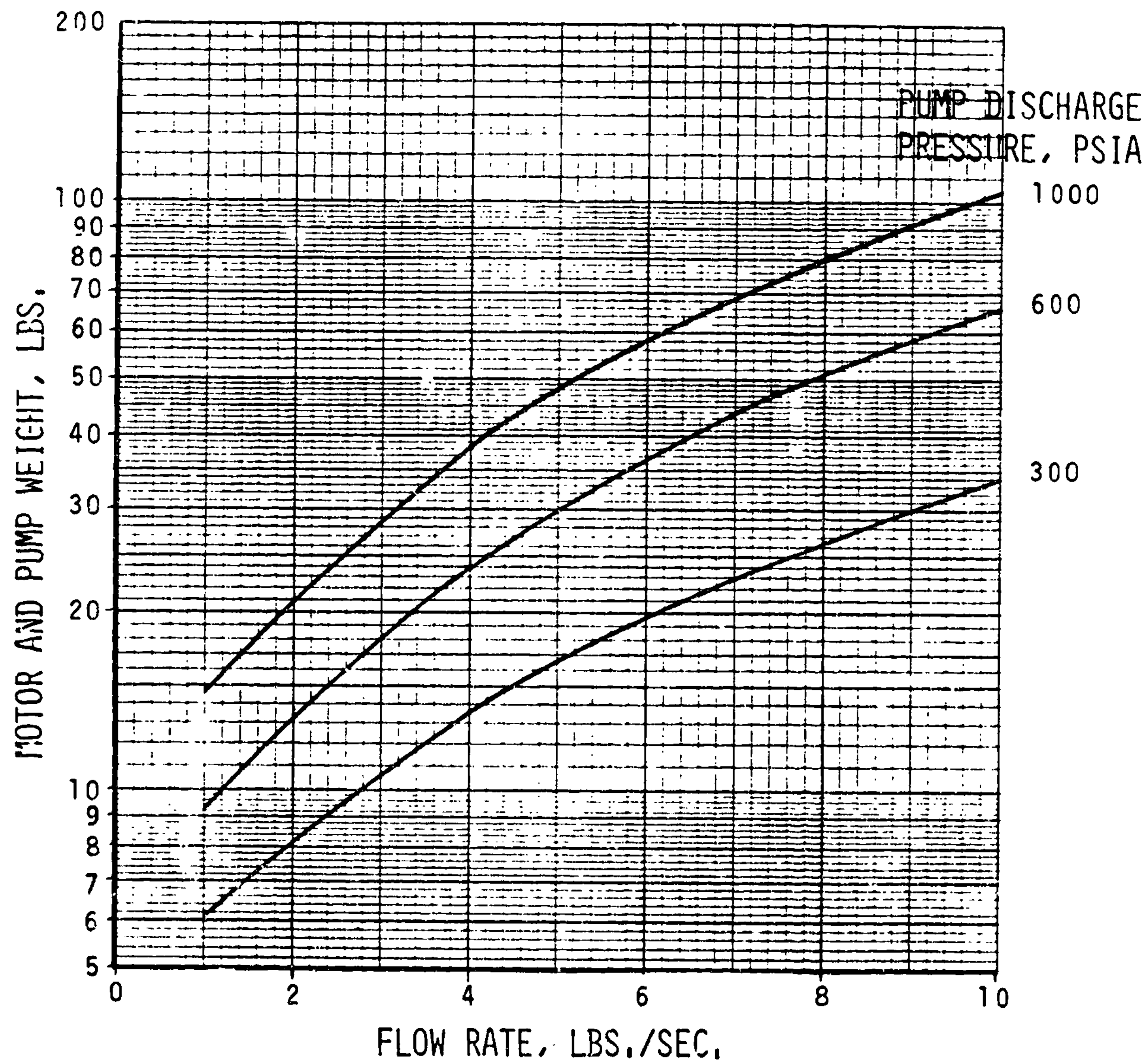


FIGURE 47 METHANE ELECTRIC MOTOR AND PUMP WEIGHT

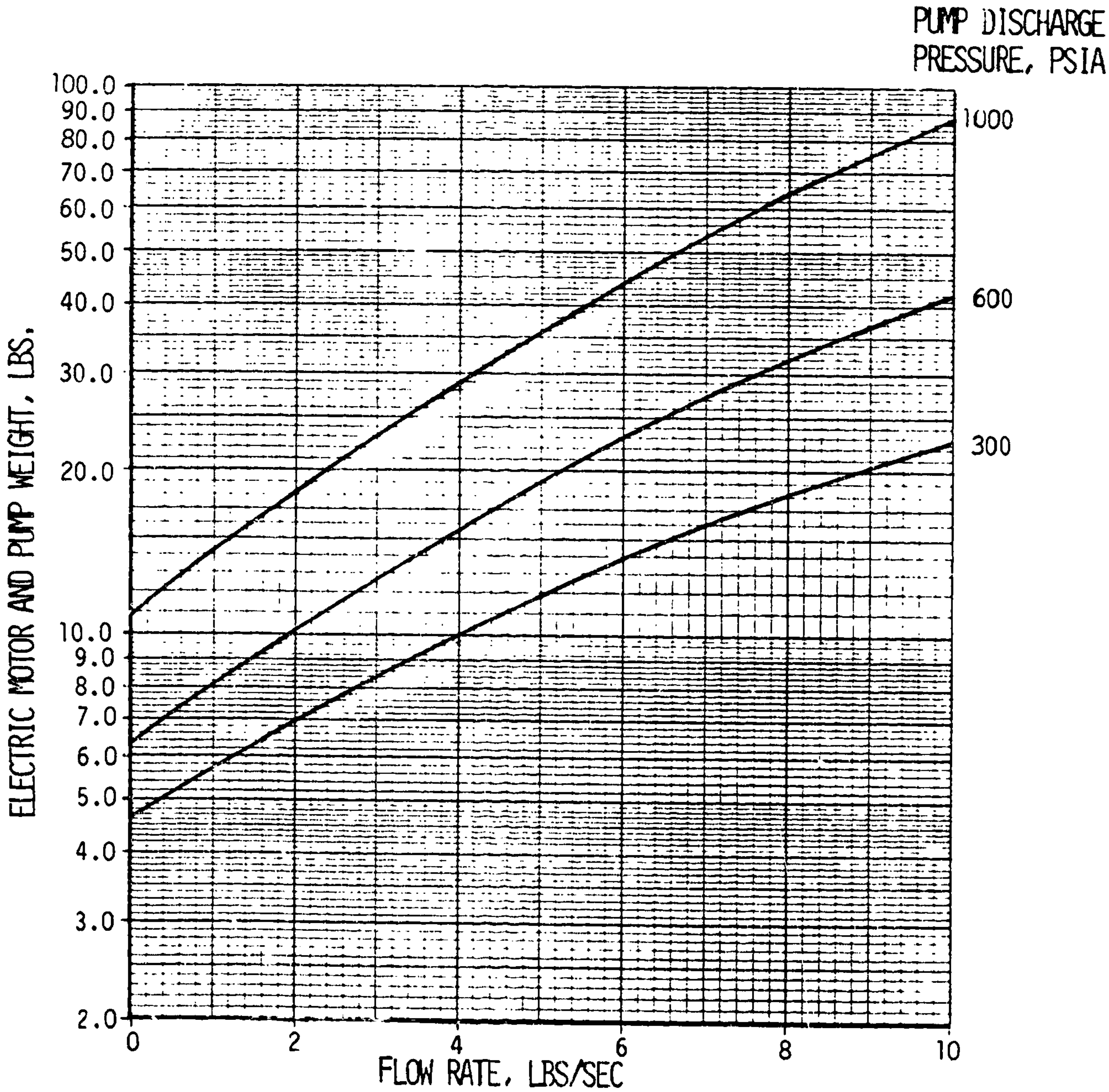


FIGURE 48 ETHANOL ELECTRIC MOTOR AND PUMP WEIGHT

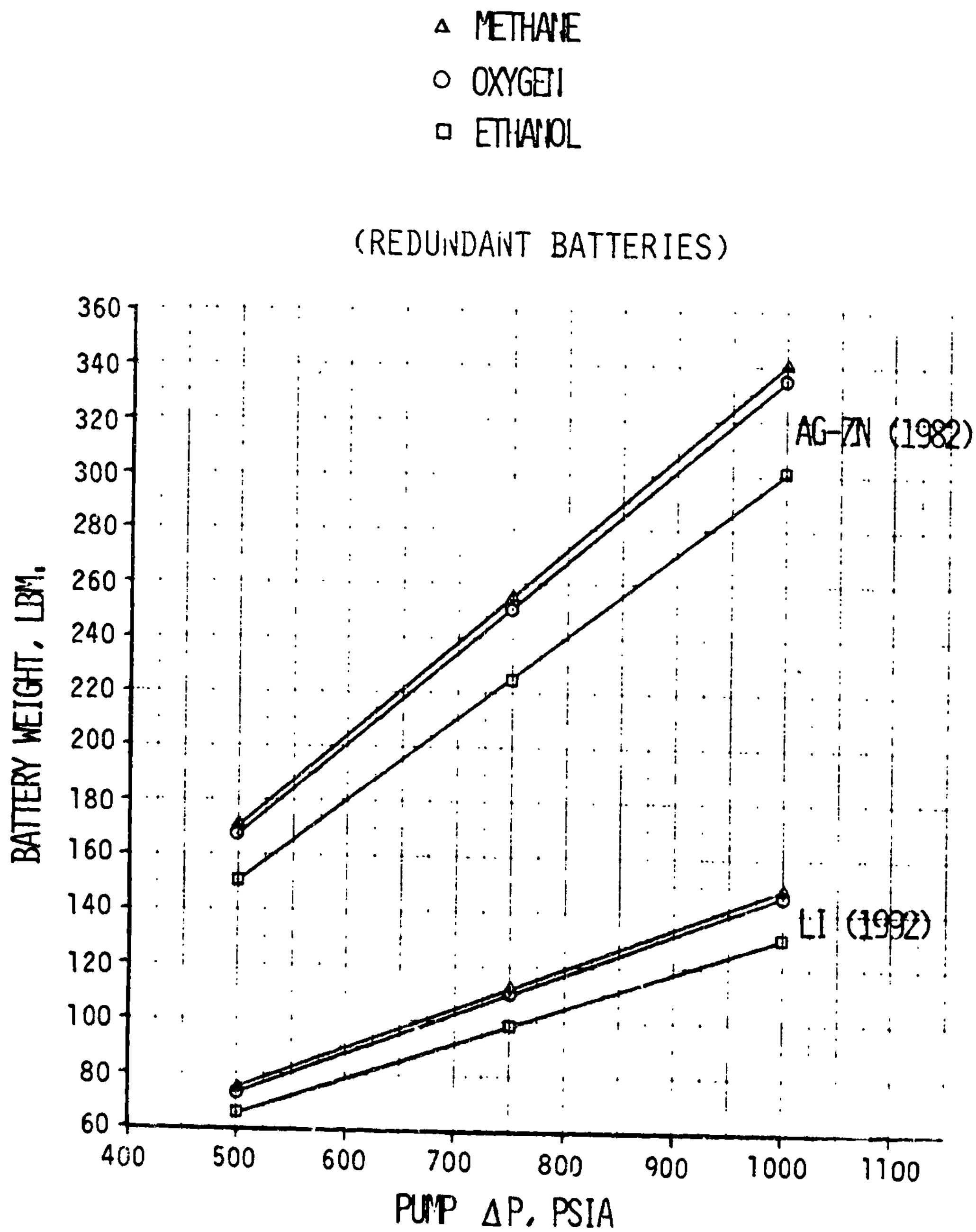


FIGURE 49 BATTERY WEIGHTS FOR ELECTRIC RCS PUMPS

• O_2 HEAT EXCHANGER LINE ABSORBS HEAT FROM THE TANK, FUEL, AND ENVIRONMENT

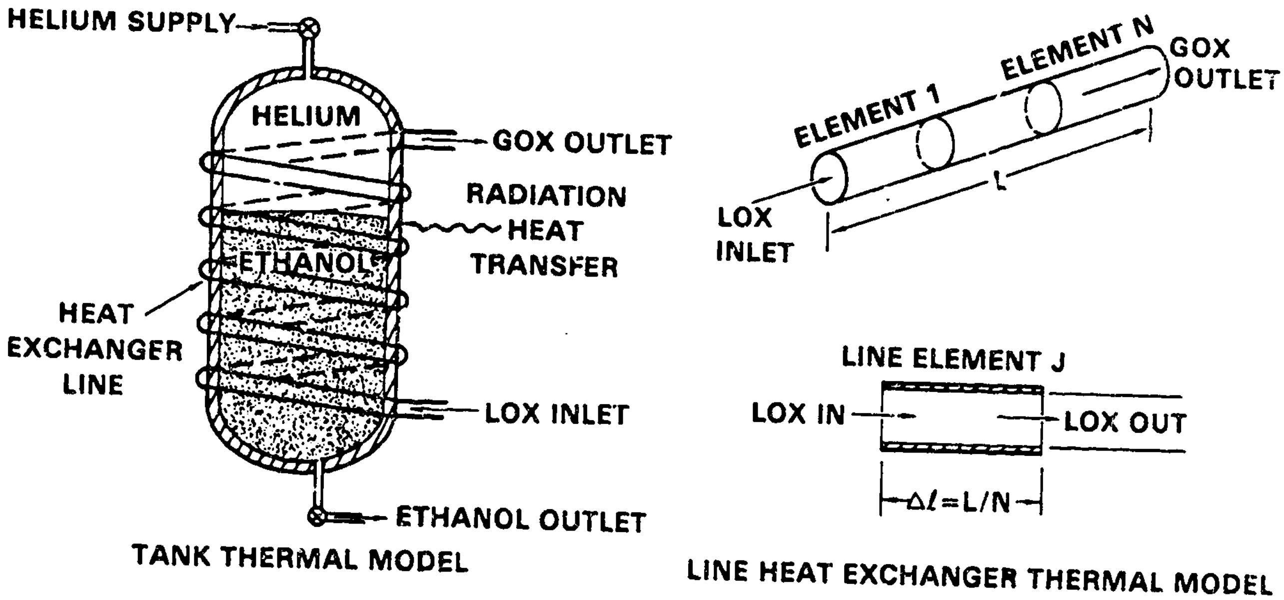


FIGURE 50 ETHANOL TANK O_2 HEAT EXCHANGER MODEL

absorbs heat from the tank wall, the environment, and liquid ethanol within the tank. The O_2 flow enters the heat exchanger as a cryogenic liquid and exits as a superheated vapor. The heat exchanger line is divided into segments, and the energy and mass conservation equations are solved for each segment. The subroutine calculates the O_2 exit temperature and liquid ethanol temperature inside the tank during specified OMS-RCS mission duty cycles. A mass inventory is made to account for the decrease in ethanol quantity during the mission.

6.3 FDLINE Code

The FDLINE code computes the thermal response of propellant contained in the feedlines during specified mission duty cycles. For the Phase II effort the code was changed to include the capability to analyze methane and to provide an improved RCS thruster heat soakback model.

The RCS feedline model was shown previously in Figure 14. The feedline from the accumulator to the thruster valves is divided into segments, and the energy and mass conservation equations are solved for each segment. The analysis accounts for heat conduction through the insulation, thruster heat soakback, and major heat leaks associated with structural members such as line supports. The thruster heat soakback model is shown in Figure 51. The heat soakback is calculated based on the thermal resistance between the injector and valve and the temperature difference provided by Figure 51. (The thermal resistance was provided by ARLC--see Reference (2) appendicies.) At the start of each thruster pulse, the temperature of the thruster injector and valve are assumed to be at ambient temperature. Upon ignition, the valve temperature decays rapidly as a result of propellant flow. At shutdown the injector temperature increases due to heat transfer from the chamber wall, and then the valve temperature begins to rise as a result of heat transfer along the thermal standoff tube. At 1 x 10^5 seconds after shutdown valve and injector temperatures are nearly equal. The FDLINE code maintains an inventory of thruster pulses and the time-between firings and then applies the injector-valve temperature difference given by Figure 51 to compute thruster heat soakback.

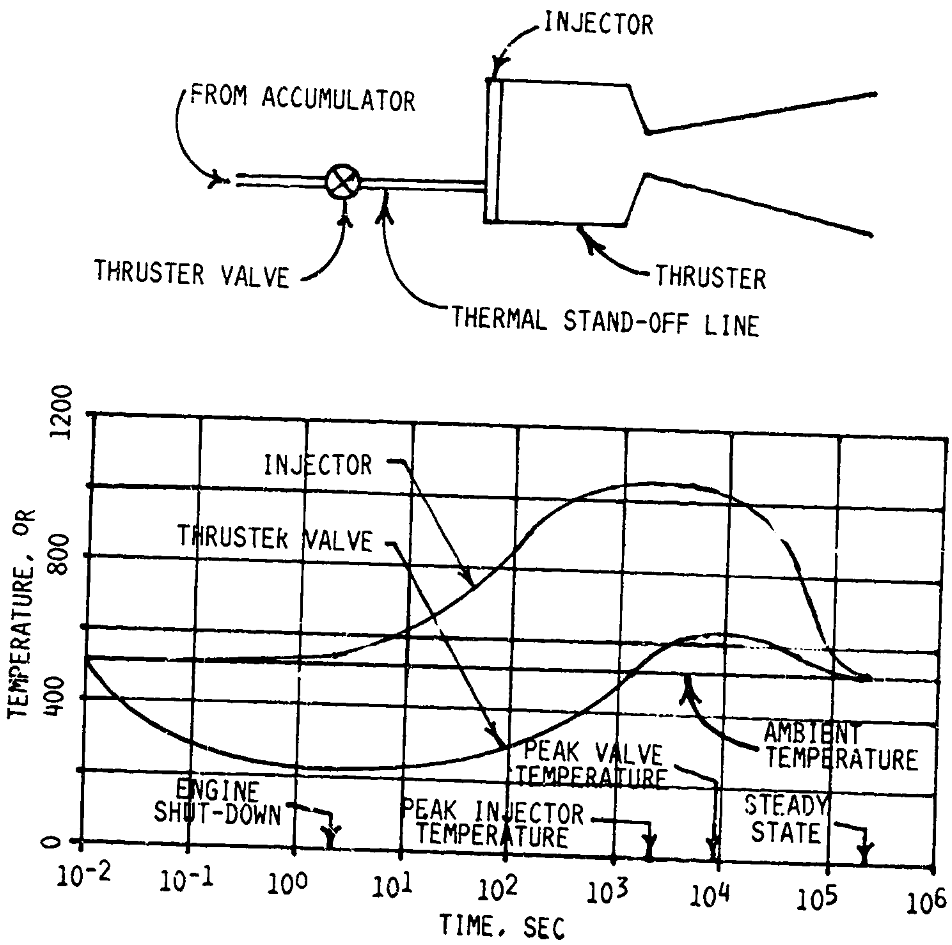


FIGURE 51 RCS THRUSTER HEAT SOAKBACK MODEL

7.0 TASK II.3--PHASE II SYSTEM EVALUATIONS

The evaluations performed in this task are summarized in Table XV. They include design definition of the Phase II options identified previously in Section 5.0 (Table XIII), design point sensitivity analyses, and side-by-side comparisons of the most attractive LOX/HC systems with a LOX/H_2 system and the current storable propellant OMS/RCS. System weight and performance data generated with the APSDS computer code to support these evaluations were provided in the Appendicies of Reference (2). The following paragraphs present the results and conclusions derived from these evaluations.

7.1 Tank Insulation Evaluations

Methane and LOX insulation concepts were evaluated for common OMS/ARCS and separate FRCS propellant tanks. Based on the Phase I results two insulation candidates were selected for evaluation--TG-15000 silica fiber insulation and aluminized mylar multi-layer insulation (MLI). The properties of the candidate insulation materials were shown in Table XII. The evaluations were performed using the TKHEAT code described in Section 3.2 applying representative OMS-RCS engine firing cycles for a 30-day mission.

Example TKHEAT code analysis results for a common methane OMS-ARCS tank are presented in Figures 52 and 53. For this example a blanket consisting of 1.5 inches of TG-15000 insulation was assumed. As shown in Figure 52 the tank pressure increases slowly from an initial value of 35 psia to a tank relief pressure of 60 psia. At the relief pressure liquid methane is withdrawn through the propellant acquisition system and routed through a thermodynamic vent system. The thermodynamic vent system consists of a coiled tank heat exchanger inside the tank insulation which absorbs heat from the environment. The environmental heat input vaporizes the methane, and the methane vapor is then vented overboard. Methane is vented until the tank pressure decays to 57 psia, and then the vent system is shutdown automatically. This vent process is then repeated for the remainder of the mission. The corresponding methane temperature history for this 30-day mission simulation is shown in Figure 53. The temperature increases slowly as a result of environmental heating during the first 200 hours of the mission. Then, during venting, the temperature cycles between 223 and 220^{o}R.

TABLE XV

PHASE II SYSTEM EVALUATION TASKS

1. Tank Insulation Evaluations (Methane and LOX)
2. RCS Feedline Insulation Evaluations (Methane and LOX)
3. GOX/Ethanol RCS Feasibility Evaluations
   - Turbopump RCS propellant feed with ethanol feedline O_2 heat exchanger
   - Electric pump RCS propellant feed with ethanol tank O_2 heat exchanger
4. LOX/Ethanol and LOX/Methane OMS-RCS Sensitivity Analyses
   - OMS and RCS chamber pressure
   - RCS accumulator blowdown pressure ratio
   - OMS and RCS specific impulse
   - propellant tank minimum gage thickness
5. Separate versus Common FRCS/Aft Propulsion Tanks
6. Convertional versus Conical Propellant Tank Shapes
7. Pump versus Pressure Fed FRCS
8. Side-by-Side OMS/ARCS Comparisons
   - LOX/ethanol
   - LOX/methane
   - LOX/H_2
   - Current N_2O_4/MMH

ORIGINAL PAGE IS
OF POOR QUALITY

- 1.5 INCHES TG-15000 INSULATION
- 30 DAY MISSION
- INITIAL METHANE LOAD = 3005 LB_M
- RELIEF PRESSURE = 60 PSIA
- ENVIRONMENTAL TEMPERATURE = 500^oR

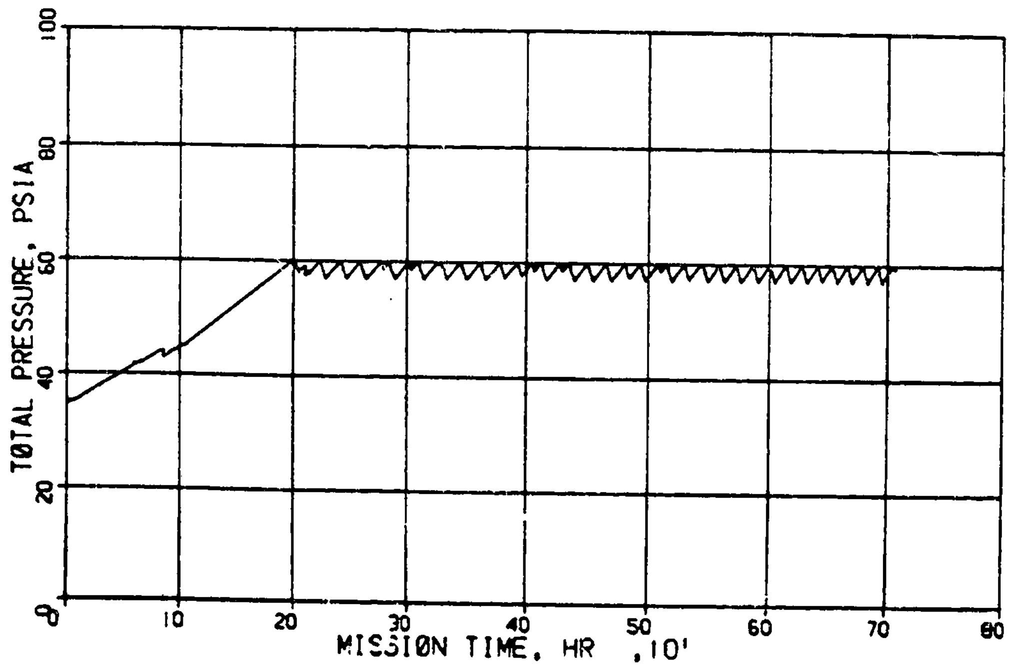


FIGURE 52 30-DAY PRESSURE PROFILE FOR COMMON OMS-ARCS TANK (METHANE)

- 1.5 INCHES TG-15000 INSULATION
- 30 DAY MISSION
- INITIAL METHANE LOAD = 3005 LB_M
- RELIEF PRESSURE = 60 PSIA
- ENVIRONMENTAL TEMPERATURE = 500^oR

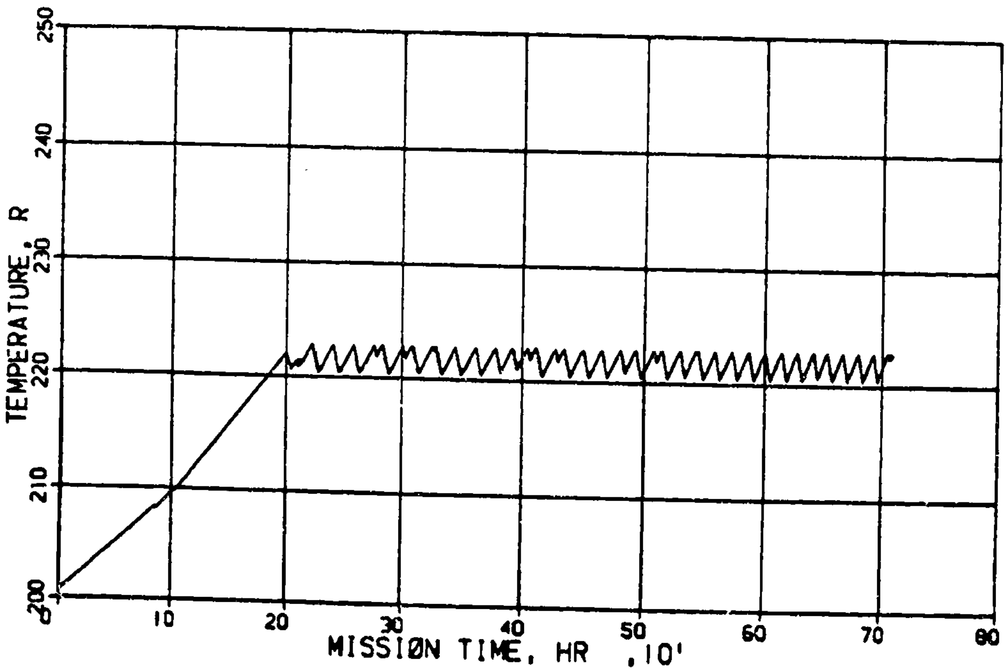


FIGURE 53 30-DAY TEMPERATURE HISTORY FOR COMMON OMS-ARCS TANK (METHANE)

The measure of tank insulation effectiveness is the propellant boil-off (vent loss) that occurs during the mission. Thirty-day vent losses for the two candidate insulation materials are compared in Figures 54 through 57 for a common OMS-ARCS tank and a separate FRCS tank. Results for methane are presented in Figures 54 and 55, whereas results for oxygen are presented in Figures 56 and 57. As shown in these figures the vent loss with 1.0 inch of MLI is approximately one-half that of 1.5 inches of TG-15000 insulation. As a result of these evaluations 1.0 inch of MLI was baselined for the LOX and methane storage tanks.

7.2 RCS Feedline Insulation Evaluations

MLI and TG-15000 insulation materials were also evaluated for LOX and methane RCS feedlines. These evaluations were performed using the FDLINE code described in Section 3.3 and employed the thruster heat soakback model described in Section 6.3. The evaluations were performed for a manifold arrangement in which all the RCS propellant is consumed through a single thruster manifold feeding the required number of primary and vernier thrusters for Orbiter three axis attitude control. (Should a thruster failure occur with this manifold arrangement--i.e., failed open thruster valve--the primary manifold would be isolated and a back-up manifold activated.)

The FDLINE code computes propellant temperature response along the feedline for specified mission duty cycles. As an example, methane temperature response for a 7-day RCS mission is shown in Figure 58. The temperature response is for a feedline node adjacent to a thruster valve which is the warmest point in the feed system. The feedline was modeled assuming one-inch of TG-15000 insulation. The mission duty cycle was modeled assuming two distinct operating modes--primary thruster firings and vernier thruster firings. Each primary thruster firing (~150 per mission) was modeled as a discrete pulse, whereas the vernier firings (~15,000 per mission) were modeled as a continuous burn at very low flowrate. As shown in Figure 58 the methane temperature at the thruster valve cools to $220^{o}R$ during primary thruster firings as warm propellant in the feedline is replaced by cold propellant from the accumulator. During periods of low flowrate vernier thruster limit cycle operation the methane temperature increases and stablizes at $268^{o}R$, which is below the vaporization limit of $282^{o}R$.

ORIGINAL PAGE IS
OF POOR QUALITY

- 30 DAY MISSION
- INITIAL METHANE LOAD = 3005 LB_M
- RELIEF PRESSURE = 60 PSIA
- ENVIRONMENTAL TEMPERATURE = 500°R

▵ 1.5 INCHES TG-15000 INSULATION

⊙ 1.0 INCH MLI

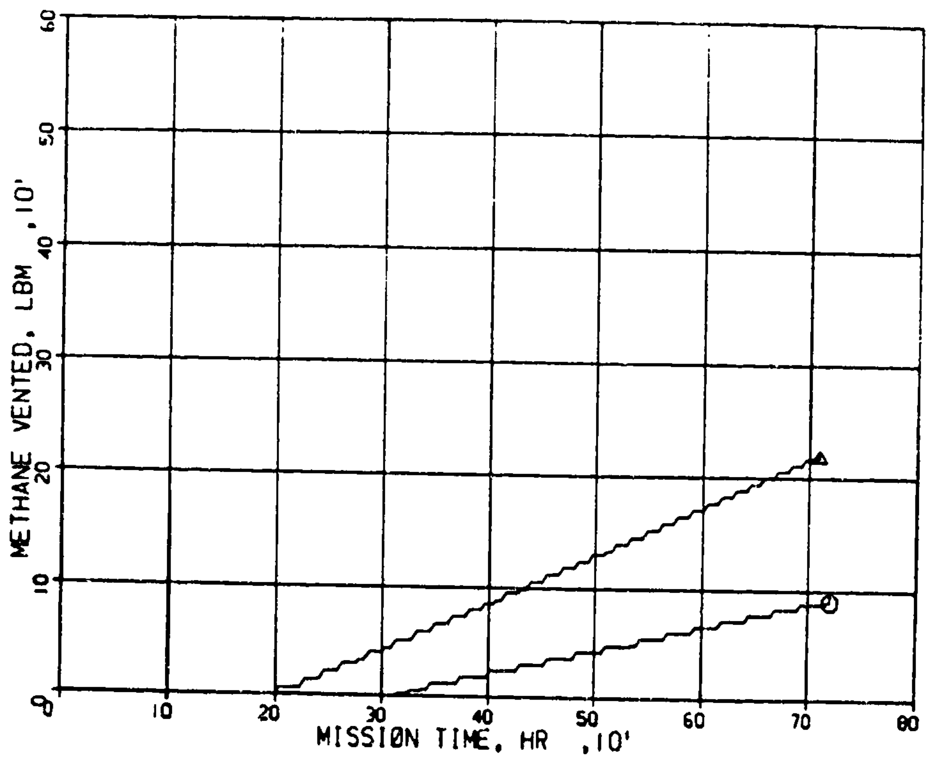


FIGURE 54 METHANE VENT LOSSES FOR COMMON OMS–ARCS TANK

- 30 DAY MISSION
- INITIAL METHANE LOAD = 683 LB_M
- RELIEF PRESSURE = 60 PSIA
- ENVIRONMENTAL TEMPERATURE = 500°R

△ 1.5 INCHES TG-15000 INSULATION

○ 1.0 INCH MLI

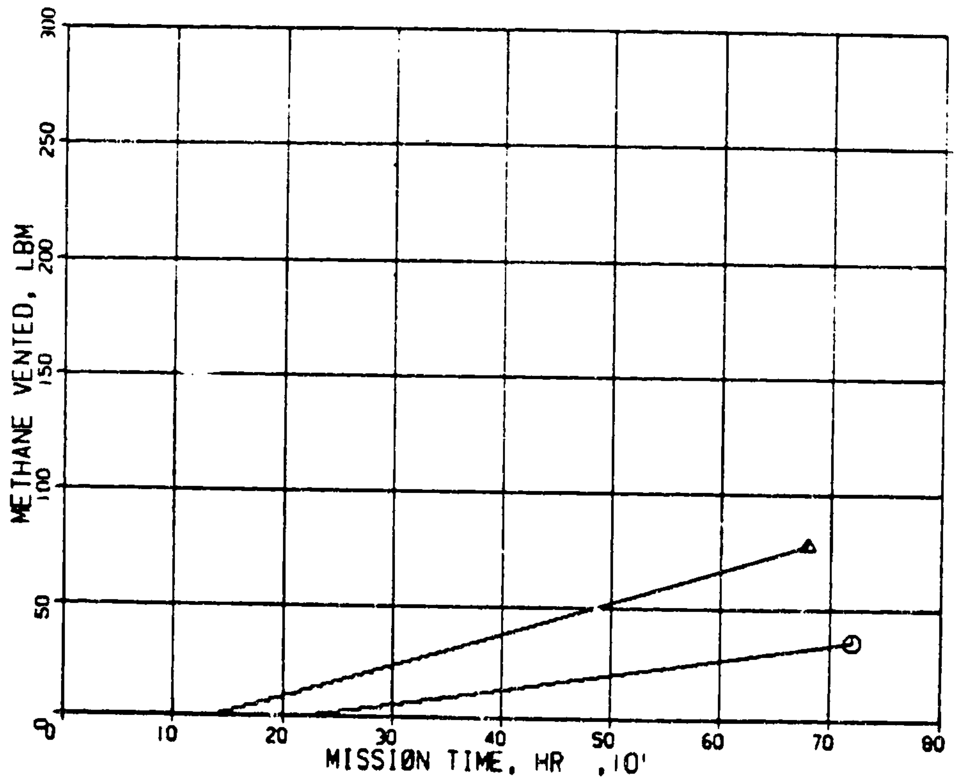


FIGURE 55 METHANE VENT LOSSES FOR FRCS TANK

- 30 DAY MISSION
- INITIAL LOX LOAD = 9606 LB_M
- RELIEF PRESSURE = 60 PSIA
- ENVIRONMENTAL TEMPERATURE = 500°R

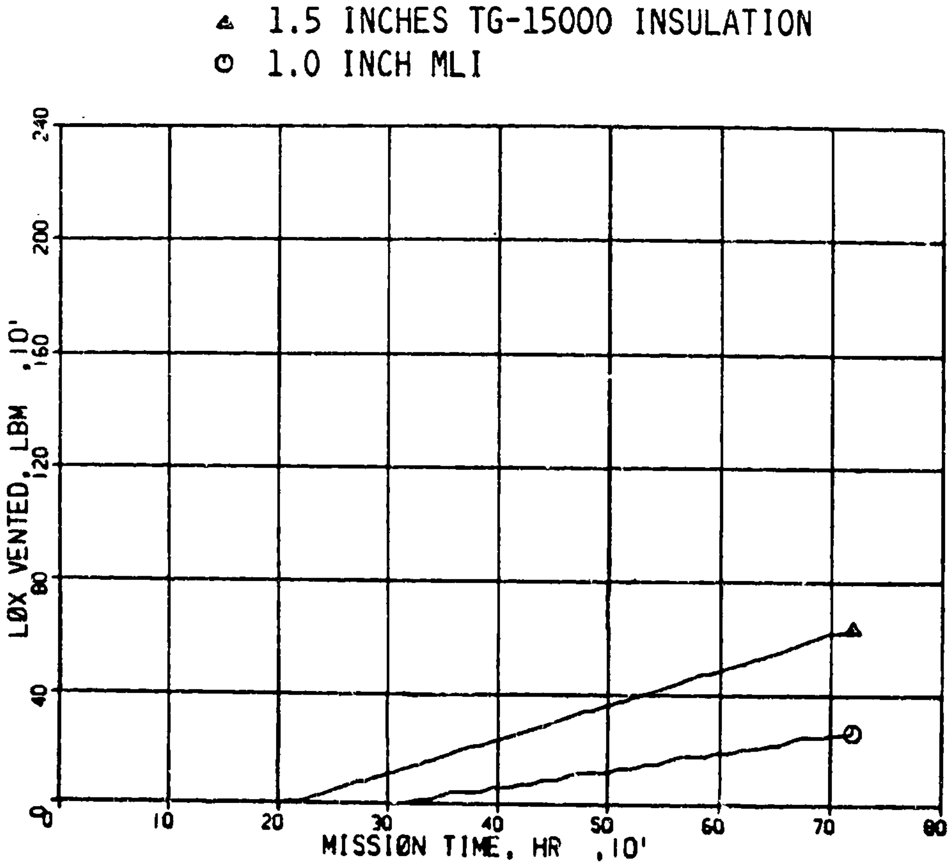


FIGURE 56 LOX VENT LOSSES FOR COMMON OMS-ARCS TANK

- 30 DAY MISSION
- INITIAL LOX LOAD = 2148 LB_M
- RELIEF PRESSURE = 60 PSIA
- ENVIRONMENTAL TEMPERATURE = 500°R

▲ 1.5 INCHES TG-15000 INSULATION
○ 1.0 INCH MLI

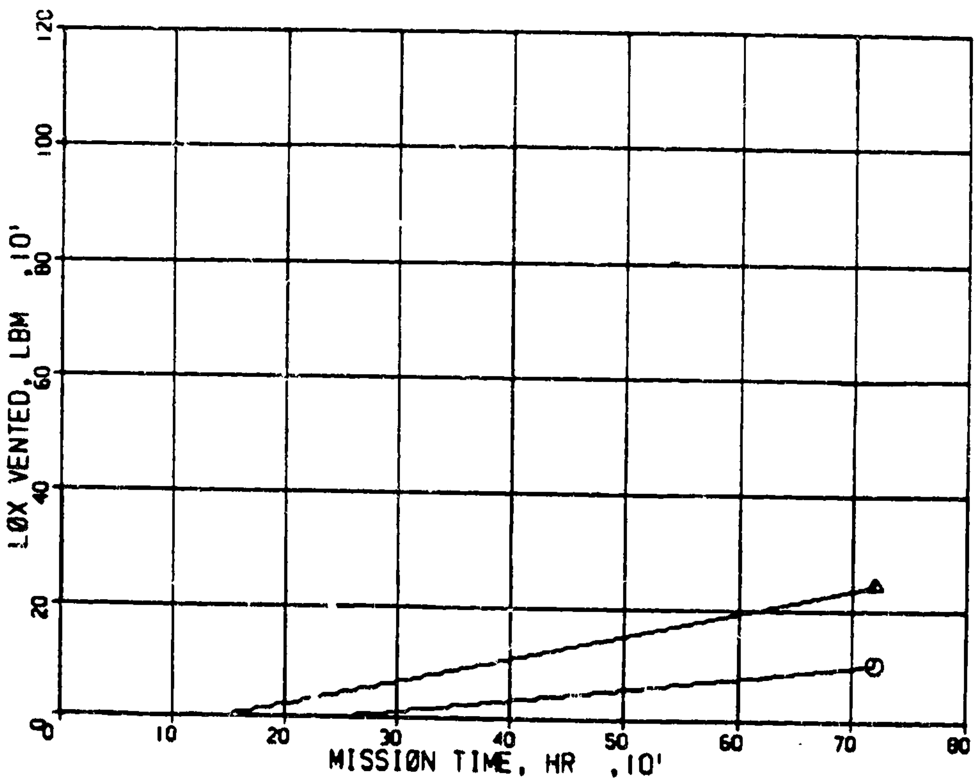


FIGURE 57 LOX VENT LOSSES FOR FRCS TANK

ORIGINAL PAGE IS
OF POOR QUALITY

- 7-DAY RCS DUTY CYCLE
- 1 IN. TG-15000 INSULATION
- PRESSURE = 500 PSIA

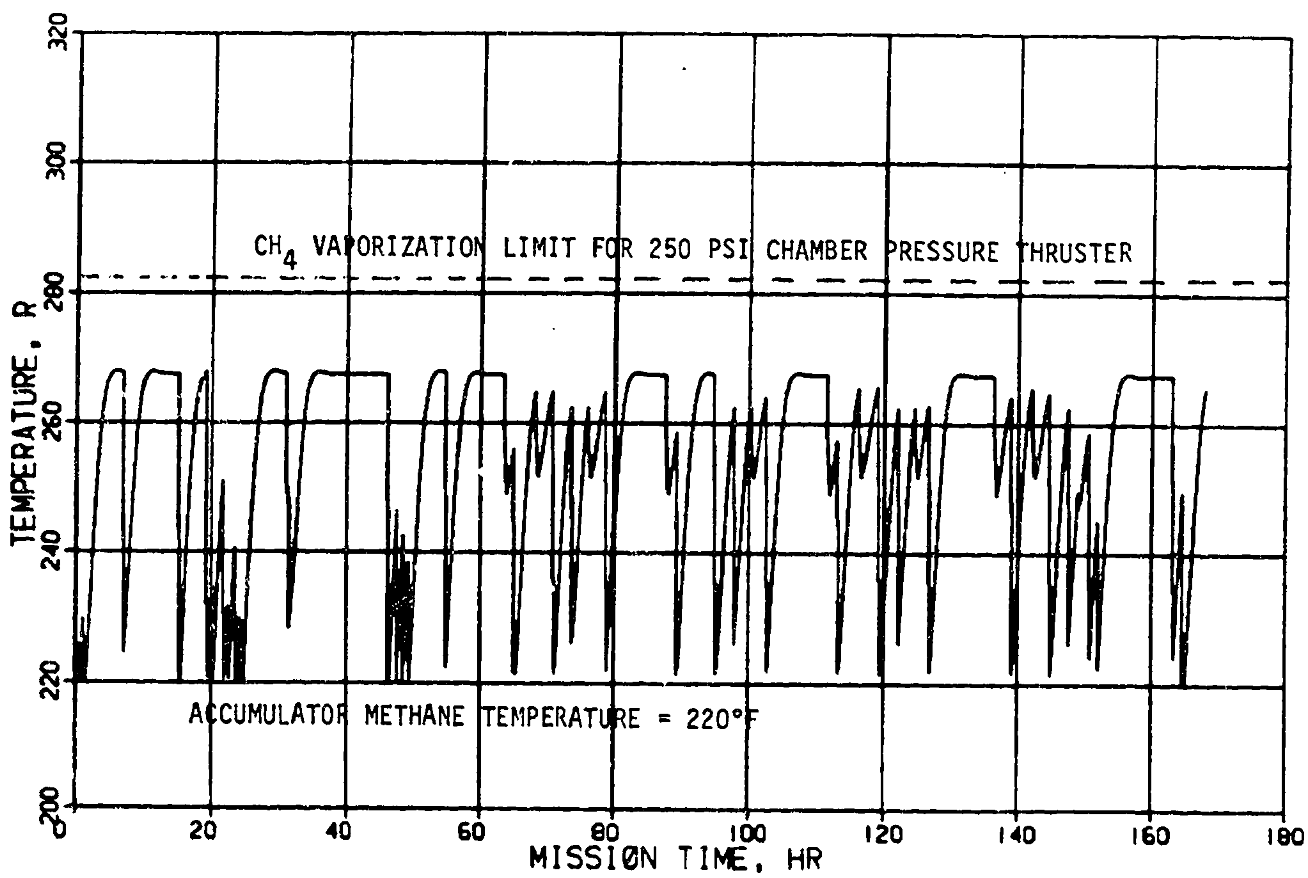


FIGURE 58 METHANE TEMPERATURE RESPONSE IN RCS FEEDLINE (TG-15000 INSULATION)

For 30-day RCS missions the vernier propellant usage rate is reduced substantially and higher feedline temperatures are attained. This is shown by Figure 59 which is a summary plot of maximum methane feedline temperature as a function of vernier usage rate and accumulator temperature for TG-15000 insulation. Whereas temperatures are maintained below the vaporization limit for the 7-day vernier thruster usage rate, they exceed the vaporization limit at the lower 30-day usage rate. A similar summary plot, presented in Figure 60 for one inch of MLI, shows that methane feedline temperatures are maintained below the vaporization limit for both the 7 and 30-day vernier thruster usage rates.

To complete the RCS feedline insulation evaluations similar analyses were performed for LOX. The results are presented in Figures 61 through 63 and show that MLI is also required for the LOX feedlines to preclude excessive temperatures for the 30-day mission. As a result of these evaluations one inch of MLI was baselined for the cryogenic LOX and methane RCS feedlines.

7.3 GOX/Ethanol RCS Feasibility Evaluations

Two feed system approaches were evaluated to determine the feasibility of gaseous O_2 (GOX) feed in the oxygen/ethanol ARCS. The first uses the OMS turbopumps to resupply the RCS accumulators and an ethanol feedline heat exchanger to gasify the RCS oxygen flow. The second uses small electric pumps to resupply the RCS accumulators and an ethanol tank heat exchanger to gasify the RCS oxygen flow. The advantage of these approaches is the elimination of insulation on the RCS oxygen accumulator and feedlines.

The first feed system approach, using the OMS turbopumps to resupply the RCS accumulators, is shown in Figure 64. This approach uses two heat exchangers upstream of the RCS accumulators to thermally condition the RCS O_2 supply and avoid the use of fuel-rich gas generator products in an O_2 heat exchanger. During RCS accumulator resupply, fuel leaving the OMS turbopump is first preheated to $660^{o}R$ in a heat exchanger by reaction products from a separate fuel-rich gas generator. The hot fuel flow is then used to thermally condition the O_2 re-supply flow from 165 to $370^{o}R$ in a passive feedline heat exchanger. The passive feedline heat exchanger operates at a low oxidizer-to-fuel flowrate ratio (1.0) to enhance its O_2 heating

- 1 IN. TG-15000 INSULATION
- PRESSURE = 500 PSIA

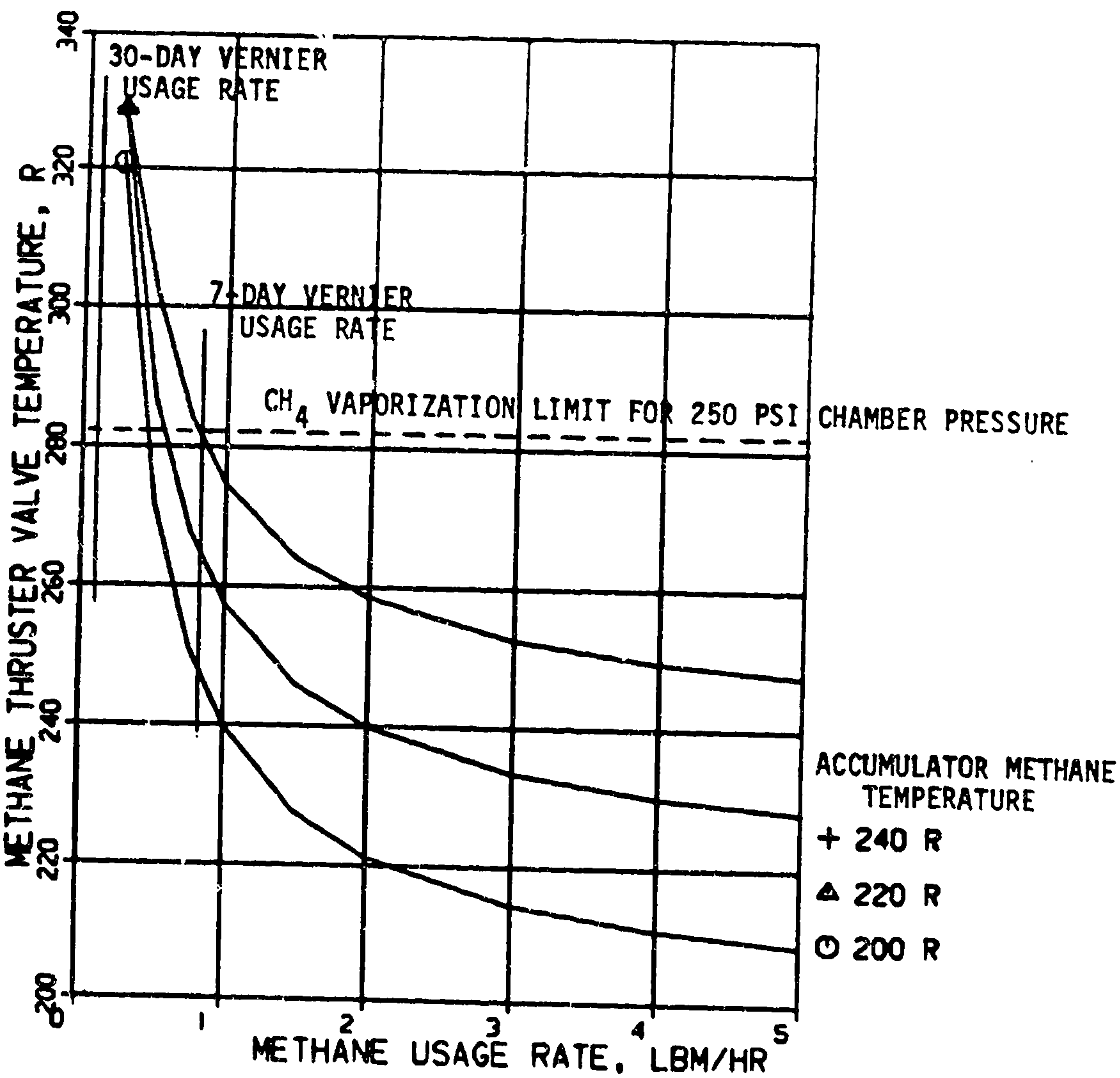


FIGURE 59 EFFECT OF METHANE USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (TG-15000 INSULATION)

ORIGINAL PAGE IS
OF POOR QUALITY

o 1 IN. MLI
o PRESSURE = 500 PSIA

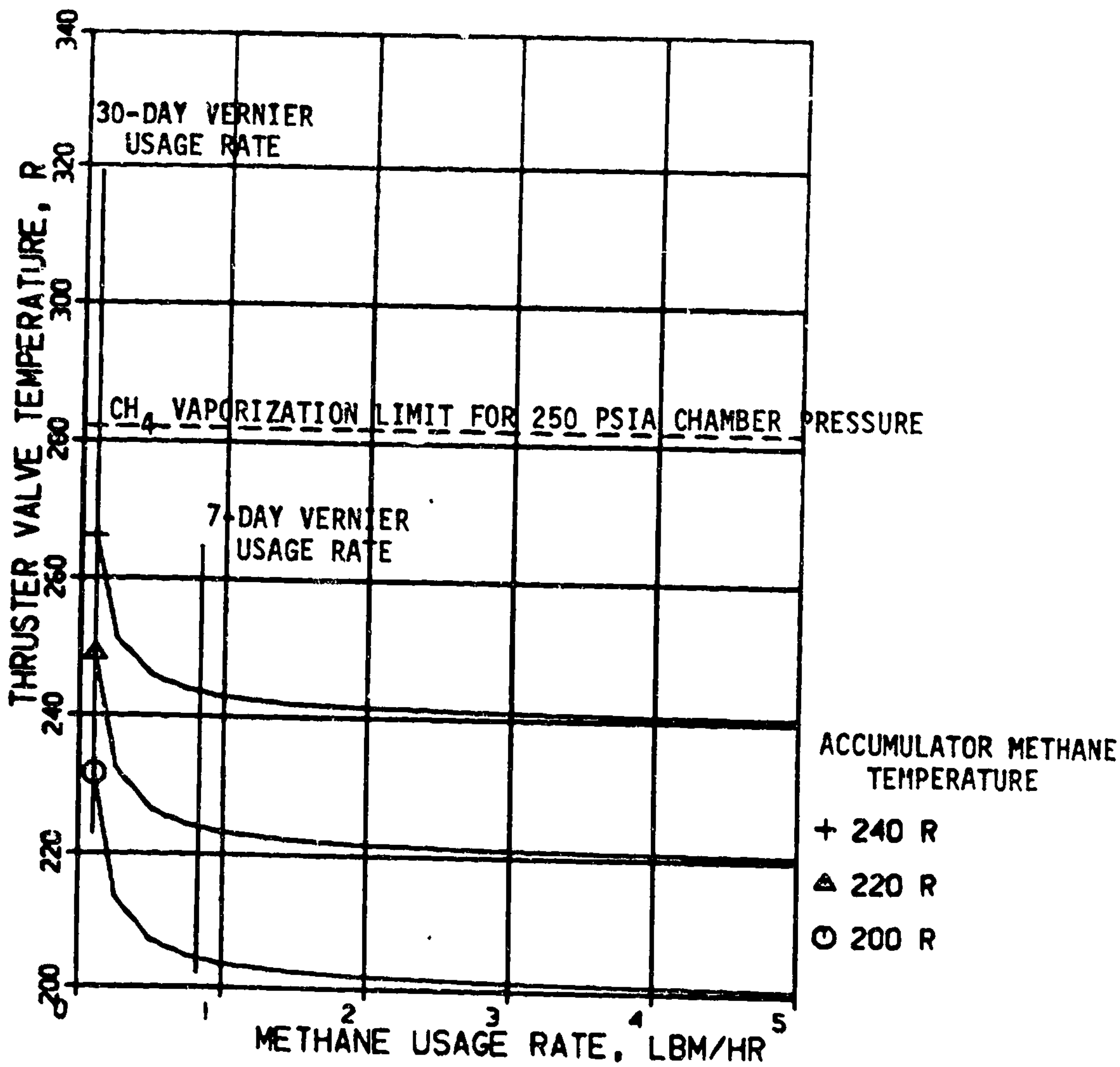


FIGURE 60 EFFECT OF METHANE USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (MLI)

- 7-DAY RCS DUTY CYCLE
- 1 IN. TG-15000 INSULATION
- PRESSURE = 500 PSIA

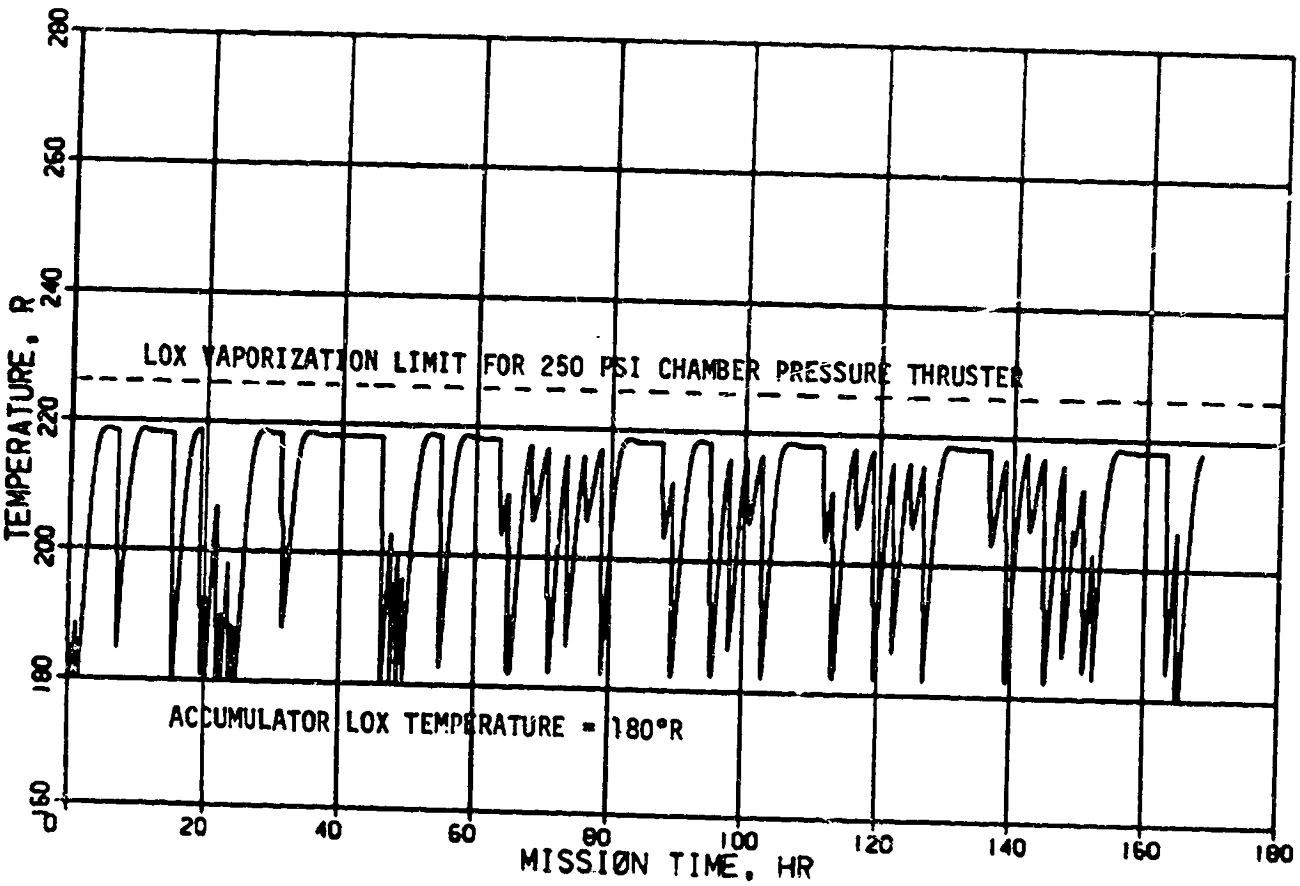


FIGURE 61 LOX TEMPERATURE RESPONSE IN RCS FEEDLINE (TG-15000 INSULATION)

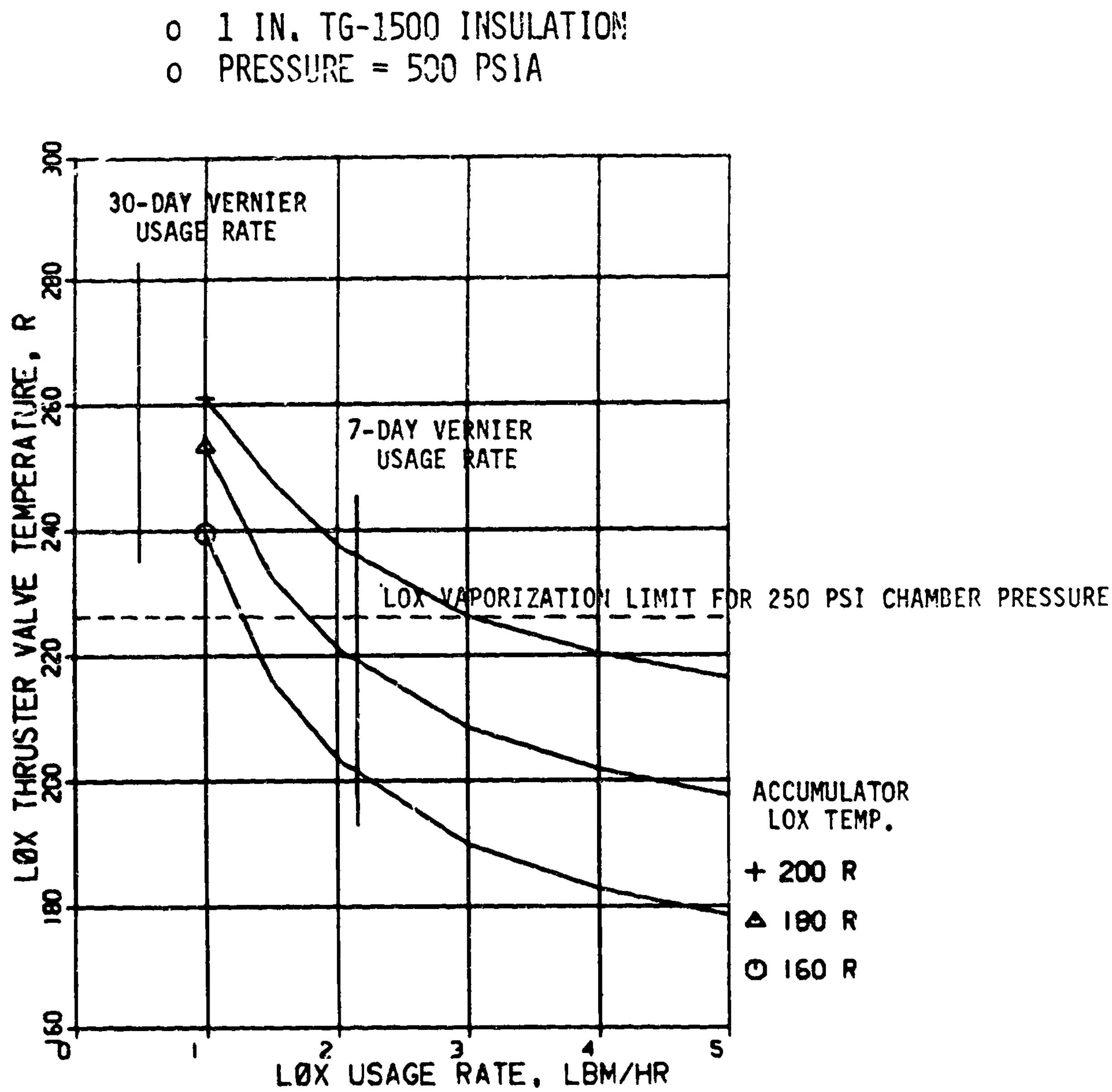


FIGURE 62 EFFECT OF LOX USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (TG-15000 INSULATION)

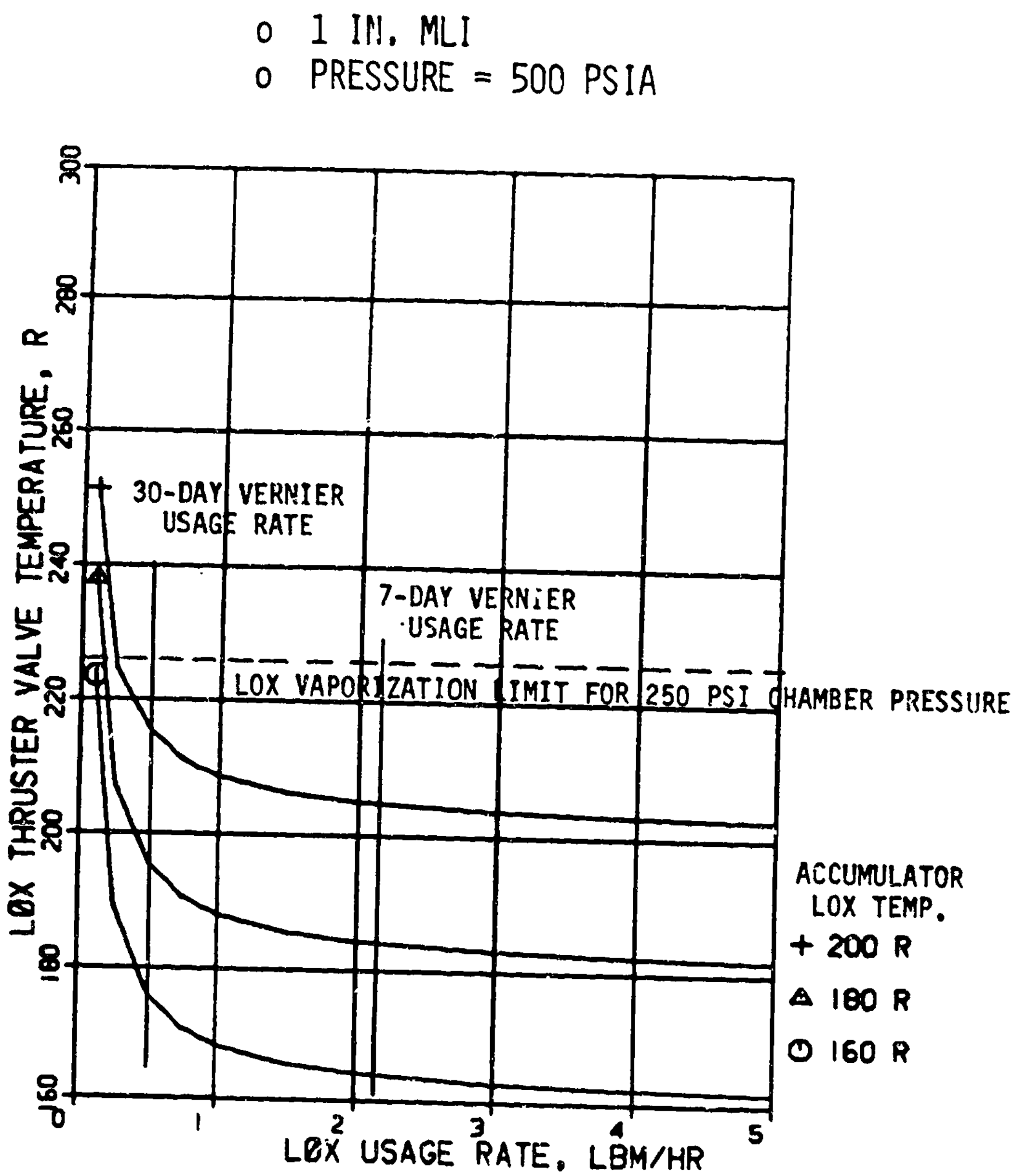


FIGURE 63 EFFECT OF LOX USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (MLI)

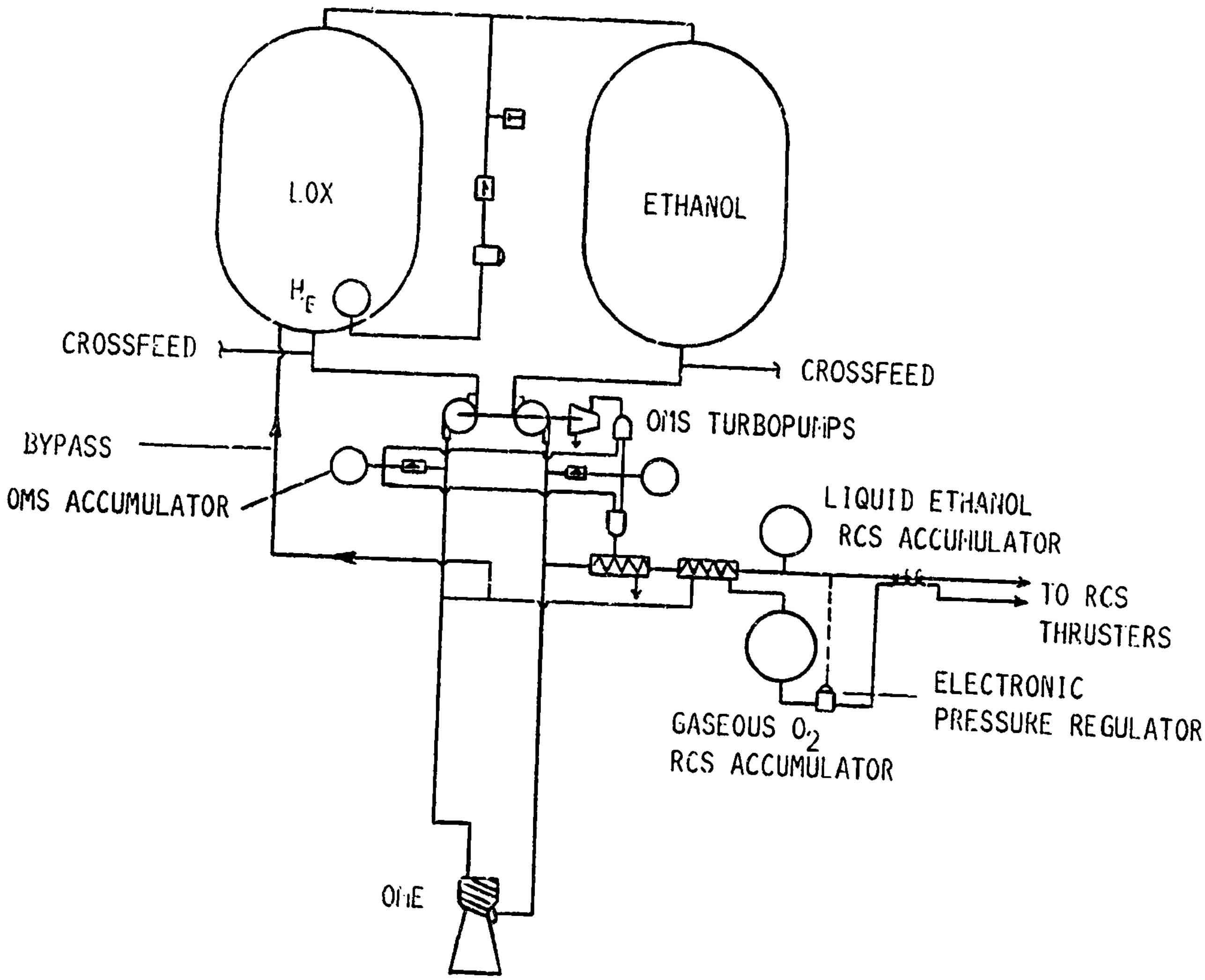


FIGURE 64 LOX/ETHANOL OMS-ARCS USING OMS TURBOPUMPS FOR RCS SUPPLY

capability. The RCS thrusters also operate at a mixture ratio of 1.0 so that the accumulator outflow is at the same mixture ratio as the resupply flow. Since the single shaft turbopumps deliver propellants at a fixed oxidizer-to-fuel flowrate ratio of 1.72:1, the excess O_2 flow is routed back to the LOX tank, by-passing the heat exchanger.

RCS accumulator operation with this OMS turbopump resupply approach was evaluated using the TKHEAT code. Temperature and pressure response in the ethanol accumulator are shown in Figure 65, while temperature and pressure response in the GOX accumulator are shown in Figure 66. Both accumulators operate in a blowdown mode. The ethanol accumulator contains a helium charge which expands with outflow and compresses with resupply flow. Resupply of both accumulators is controlled by pressure switches in the ethanol accumulator. As shown in Figure 65 resupply flow is initiated when the ethanol accumulator pressure decays to 500 psia and is terminated when the pressure rebuilds to 775 psia. The temperature of the ethanol in the accumulator decays during resupply as a result of the cold resupply flow (370^{o}F) and then increases as a result of environmental heating after resupply is cut-off. A minimum ethanol accumulator temperature of 370^{o}R is reached 24 hours into the mission during the period of maximum RCS usage. The O_2 accumulator (Figure 66) cycles with the same frequency as the ethanol accumulator but operates over a wider pressure range (660 to 1260 psia). The minimum O_2 accumulator temperature (350^{o}R) also occurs 24 hours into the mission.

Despite the wide variations in accumulator pressures and temperatures adequate control over RCS thruster mixture ratio is achieved through use of an electronic pressure regulator and thermally shorted feedlines downstream of the accumulators (Figure 64). The O_2 accumulator outlet pressure is controlled in response to ethanol accumulator pressure with the electronic pressure regulator, while O_2 and ethanol fluid temperatures are equalized with the thermally shorted feedlines.

The results of Figures 65 and 66 demonstrate the feasibility of a hybrid RCS feed system (gaseous O_2 and liquid ethanol) in which OMS turbopumps are used for accumulator resupply. However, this feed system approach has the following disadvantages:

- OMS TURBOPUMPS USED TO RE-SUPPLY RCS ACCUMULATORS
- LIQUID ETHANOL ACCUMULATOR VOLUME = 2.47 FT^3
- RE-SUPPLY CONDITIONS
  - FLOWRATE = 10.8 LB_M/SEC
  - TEMPERATURE = 370°R
  - PRESSURE = 1250 PSIA
- ACCUMULATOR RE-SUPPLY SWITCHING PRESSURES
  - INITIATION = 500 PSIA
  - CUT-OFF = 775 PSIA

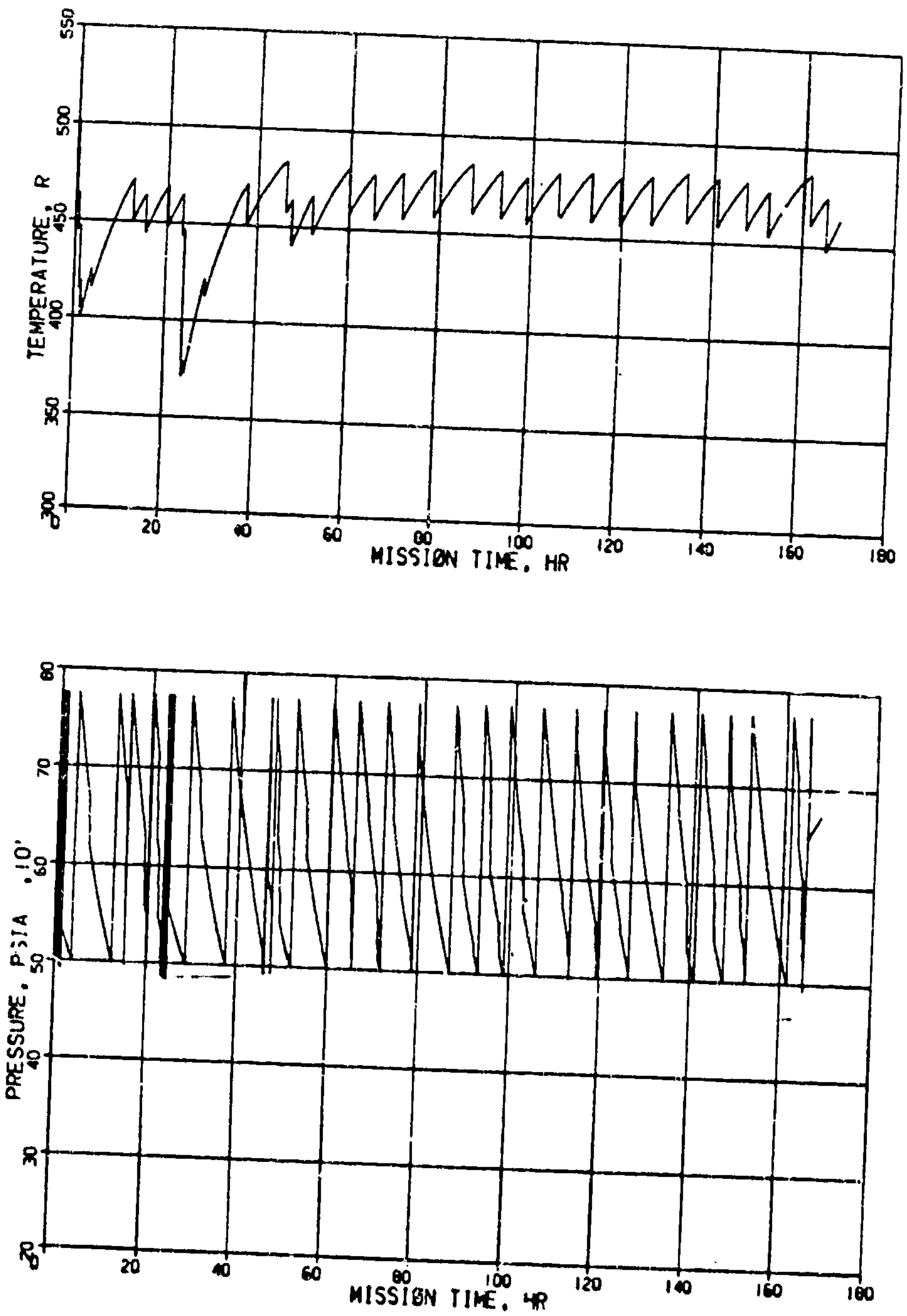
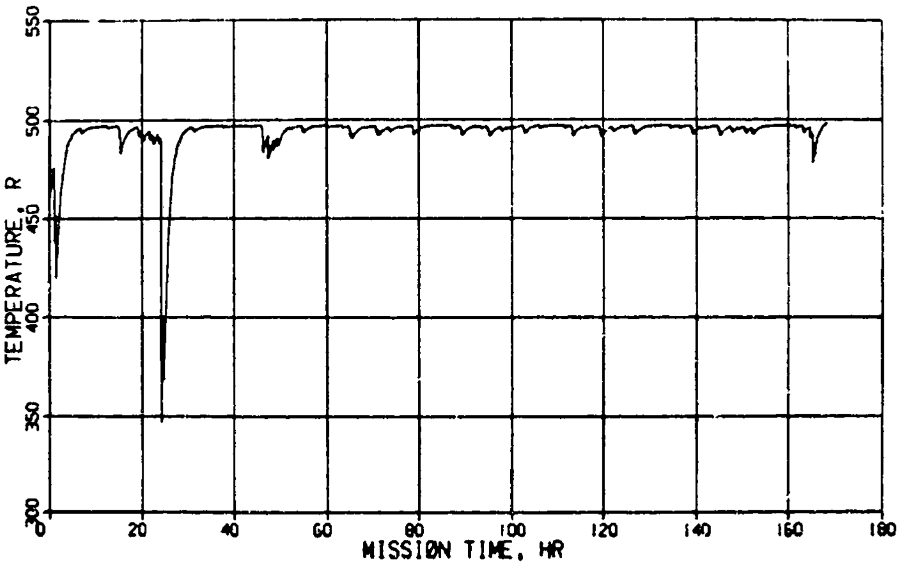


FIGURE 65 RCS ETHANOL ACCUMULATOR MISSION RESPONSE (OMS TURBOPUMP RESUPPLY)

- OMS TURBOPUMPS USED TO RE-SUPPLY RCS ACCUMULATORS
- GASEOUS O_2 ACCUMULATOR VOLUME = 13.8 FT^3
- RE-SUPPLY CONDITIONS
  FLOWRATE = 10.8 LB_M/SEC
  TEMPERATURE = 370°R
  PRESSURE = 1250 PSIA



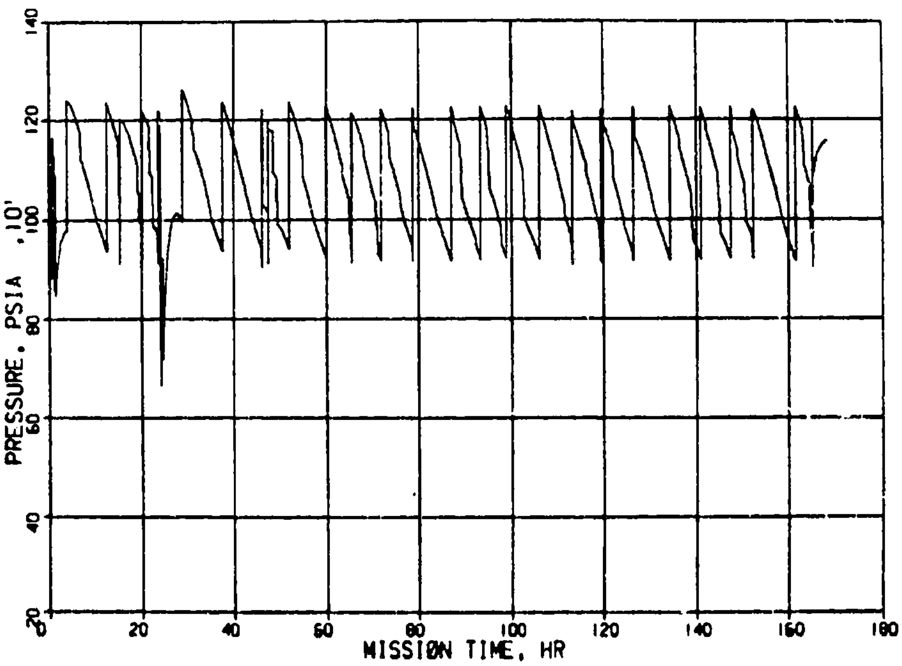


FIGURE 66 RCS GOX ACCUMULATOR MISSION RESPONSE
(OMS TURBOPUMP RESUPPLY)

- large number of turbopump cycles (~50 per mission)
- complexity associated with the use of an O_2 heat exchanger by-pass circuit and a separate gas generator for fuel pre-heating
- low RCS performance (gas generator vent losses coupled with low RCS mixture ratio).

The second feed system approach, using dedicated electric motor pumps to resupply the RCS accumulators, is illustrated in Figure 67. In this approach O_2 thermal conditioning is achieved using a passive ethanol tank heat exchanger. The O_2 enters the heat exchanger as a liquid at cryogenic temperature, absorbs heat from the environment, tank wall, and ethanol inside the tank and exits the heat exchanger as a superheated vapor. The effectiveness of the ethanol tank heat exchanger is shown in Figures 68 and 69 for a representative 7-day OMS-RCS mission duty cycle. The heat exchanger was sized for two primary RCS thrusters firing simultaneously in order to meet the back-up RCS deorbit burn requirement. Figure 68 shows the O_2 inlet and outlet temperature histories over the 7-day priod. The coldest O_2 outlet temperature is 425°R and occurs 24 hours into the mission during the period of maximum RCS usage. Figure 69 shows the corresponding temperature and quantity of ethanol remaining as a function of mission time. The coldest ethanol temperature (430°R) also occurs at the 24 hour point.

Examples of RCS accumulator temperature-pressure response with the electric pump resupply approach are shown in Figures 70 and 71. Figure 70 shows the response of the liquid ethanol accumulator, while Figure 71 shows the response of the gaseous O_2 accumulator. For these examples the temperatures of the fuel and oxidizer resupply flows were set equal to their minimum values (430 and 425°R, respectively). In order to minimize electric motor weight and power requirements pump discharge pressures were set at 500 psia. Unlike the preceeding OMS-RCS concept which used the OMS turbopumps for resupply, the ethanol and O_2 accumulators do not have to be resupplied at the same time, and the RCS thrusters can be operated at optimum mixture ratio (1.3 to 1.4). Similar to the preceeding concept an electronic pressure regulator and thermally shorted feedlines are employed downstream of the accumulators to control RCS thruster mixture ratio (Figure 67).

The results of Figures 68 through 71 demonstrate the feasibility of a hybrid RCS feed system (gaseous O_2 and liquid ethanol) in which electric pumps are used for

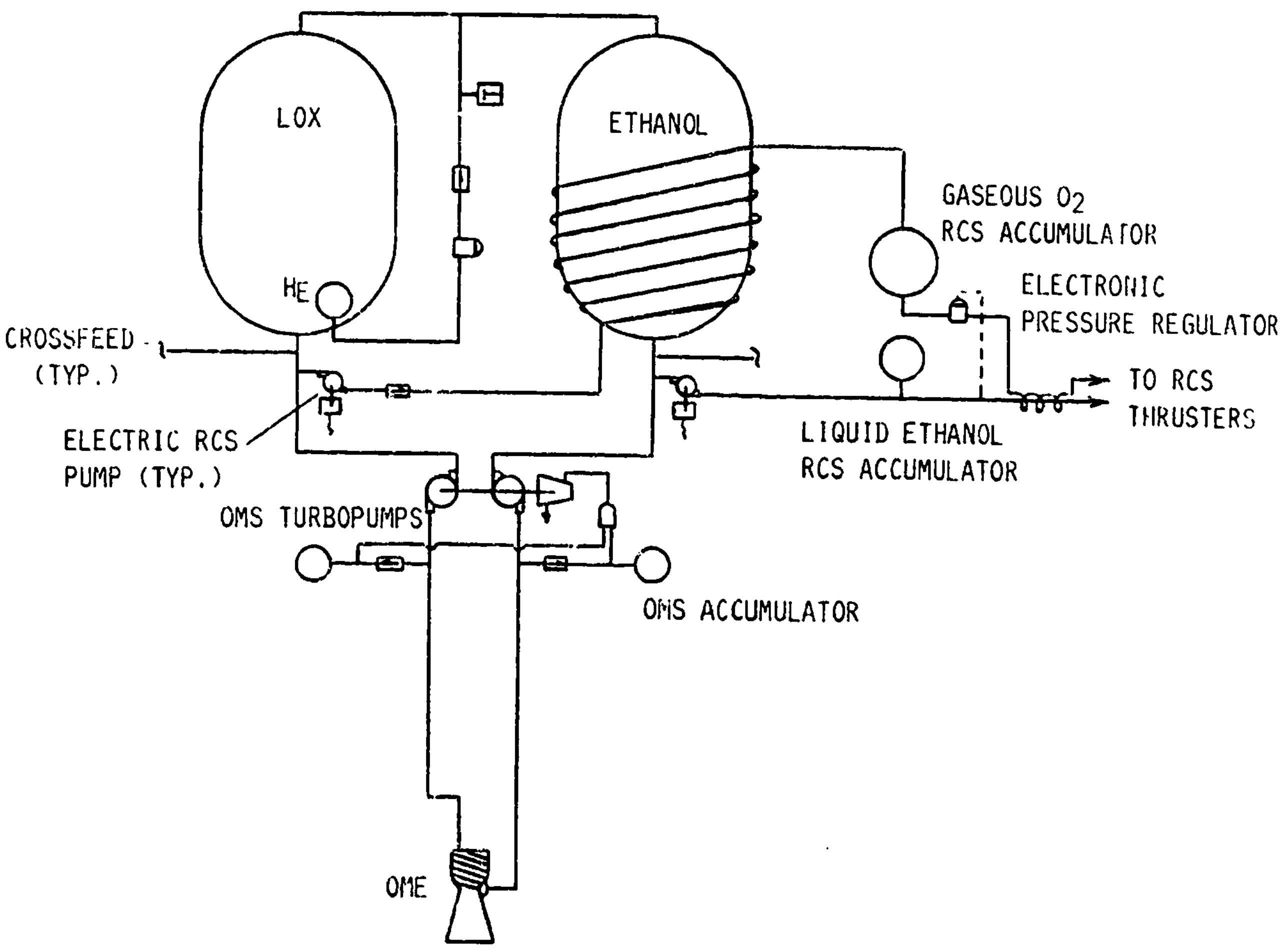


FIGURE 67 LOX/ETHANOL OMS-ARCS USING ELECTRIC MOTOR PUMPS FOR RCS SUPPLY

- 7-DAY OMS-RCS MISSION DUTY CYCLE
- HEAT EXCHANGER O_2 FLOWRATE = 3.3 LB_M/SEC
- HEAT EXCHANGER INLET TEMP. = 162^oR
- HEAT EXCHANGER INLET PRESS. = 500 PSIA

} DURING RE-SUPPLY

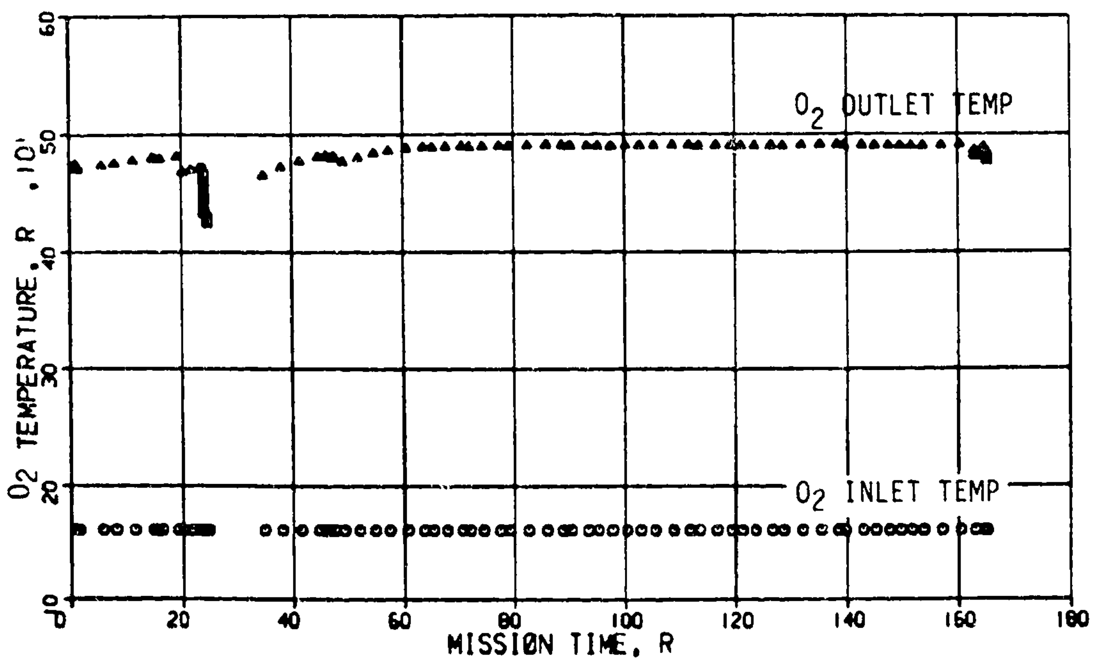
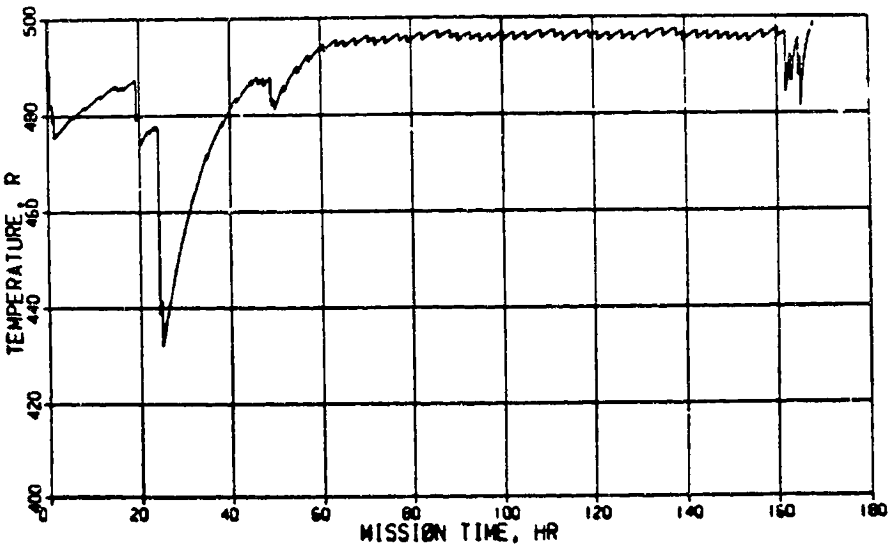


FIGURE 68 O_2 TEMPERATURE HISTORIES FOR PASSIVE ETHANOL TANK HEAT EXCHANGER

ORIGINAL ... OF POOR ...

- 7-DAY OMS-RCS MISSION DUTY CYCLE
- HEAT EXCHANGER O_2 FLOWRATE = 3.3 LB_M/SEC
- HEAT EXCHANGER O_2 INLET TEMP. = 162^oR
- HEAT EXCHANGER O_2 INLET PRESS. = 500 PSIA

} DURING RE-SUPPLY



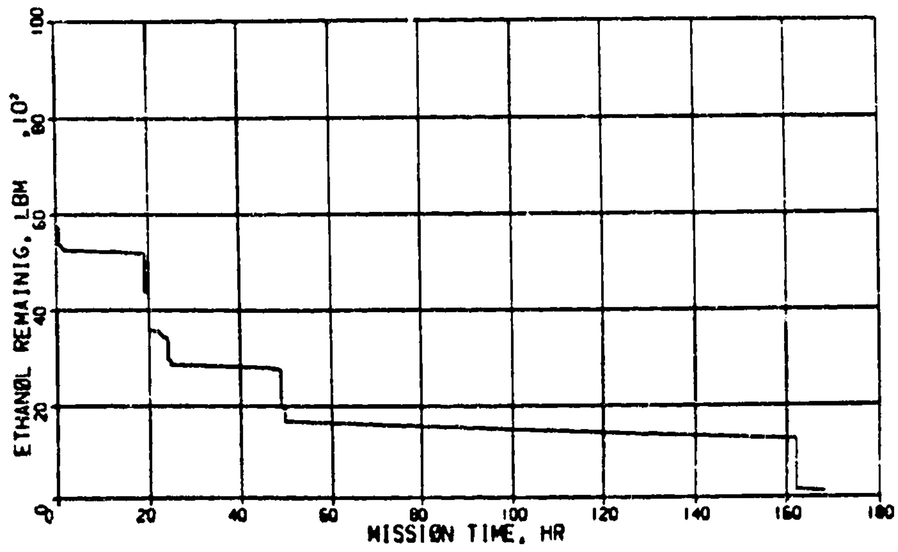
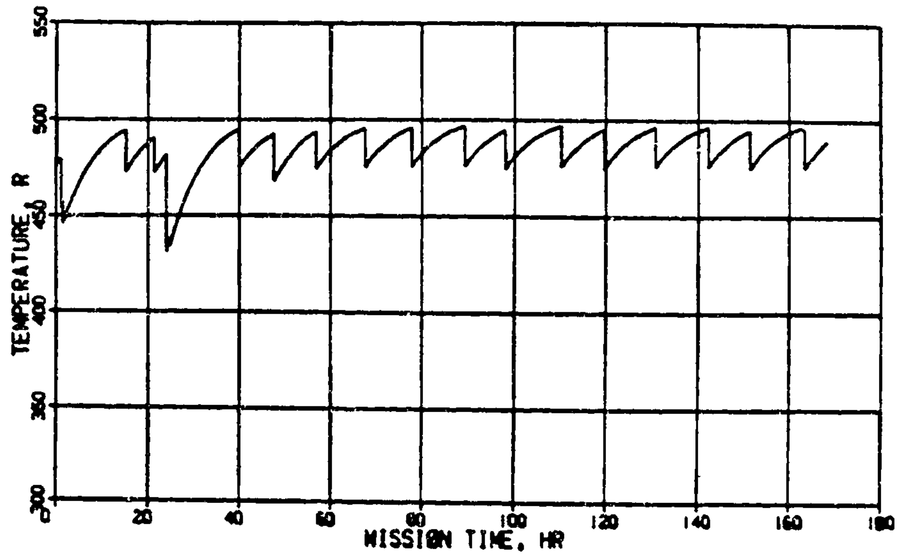


FIGURE 69 ETHANOL TEMPERATURE AND QUANTITY HISTORIES FOR PASSIVE ETHANOL TANK HEAT EXCHANGER

- ELECTRIC PUMPS USED TO RE-SUPPLY RCS ACCUMULATORS
- LIQUID ETHANOL ACCUMULATOR VOLUME=2.47 FT.^{3}
- RE-SUPPLY CONDITIONS
  - FLOWRATE = 2.5 LB_M/SEC
  - TEMPERATURE = 430°R
  - PRESSURE = 500 PSIA
- ACCUMULATOR RE-SUPPLY SWITCHING PRESSURES
  - INITIATION = 350 PSIA
  - CUT-OFF = 500 PSIA



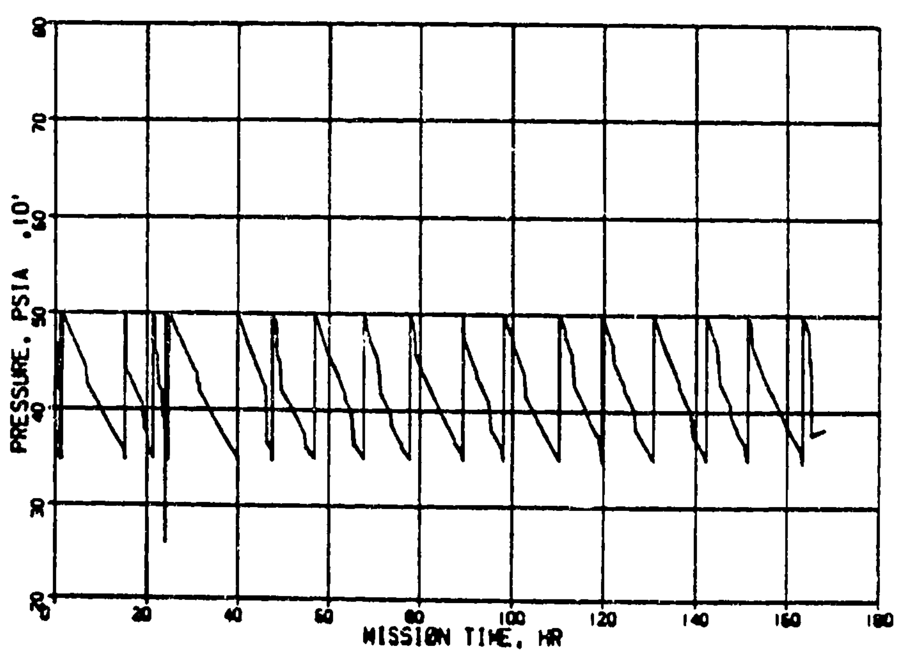
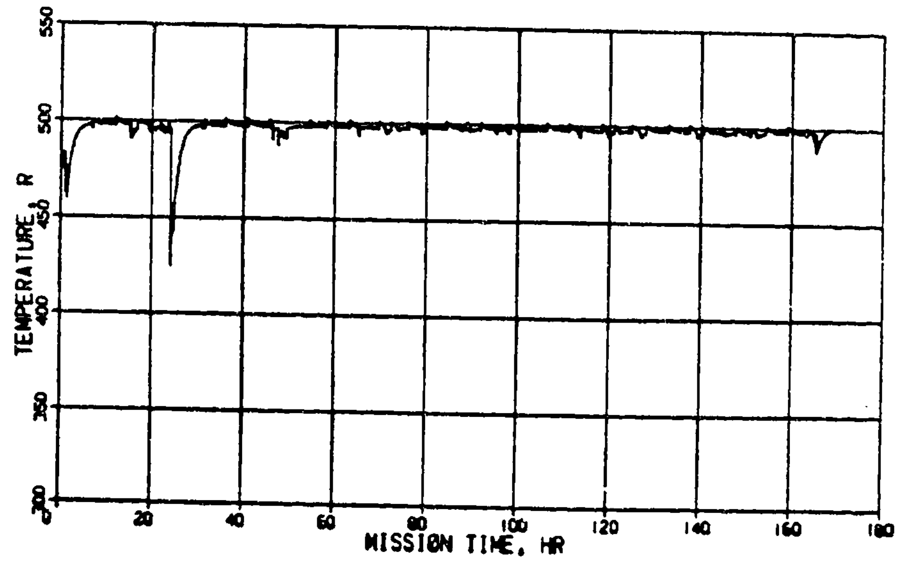


FIGURE 70 RCS ETHANOL ACCUMULATOR MISSION RESPONSE
(ELECTRIC PUMP RESUPPLY)

- ELECTRIC PUMPS USED TO RE-SUPPLY RCS ACCUMULATORS
- GASEOUS O_2 ACCUMULATOR VOLUME = 13.8 FT^3
- RE-SUPPLY CONDITIONS
  - FLOWRATE = 3.3 LBM/SEC
  - TEMPERATURE = 425^oR
  - PRESSURE = 500 PSIA
- ACCUMULATOR RE-SUPPLY SWITCHING PRESSURES
  - INITIATION = 350 PSIA
  - CUT-OFF = 500 PSIA



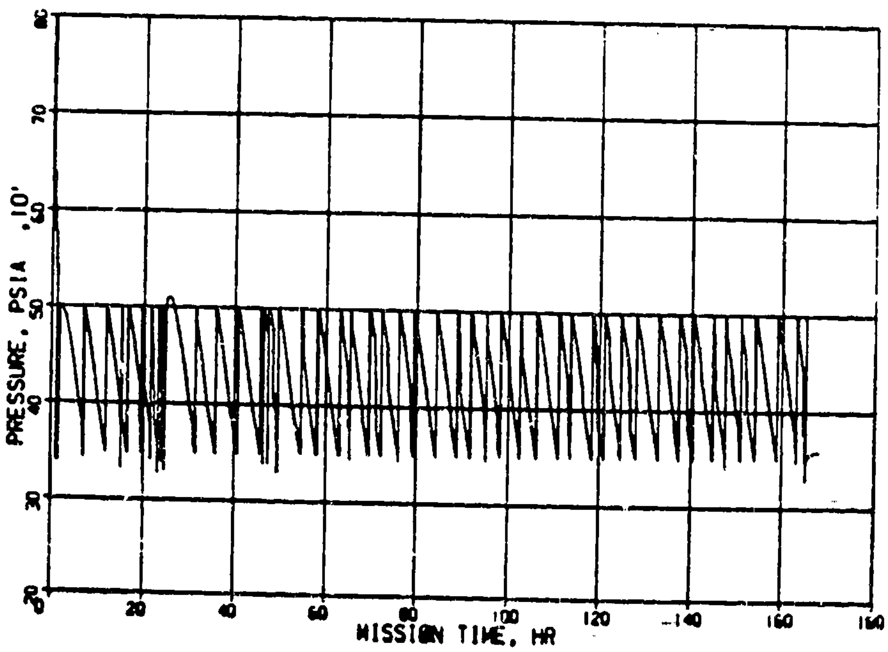


FIGURE 71 RCS GOX ACCUMULATOR MISSION RESPONSE (ELECTRIC PUMP RESUPPLY)

accumulator re-supply and a passive ethanol tank heat exchanger is used for O_2 thermal conditioning. The advantages of this concept are its simplicity (no active gas generator--heat exchangr assembly or by-pass circuit), high RCS specific impulse (no vent losses), and the low number of OMS turbopump cycles. Its disadvantages are the lower RCS flow (thrust) capability due to the passive tank exchanger and weight/power penalties associated with electric pumps. Because of its attractiveness, the electric pump resupply approach with passive ethanol tank O_2 heat exchanger was baselined for the LOX/ethanol OMS-ARCS. An attractive back-up thermal conditioning approach is the dual fuel heat exchanger concept of Figure 41 which eliminates the use of hot, fuel-rich gas generator products to thermally condition the O_2.

7.4 LOX/Ethanol and LOX/Methane OMS-ARCS Sensitivity Analyses

The selected baseline feed systems for LOX/ethanol and LOX/methane are shown in Figures 72 and 73, respectively. Both concepts employ common OMS-ARCS propellant tanks, dedicated electric pumps for RCS supply, and component redundancy for satisfying the fail-operational/fail-safe reliability requirement. Redundant lithium batteries were baselined for powering the electric RCS pumps. In-line entry sumps are provided just downstream of the propellant tanks. These sumps remain full during the mission and provide a dedicated propellant supply for ARCS operation during entry. Overboard abort dump systems are provided just downstream of the entry sumps. The OMS engine system employs a single turbine for driving both the fuel and oxidizer pumps. A gas generator cycle is used for LOX/ethanol, whereas a methane expander cycle is used for LOX/methane. The LOX/ethanol ARCS is a hybrid feed system delivering gaseous O_2 and liquid ethanol to the thrusters through uninsulated accumulators and feedlines. The O_2 thermal conditioning is provided by a passive ethanol tank heat exchanger. The LOX/methane ARCS is a liquid feed system delivering cryogenic propellants to the thrusters through insulated accumulators and feedlines.

Sensitivity analyses were performed for both system concepts to define optimum chamber pressures and accumulator blowdown ratios and to determine the impact of variations in engine specific impulse and propellant tank minimum gage thickness. The results of these analyses are presented in the following paragraphs.

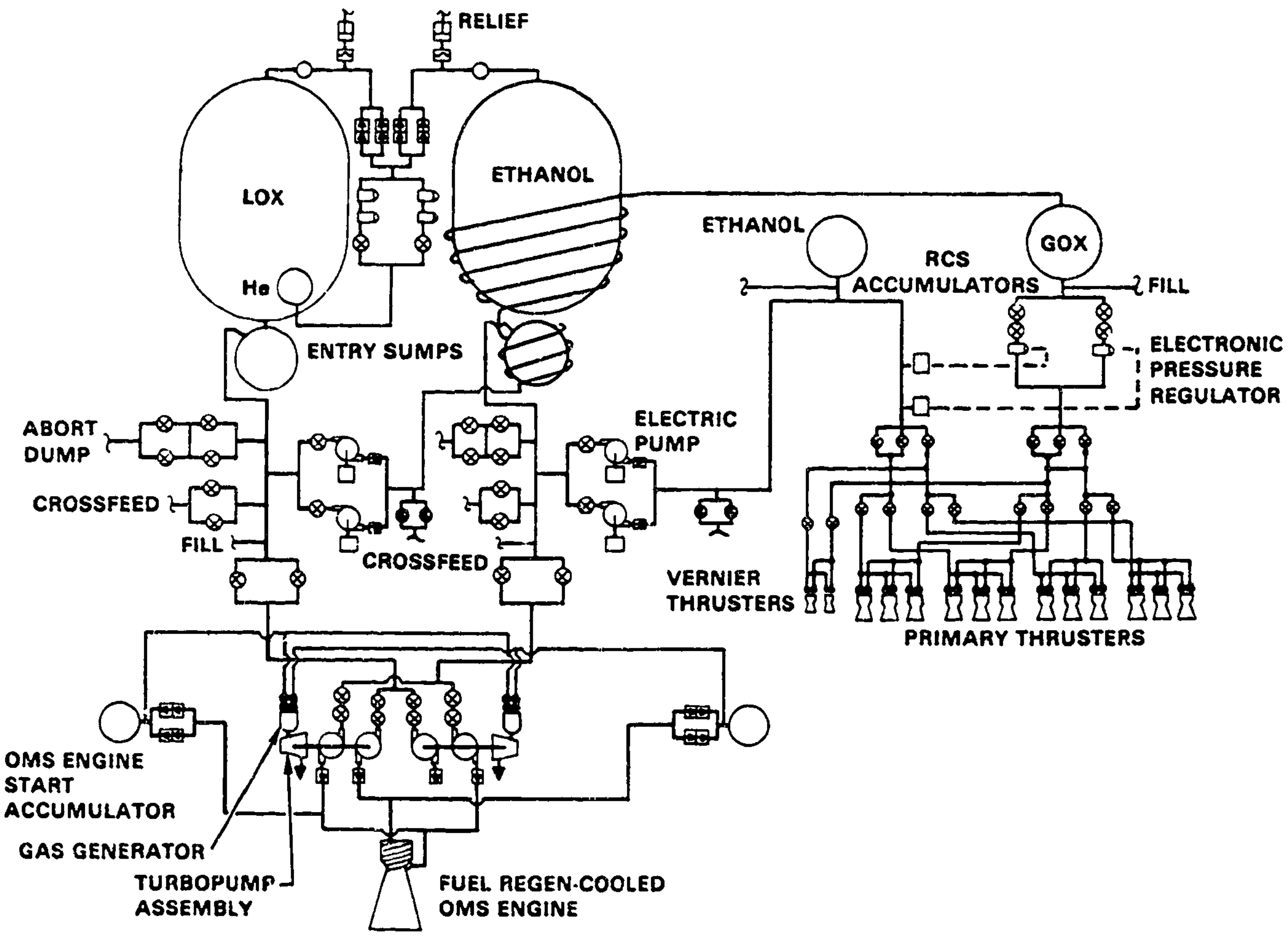


FIGURE 72 BASELINE LOX/ETHANOL OMS-ARCS

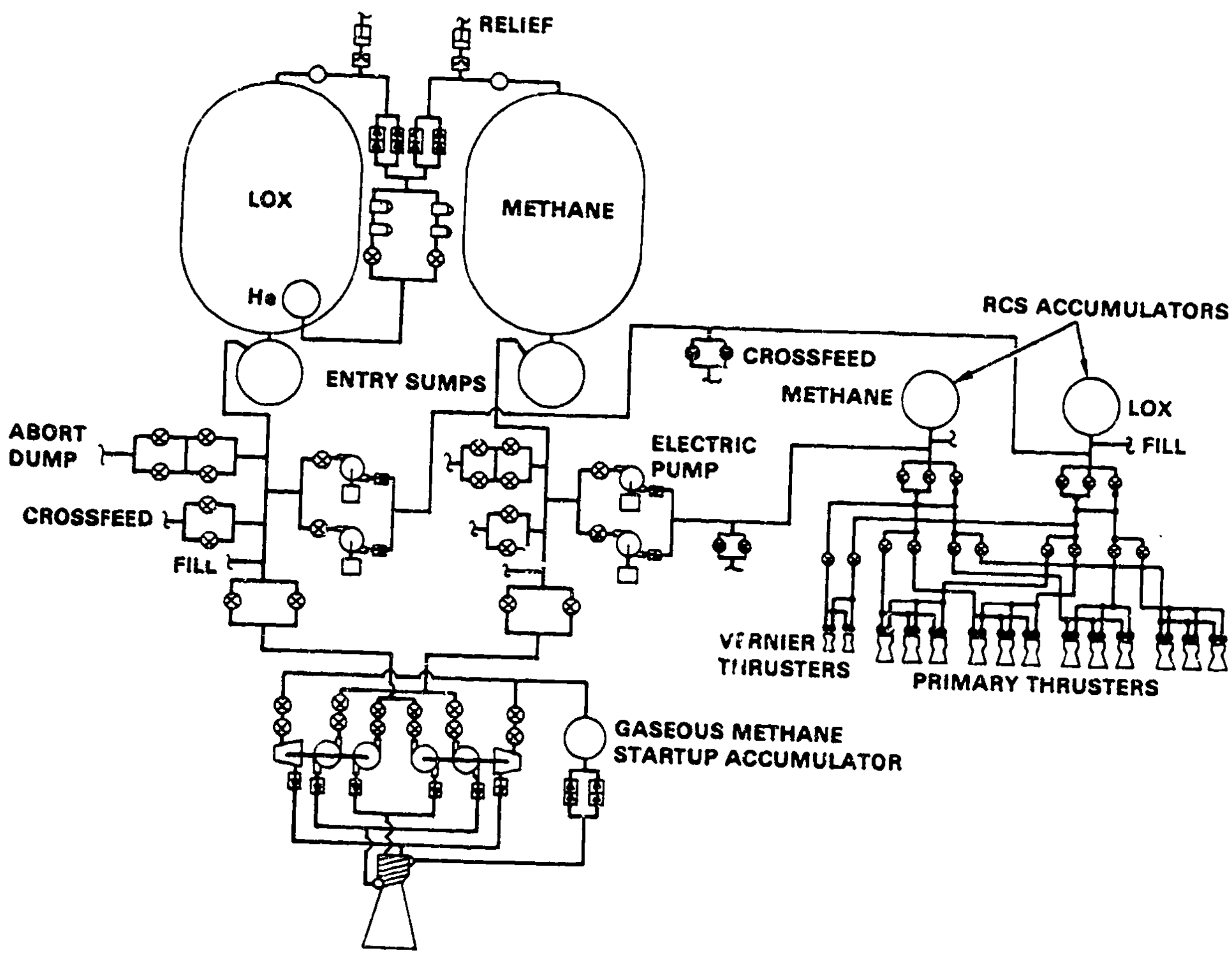


FIGURE 73 BASELINE LOX/METHANE OMS-ARCS

7.4.1 Chamber Pressure Sensitivity Analyses - The weight sensitivity of the LOX/ethanol system to OMS engine chamber pressure is shown in Figure 74. An OMS chamber pressure of 600 psia was selected as near optimum for the LOX/ethanol system. Lower chamber pressures provide lower performance and higher system weights, while higher chamber pressures require supplementary film cooling and more complex chamber designs. OMS chamber pressure sensitivities were not developed for the LOX/methane system since chamber pressures greater than 400 psia were not practical with the expander cycle due to insufficient energy for powering the turbine. As a result, an OMS chamber pressure of 400 psia was selected for the LOX/methane system to provide the highest practical performance and minimize system weight.

The weight sensitivities of the LOX/ethanol and LOX/methane systems to RCS engine chamber pressure are presented in Figure 75. An RCS chamber pressure of 100 psia was selected as near optimum for both systems because it provides low weight and minimizes the size and power requirements for the electric motor pumps.

7.4.2 RCS Accumulator Blowdown Pressure Ratio Sensitivity Analyses - System weight sensitivities to RCS accumulator blowdown ratio are presented in Figures 76 through 78. These data were based on propellant quantities constrained by the current pod envelope and the use of aluminum accumulators. The higher system weights associated with higher blowdown ratios are primarily the result of increased electric motor and battery weights (higher pump discharge pressures). As shown in Figure 76 a blowdown ratio of 2.0 was selected for the gaseous O_2 accumulator in the LOX/ethanol system since it provides minimum weight. A blowdown ratio of 1.67 was selected for the liquid ethanol accumulator (Figure 77) because it provides low weight and a reasonable thruster inlet pressure range. (The gaseous O_2 accumulator outlet pressure is regulated in response to the ethanol accumulator outlet pressure using an electronic pressure regulator--Figure 72.) Similarly, blowdown pressure ratios of 1.67 were selected for the liquid RCS accumulators in the LOX/methane system (Figure 78).

7.4.3 Sensitivity to OMS and RCS Engine I_{SP} - Weight and performance sensitivities to OMS and RCS engine specific impulse are presented in Figures 79 through 86 for the LOX/ethanol and LOX/methane systems. The weight sensitivities were computed by

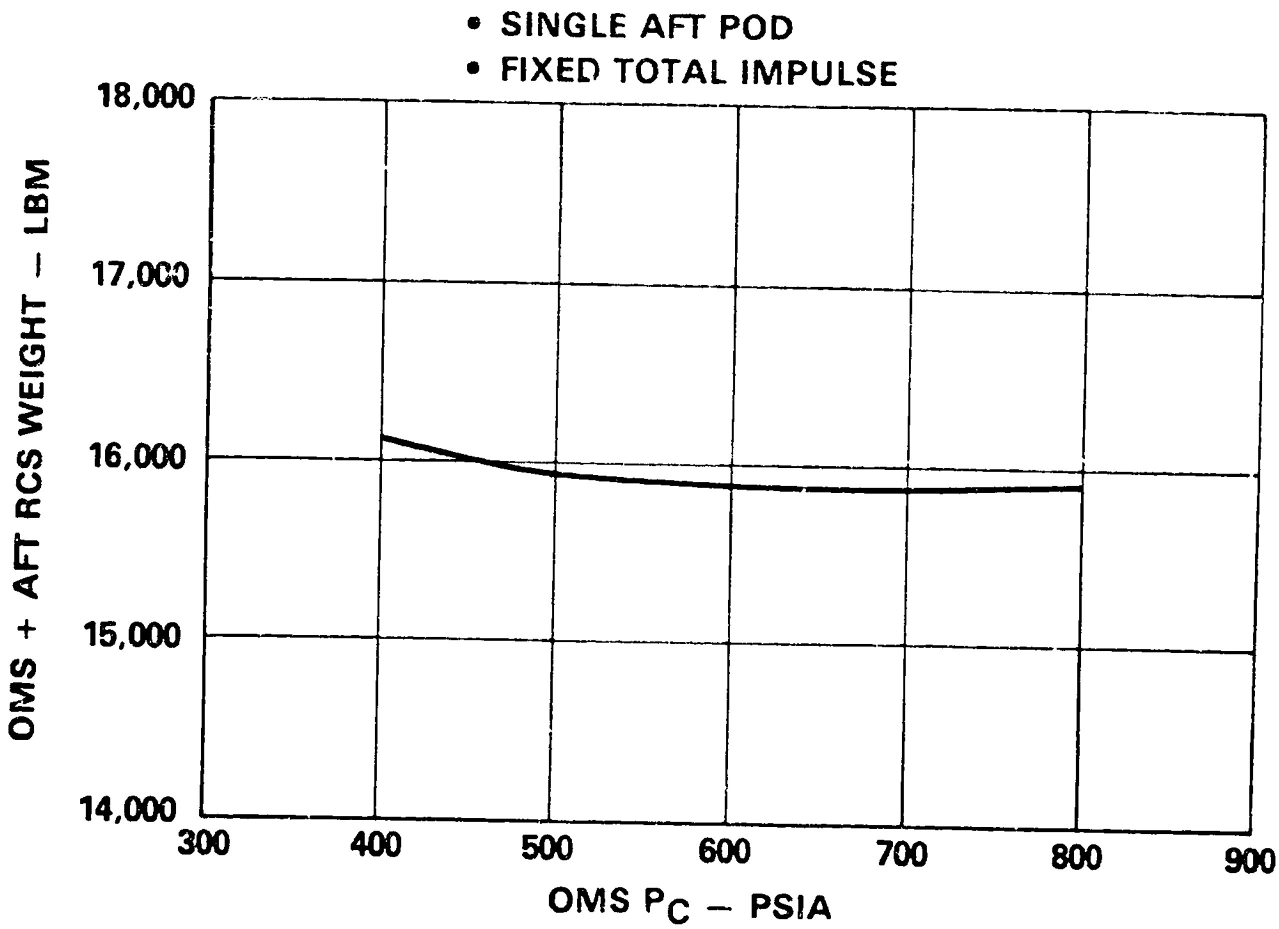
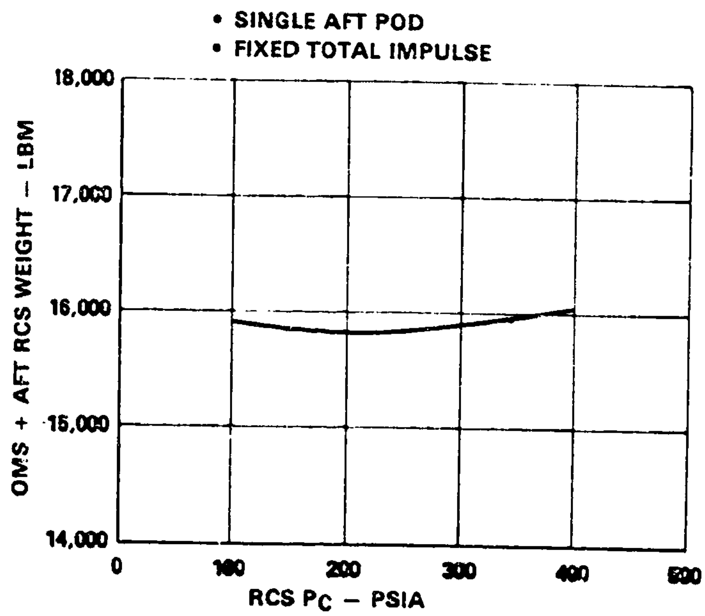


FIGURE 74 SENSITIVITY OF LOX/ETHANOL SYSTEM TO OMS CHAMBER PRESSURE

LOX/ETHANOL



LOX/METHANE

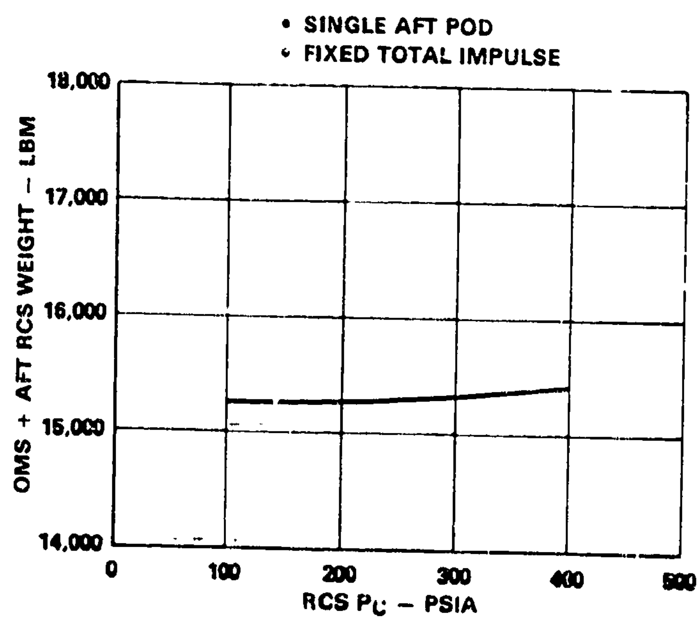


FIGURE 75 SENSITIVITY OF LOX/ETHANOL AND LOX/METHANE SYSTEMS TO RCS CHAMBER PRESSURE

ORIGINAL PAGE IS
OF POOR QUALITY

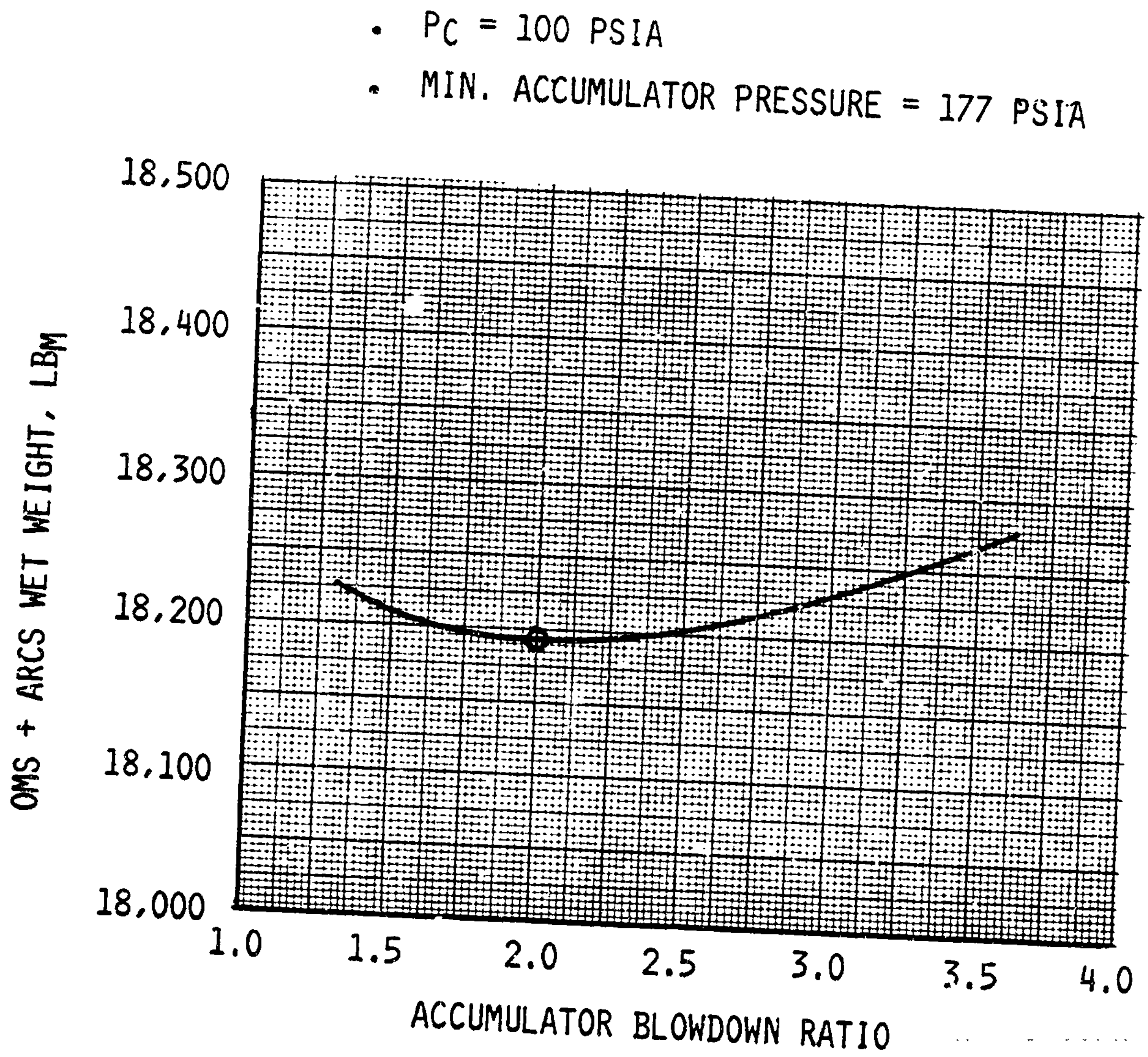


FIGURE 76 RCS GOX ACCUMULATOR BLOWDOWN PRESSURE RATIO SENSITIVITY

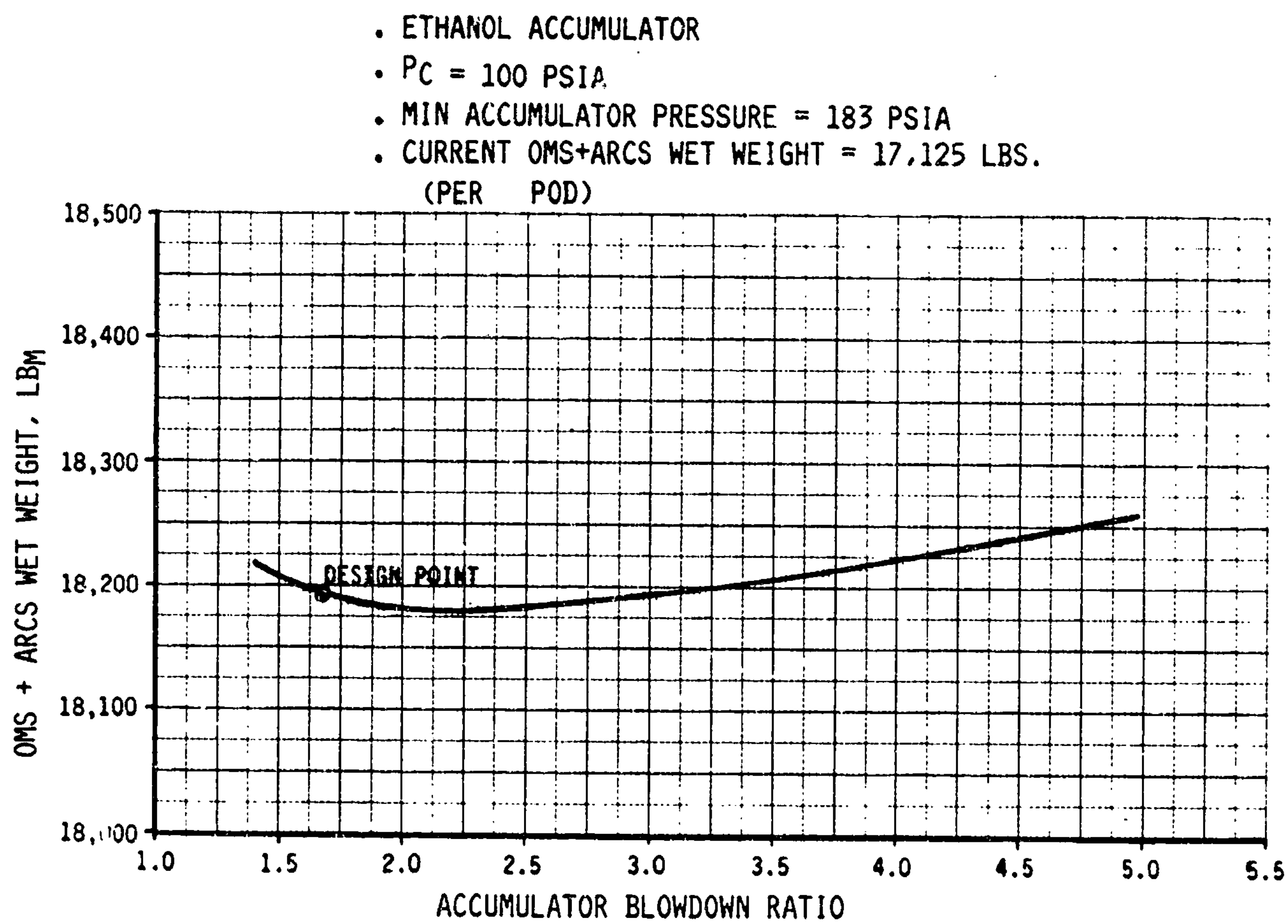


FIGURE 77 RCS LIQUID ETHANOL ACCUMULATOR BLOWDOWN PRESSURE RATIO SENSITIVITY

ORIGINAL PAGE IS
OF POOR QUALITY

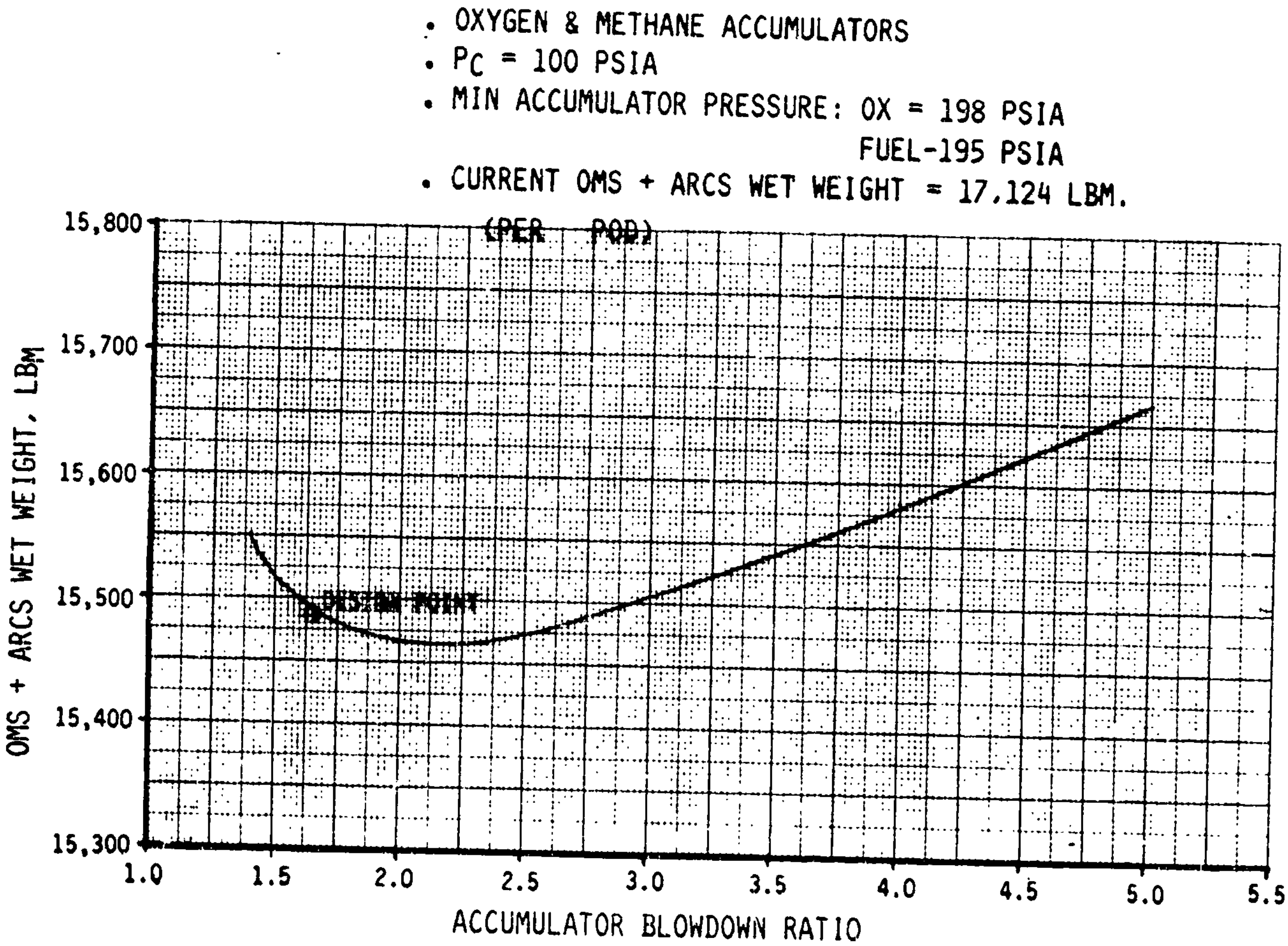


FIGURE 78 RCS LOX/METHANE ACCUMULATOR BLOWDOWN PRESSURE RATIO SENSITIVITY

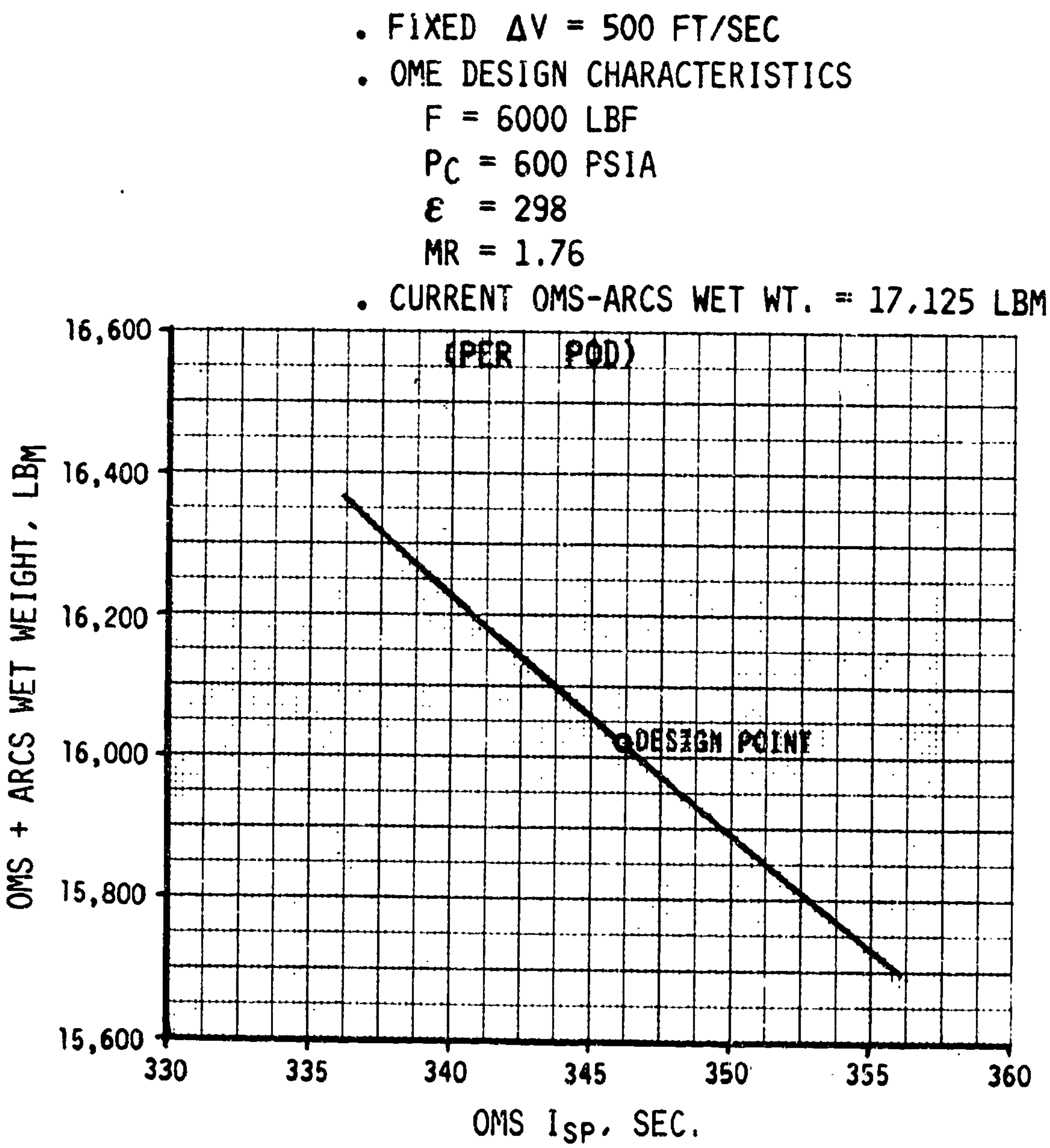


FIGURE 79 **LOX/ETHANOL OMS I_{SP} SENSITIVITY (POD ΔV = 500 FT/SEC)**

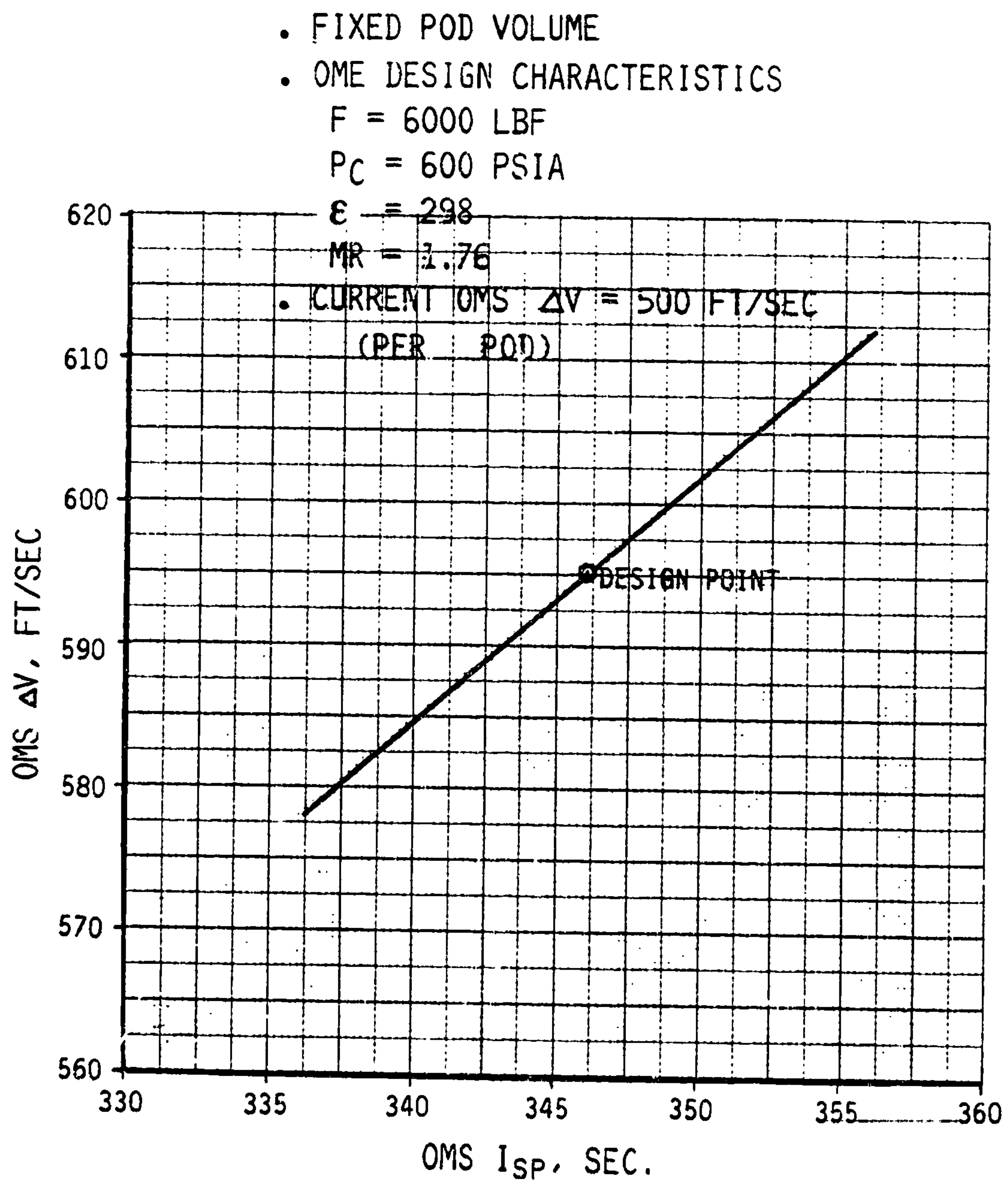


FIGURE 80 LOX/ETHANOL OMS I_{SP} SENSITIVITY (FIXED POD VOLUME)

ORIGINAL PAGE IS
OF POOR QUALITY

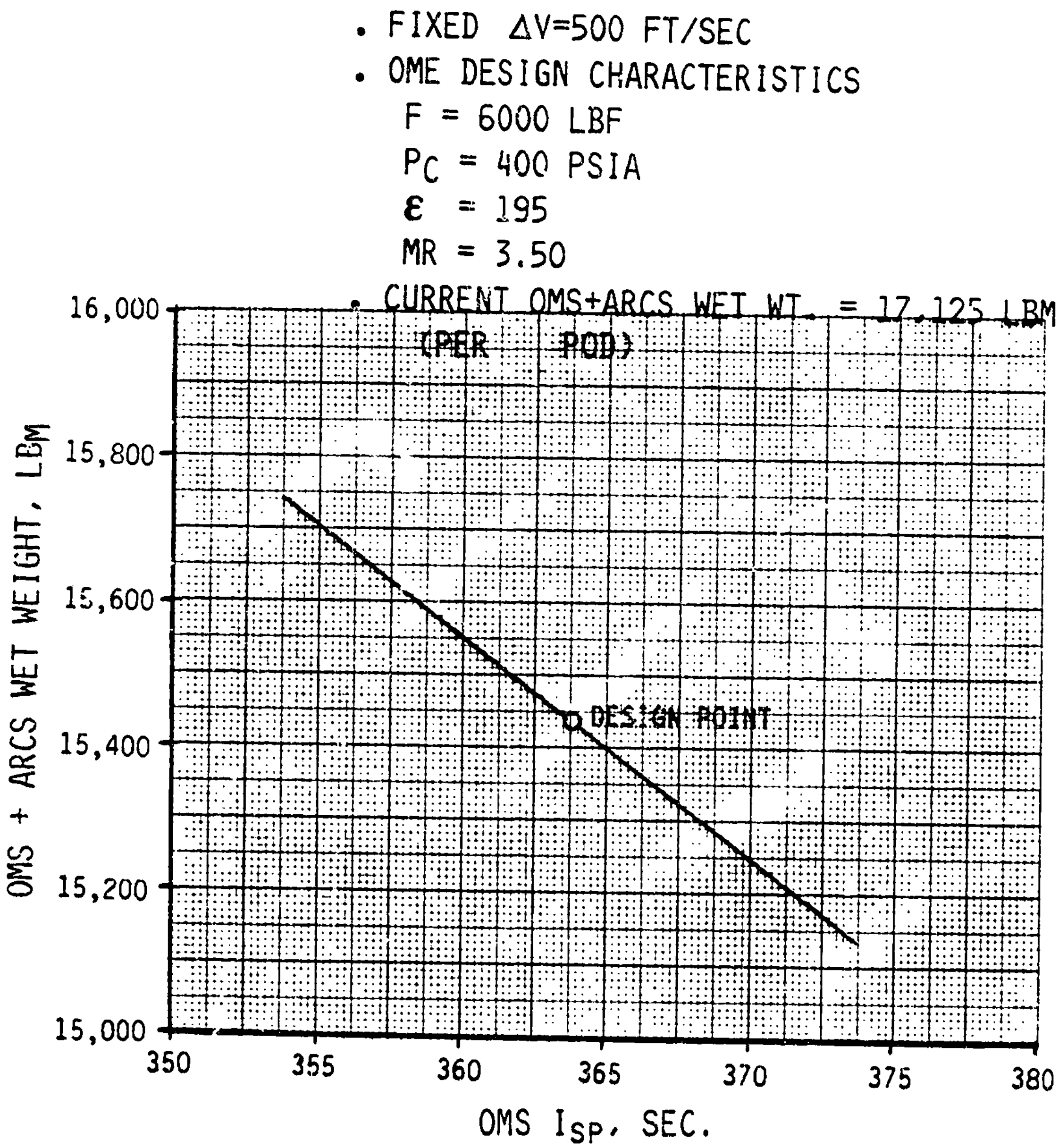


FIGURE 81 LOX/METHANE OMS I_{SP} SENSITIVITY (POD ΔV = 500 FT/SEC)

- FIXED POD VOLUME
- OME DESIGN CHARACTERISTICS
  - F = 6000 LBF
  - P_C = 400 PSIA
  - ε = 195
  - MR = 3.50
- CURRENT OMS ΔV = 500 FT/SEC (PER POD)

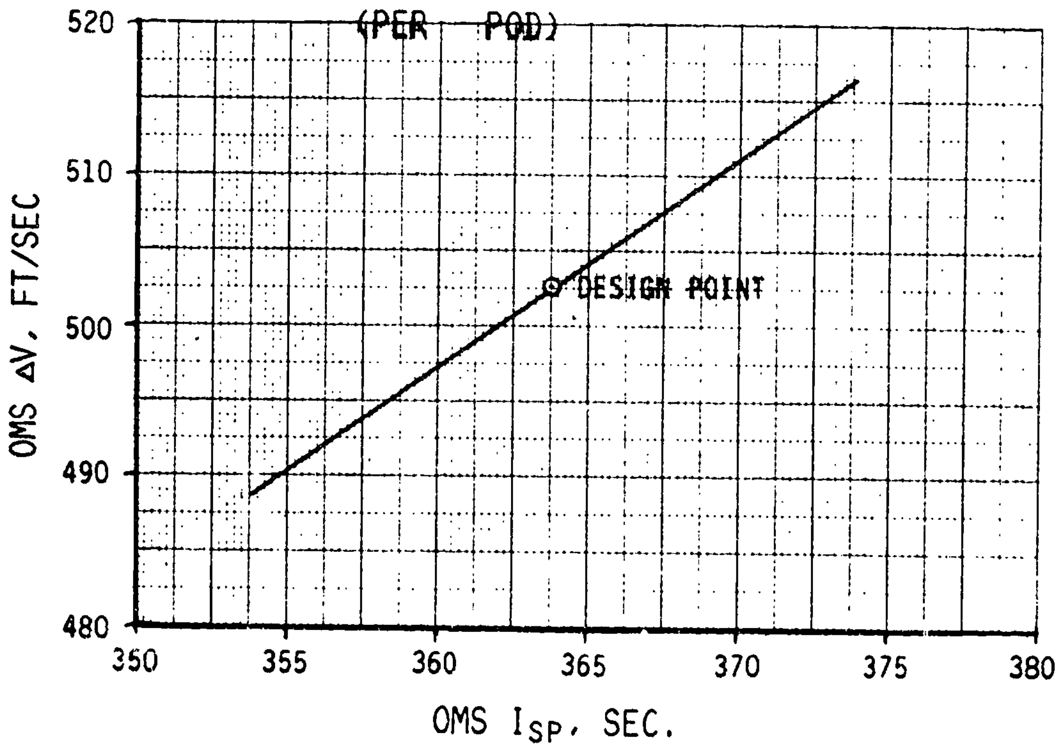


FIGURE 82 LOX/METHANE OMS I_{SP} SENSITIVITY (FIXED POD VOLUME)

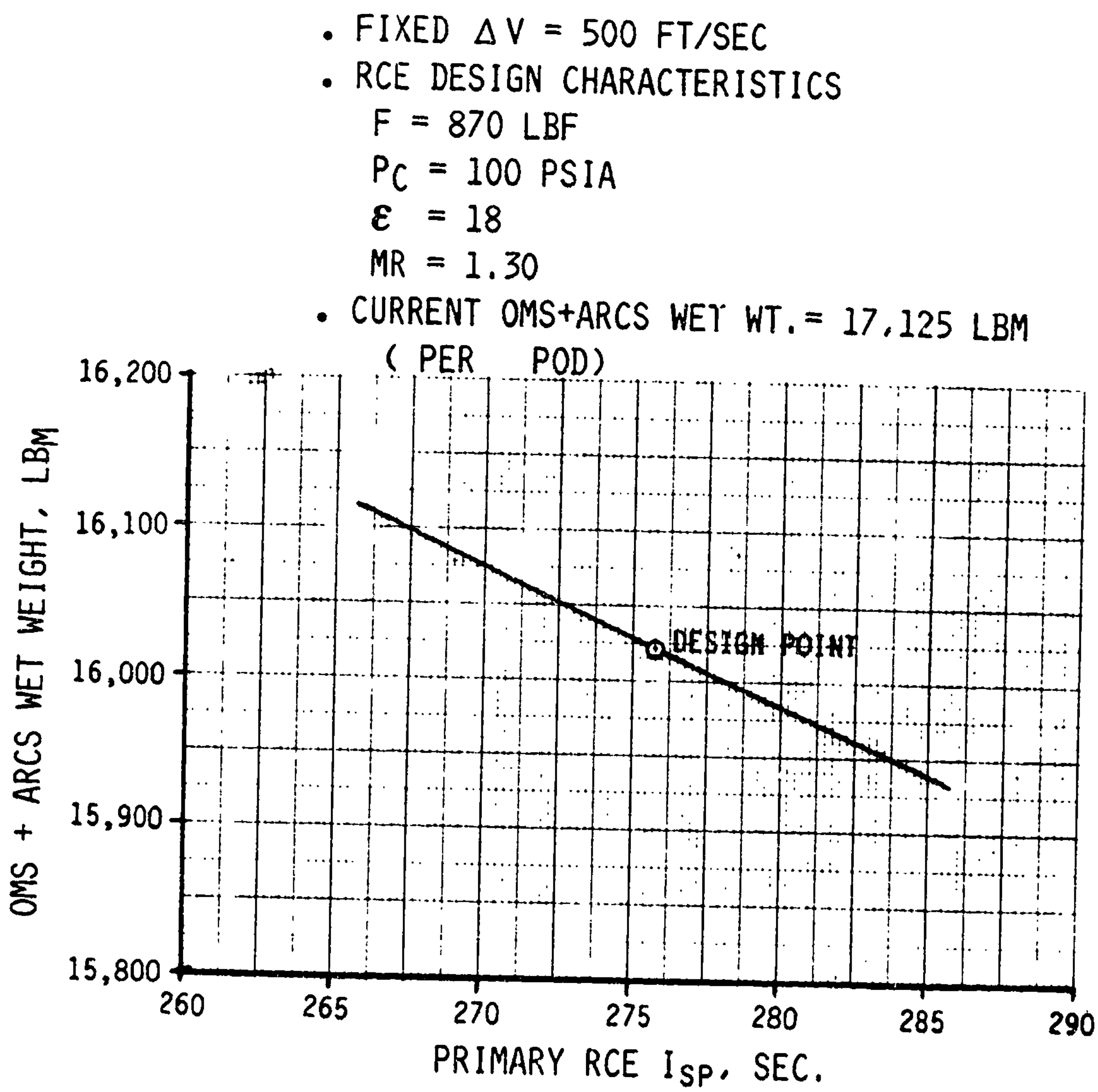


FIGURE 83 LOX/ETHANOL RCS I_{SP} SENSITIVITY (POD ΔV = 500 FT/SEC)

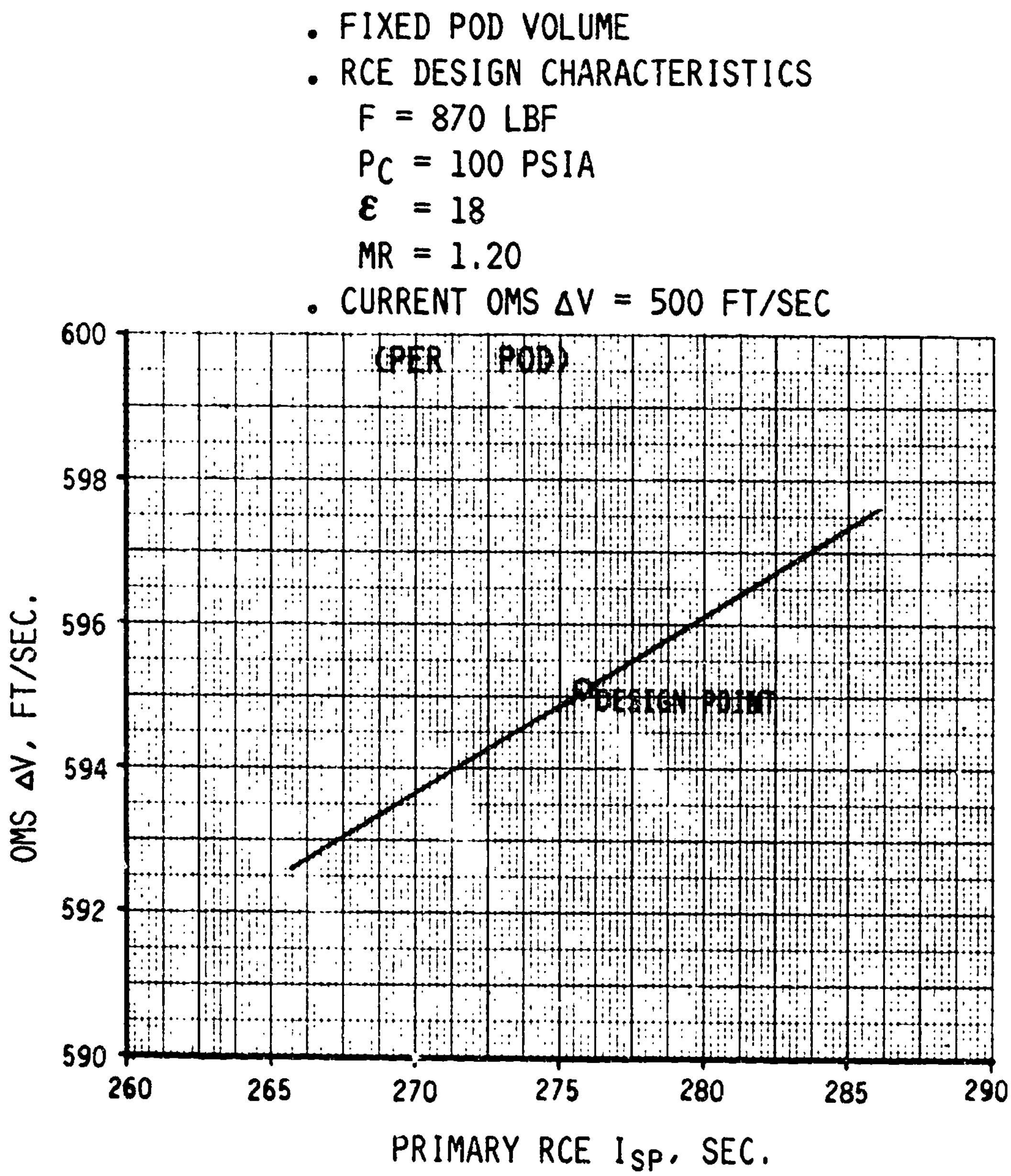


FIGURE 84 LOX/ETHANOL RCS I_{SP} SENSITIVITY (FIXED POD VOLUME)

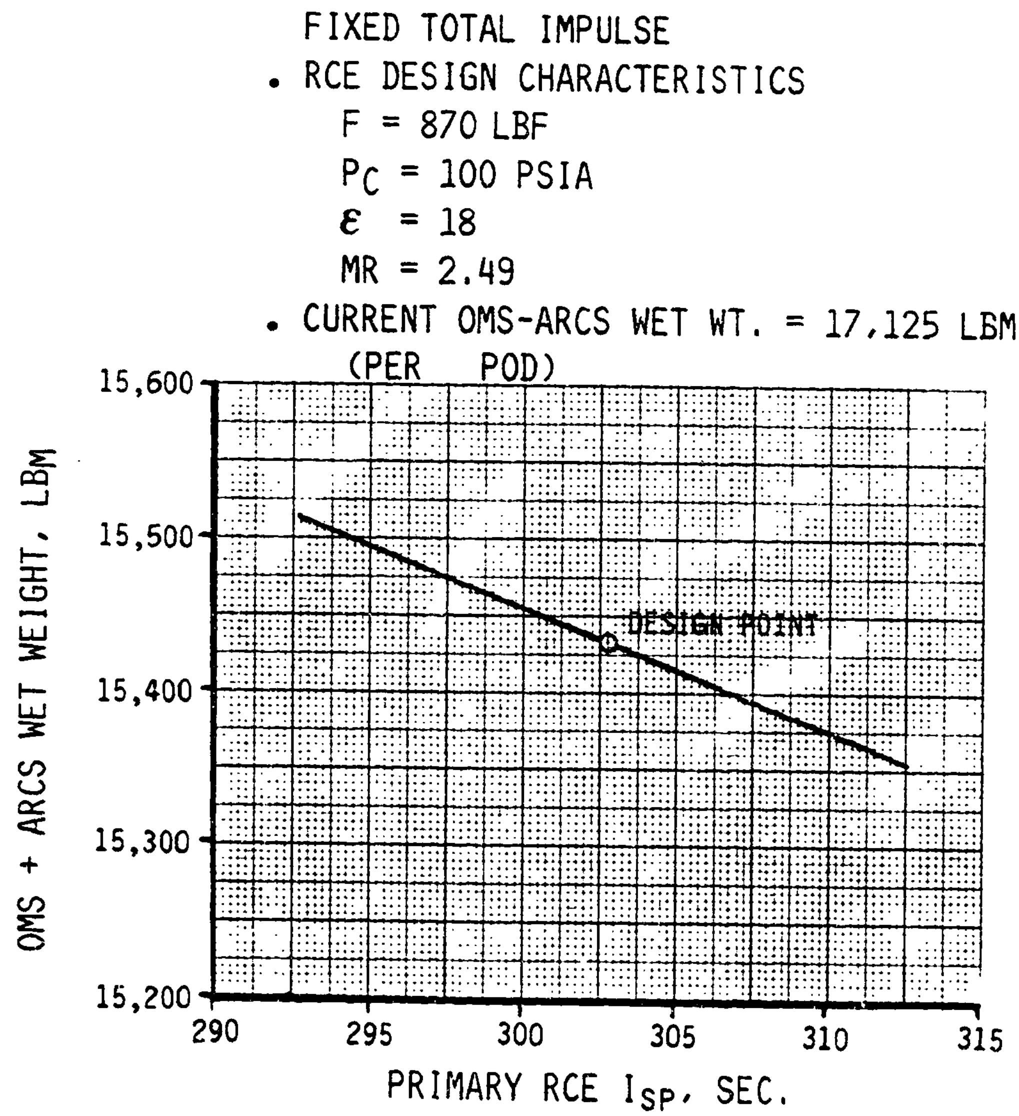


FIGURE 85 LOX/METHANE RCS I_{SP} SENSITIVITY (POD ΔV = 500 FT/SEC)

- FIXED POD VOLUME
- RCE DESIGN CHARACTERISTICS
  F = 870 LBF
  P_C = 100 PSIA
  ε = 18
  MR = 2.49
- CURRENT OMS ΔV = 500 FT/SEC (PER POD)

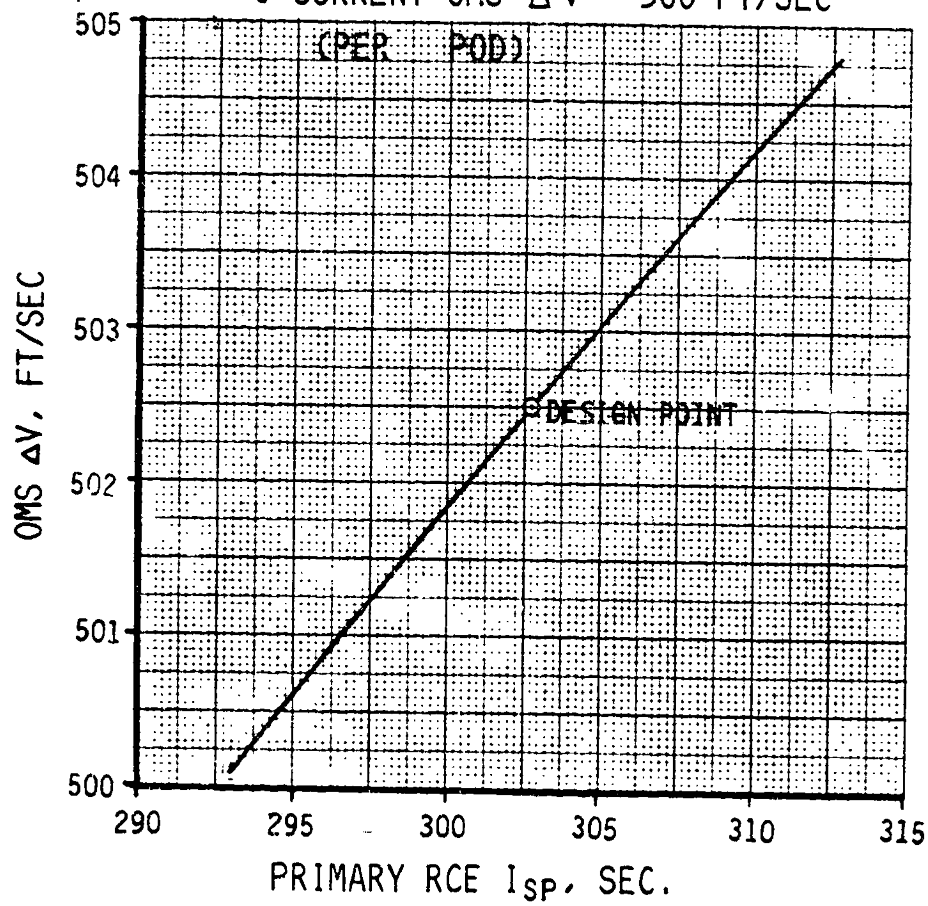


FIGURE 86 LOX/METHANE RCS I_{SP} SENSITIVITY (FIXED POD VOLUME)

limiting the OMS ΔV and aft-RCS total impulse to their current values, while the OMS performance (ΔV) sensitivity was developed by constraining the system volume to the current aft pod envelope.

7.4.4 Sensitivity to Tank Wall Minimum Gage Thickness - System weight sensitivities to propellant tank wall minimum gage thickness are shown in Figures 87 and 88. These data were generated assuming 2219-T87 aluminum tanks for both fuel and oxidizer and sizing the tanks to make maximum use of the current pod envelope. A design minimum gage thickness of 0.06 inches was selected to provide resistance against handling loads.

7.5 Separate versus Common FRCS/Aft Propulsion Tanks

Comparisons of separate versus common propellant tanks for the FRCS and aft propulsion pods are shown in Figure 89. These comparisons were performed for LOX/ethanol with the pod volume constrained to the current dimensions. For the common system, feedlines are routed along the length of the Orbiter to interconnect the forward and aft pods (Figure 4) As shown in Figure 89 the common system provides lower OMS ΔV capability due the loss of available propellant volume in the nose. (For these comparisons, 100% of the current RCS total impulse requirement was provided.) This loss in propellant volume can be compensated for by employing conical shaped tanks in aft pods as discussed below.

7.6 Conventional versus Conical Propellant Tank Shapes

Comparisons of OMS ΔV capability for conventional and conical shaped propellant tanks are presented in Figure 90. The conical shaped tank employs a conical barrel section with an ellipsoidal end dome and hemispherical forward dome. This geometry enables the propellant tank to conform more closely to the pod moldline and provides increased propellant volume within the pod. As shown by Figure 90 an OMS ΔV of 630 ft/sec per pod can be achieved using conical tanks in the integrated forward and aft propulsion system concept. This is well in excess of the 500 ft/sec provided by the current storable system. Furthermore, if conical tanks are employed for a separate aft propulsion system (OMS and ARCS), an OMS ΔV of 690 ft/sec could be achieved. On the basis of this evaluation it was concluded that

ORIGINAL PAGE IS OF POOR QUALITY

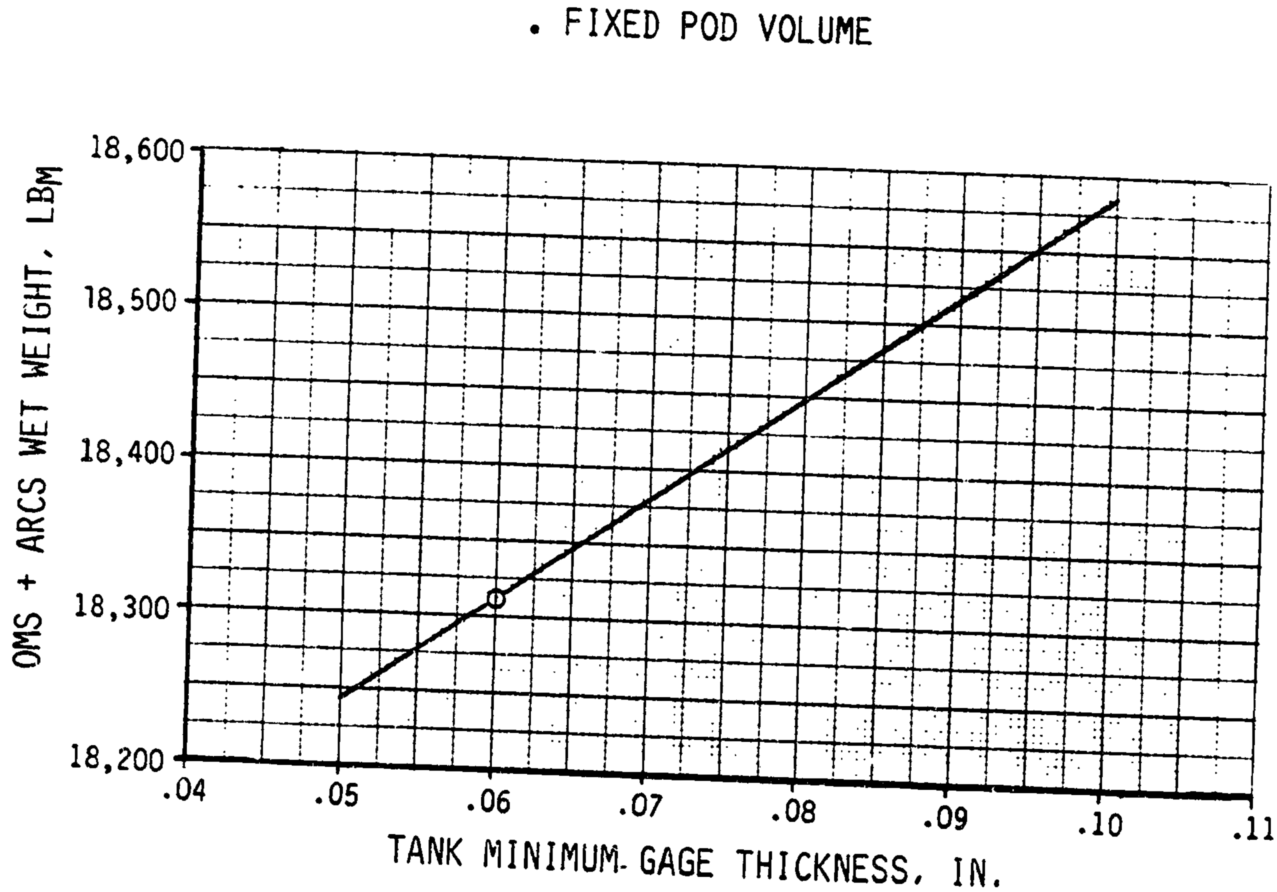


FIGURE 87 LOX/ETHANOL TANK MINIMUM GAGE SENSITIVITY

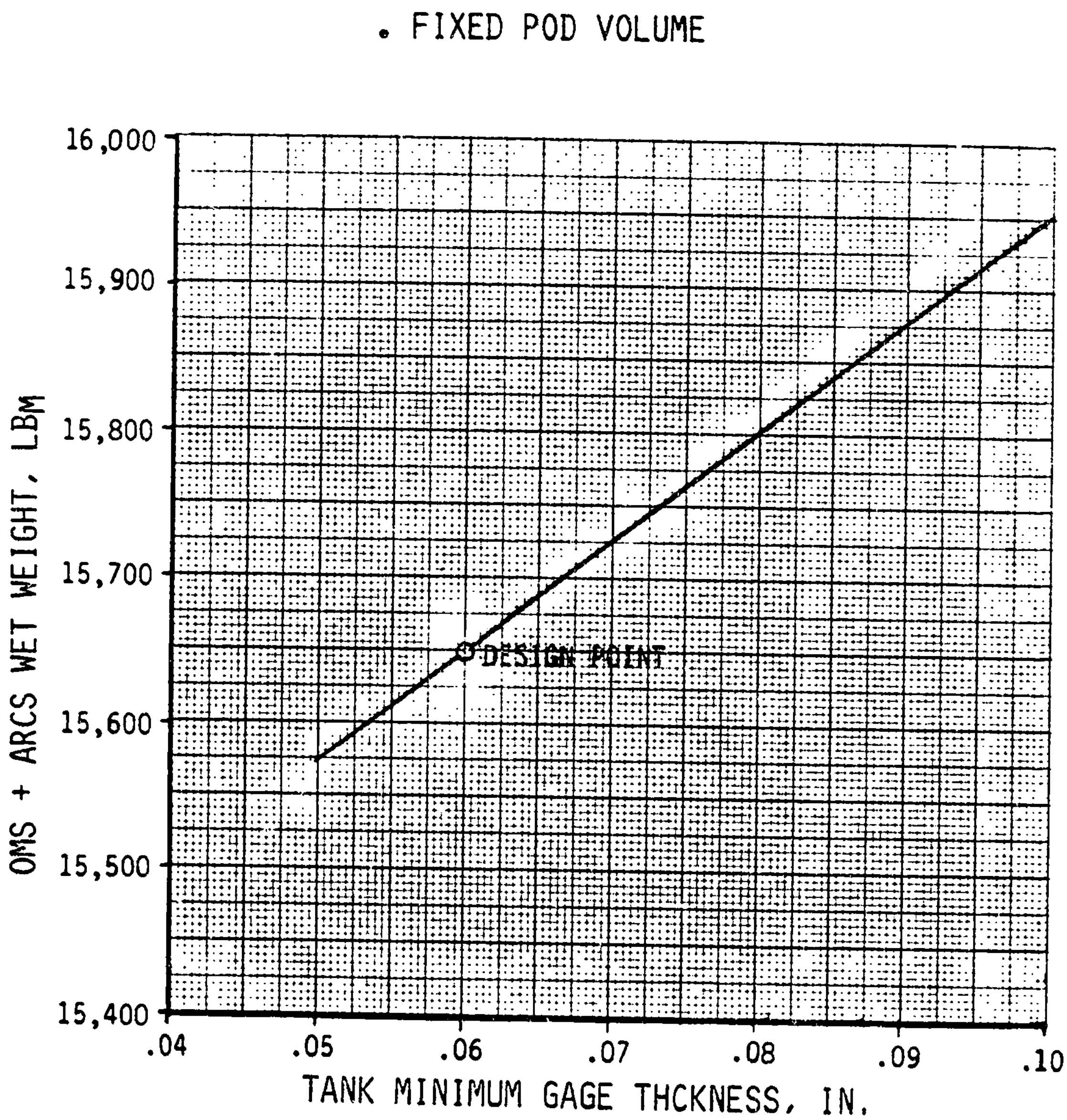


FIGURE 88 LOX/METHANE TANK MINIMUM GAGE SENSITIVITY

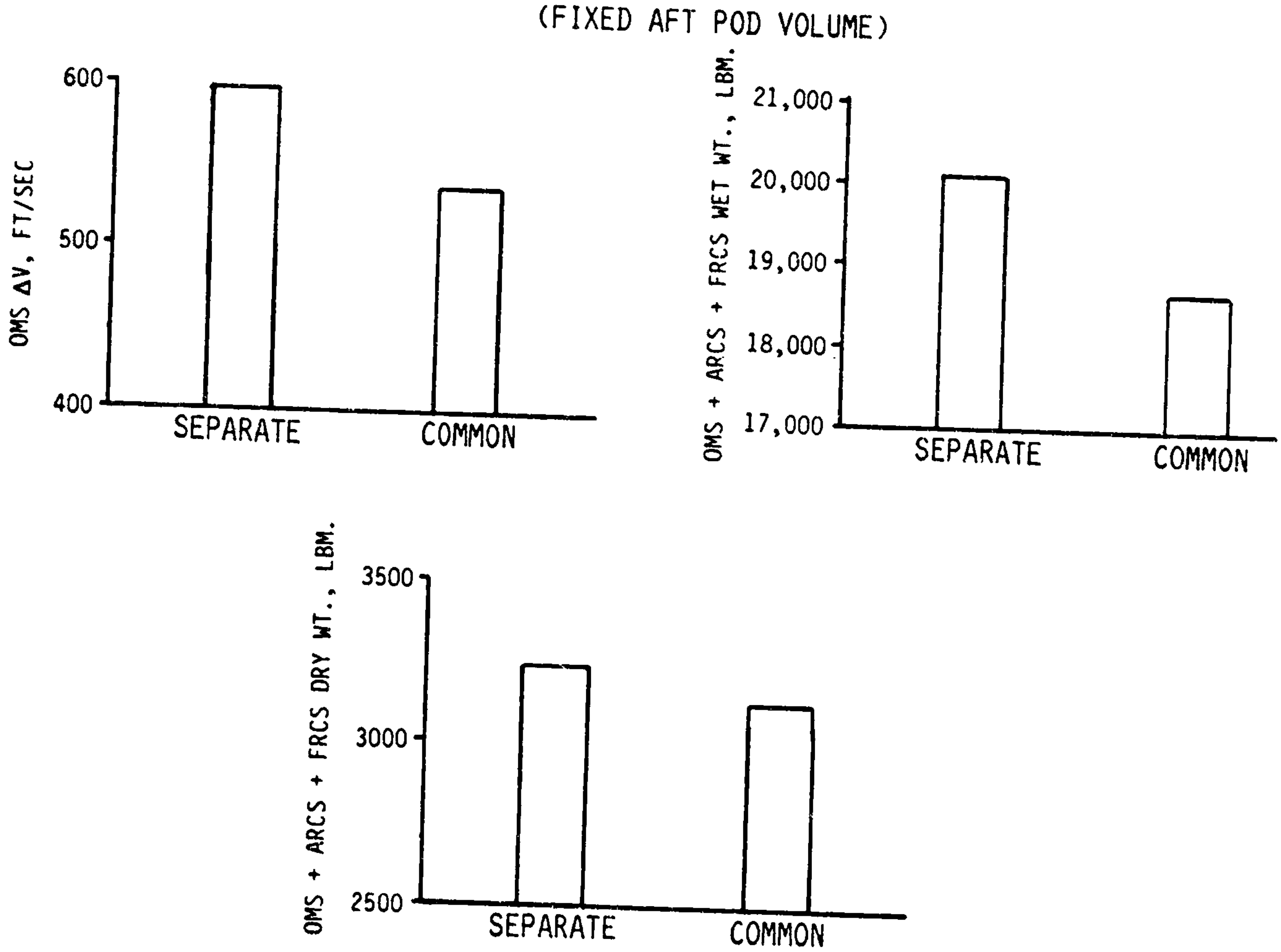


FIGURE 89 SEPARATE VS. COMMON FRCS/AFT PROPULSION TANKS (LOX/ETHANOL)

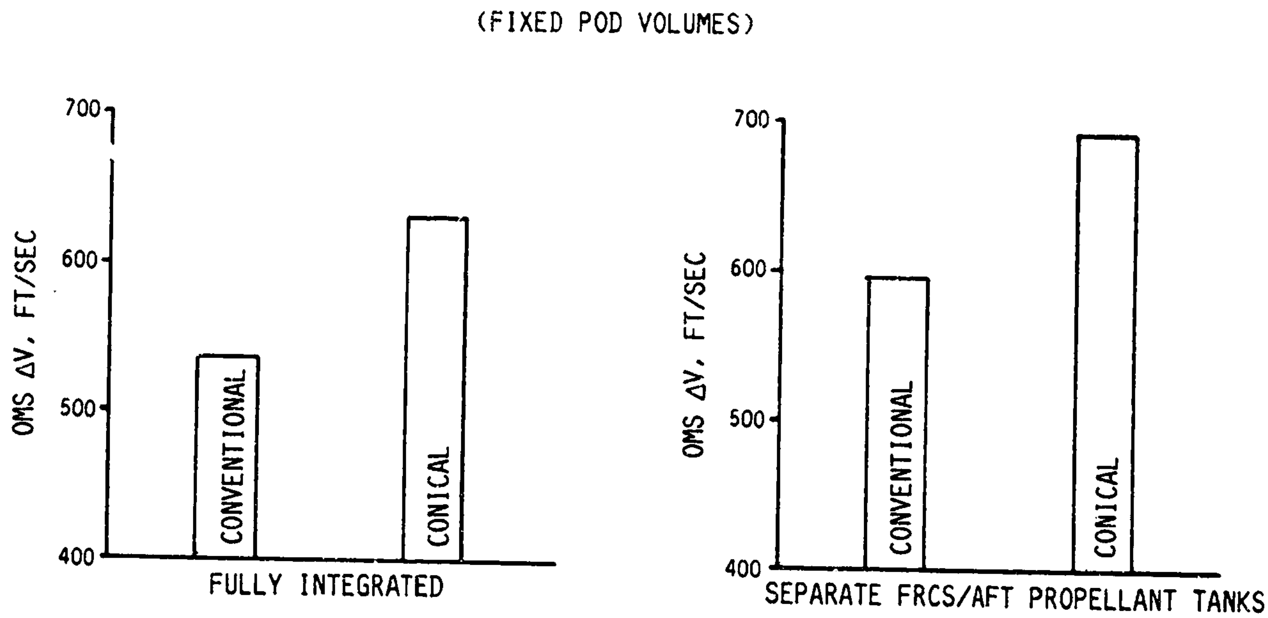


FIGURE 90 CONVENTIONAL VS. CONICAL PROPELLANT TANK SHAPES (LOX/ETHANOL)

a conical propellant tank can provide a substantial increase in ΔV and total impulse capability for a pump fed system.

7.7 Pump versus Pressure Fed FRCS

Comparisons of pressure and electric pump fed FRCS are presented in Figure 91. These comparisons are for a separate LOX/methane FRCS having a thruster chamber pressure of 100 psia, which was found to be near optimum for both the pressure and electric pump fed FRCS. As shown in Figure 91 the pressure fed FRCS has lower wet and dry weights. As such, a pressure fed system (Figure 21) was baselined for a separate FRCS. It is not only lower in weight but has fewer components (no pumps, liquid accumulators, or batteries) and provides the same performance (I_{SP}) as the electric pump fed system.

7.8 Side-By-Side OMS/ARCS Comparisons

The final effort in the Phase II System Evaluation task was to perform a side-by-side comparison of the LOX/ethanol and LOX/methane OMS-ARCS with a similarly configured LOX/H_2 system, as well as the current storable OMS-ARCS. The resulting weight and performance comparisons are presented in Figure 92. The LOX/H_2 system was configured to the same groundrules as the LOX/methane OMS-ARCS (Figure 73) and employed a cryogenic liquid feed system for the ARCS. However, because of its low ΔV capability (150 ft/sec) it is not a practical contender for a "second generation" OMS-RCS. The LOX/ethanol is the best system concept because of its high ΔV and total impulse capability. Ethanol is a storable propellant which does not require a tank insulation system. Insulation is also avoided in the RCS feed system (accumulators and lines) by thermally conditioning the RCS O_2 supply to a superheated vapor (Figure 72).

(FIXED TOTAL IMPULSE)

CHAMBER PRESSURE = 100 PSIA

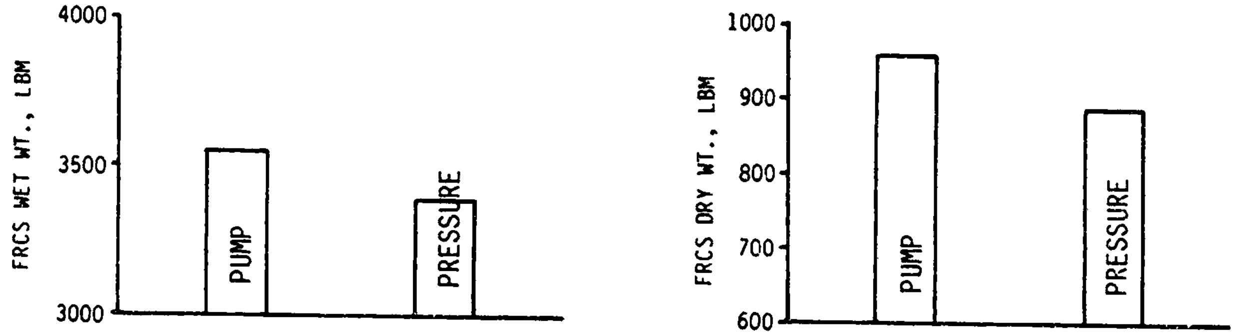


FIGURE 91 PUMP VS. PRESSURE FED FRCS (LOX/METHANE)

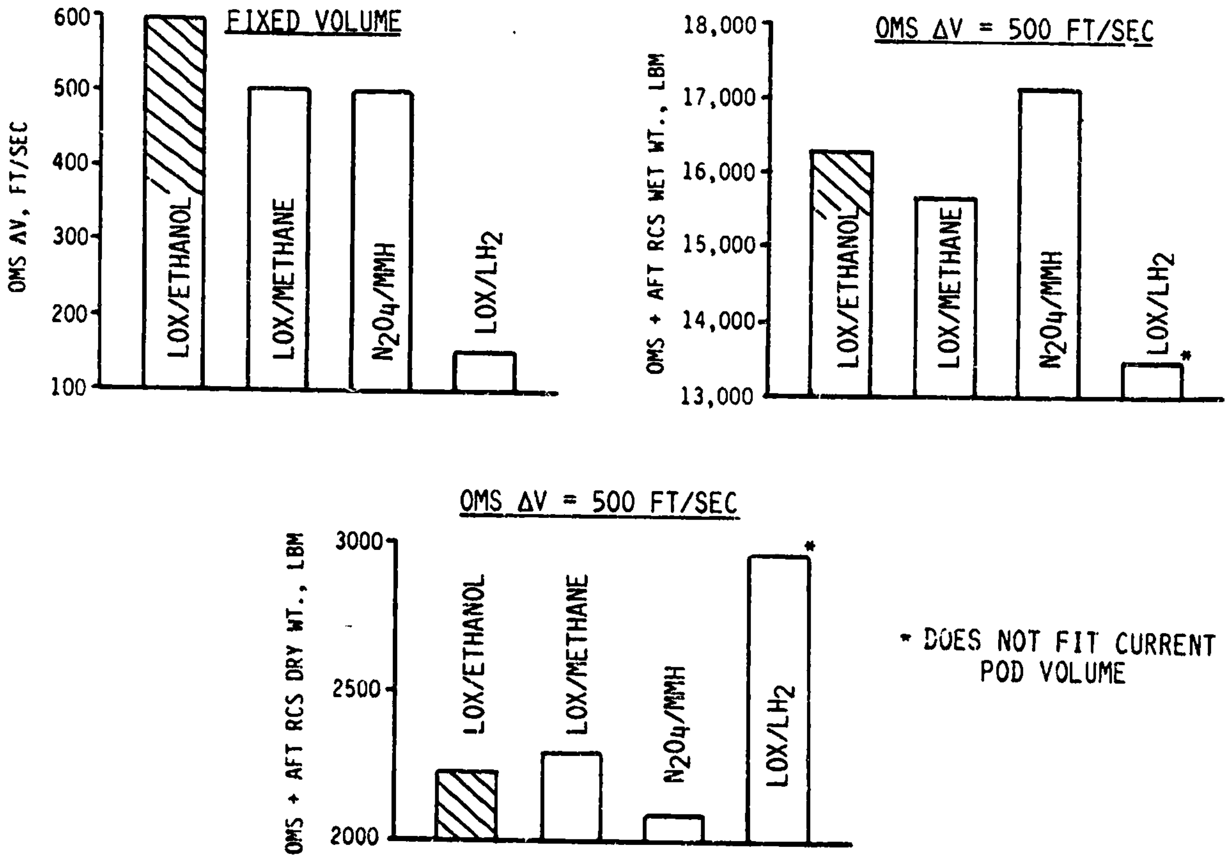


FIGURE 92 COMPARISON OF LOX/HC, LOX/H_2, AND N_2O_4/MMH OMS-ARCS

8.0 CONCLUSIONS AND RECOMMENDATIONS

The overall study conclusions are summarized in Table XVI. An integrated LOX/ethanol OMS-ARCS (Figure 72) was selected as the best system approach because of its superiority in terms of OMS ΔV and RCS total impulse capability. The LOX/ethanol system allows use of a simple, non-insulated RCS feed system, and recent tests--Reference (3)--have shown that the LOX/ethanol propellant combination is clean burning (non-coking). Because the propellants are low in cost, non-toxic, and non-corrosive, the operational costs for a LOX/ethanol OMS-RCS would be substantially less than the current N_2O_4/MMH system.

A pump fed OMS was selected over a pressure fed system because of overriding weight and performance advantages. For two pods the pump fed OMS is approximately 3000 lbs lighter than a pressure fed system. In addition, a single turbine drive for both the fuel and oxidizer pumps was recommended to reduce feed system weight and complexity.

Common propellant tanks were recommended over separate tanks for the OMS and ARCS propellants because they provide improved propellant packaging (higher ΔV and total impulse capability) and greater mission flexibility. Furthermore, to provide maximum performance and avoid using the OMS turbopumps for ARCS propellant feed, small, dedicated electric RCS pumps were recommended for resupplying the ARCS accumulators.

A hybrid, ambient temperature RCS propellant feed system was recommended to eliminate the need for insulating the RCS accumulators and feedlines. The RCS oxygen supply is thermally conditioned to a superheated vapor using a passive ethanol tank heat exchanger which avoids the complexity and vent penalties associated with active hot gas generator--heat exchanger assemblies.

The new technology requirements associated with this feed system approach are identified in Table XVII, while recommendations for future feed system studies are summarized in Table XVIII.

TABLE XVI

OVERALL STUDY CONCLUSIONS

Best Fuel--Ethanol

- highest ΔV and total impulse capability (OMS $\Delta V \sim 600$ ft/sec per pod)
- non-coking
- earth storable (vapor pressure slightly higher than MMH)
- good technology base for engine development

Most Attractive System Concept

- pump fed OMS with single turbine driving both fuel and oxidizer pumps
  - overriding weight and prformance advantages (pump fed OMS provides 3000 lb weight advantage over pressure fed OMS--2 pods)
  - single turbine reduces system complexity
- common OMS/AFT RCS propellant tanks (common tanks provide 18 ft^3 more propellant volume than separate tanks)
  - high ΔV and total impulse capability
  - greater mission flexibility
- electric pumps for AFT-RCS feed
  - turbopumps cycled only during OMS burns (cycle life reduced by factor of 6)
  - high RCS performance (electric pump RCS I_{SP} is 21 seconds higher than turbopump RCS I_{SP})
- hybrid ambient temperature RCS propelant feed (GOX/liquid ethanol) (no accumulator or feedline insulation required)
- passive ethanol tank heat exchanger for O_2 thermal conditioning
  - low feed system complexity (no gas generators for thermal conditioning)
  - no I_{SP} penalty (gas generator vent loss)

TABLE XVII
NEW TECHNOLOGY REQUIREMENTS

Feed System

- thermal management system for cryogenic LOX tank
  - insulation
  - thermodynamic vent
  - auxiliary cooling
- passive ethanol tank O_2 heat exchanger
- surface tension screen propellant acquisition for common OMS-AFT RCS tank (cryogenic)
- improved propellant gaging approach
- electronic pressure regulator for controlling RCS GOX accumulator outlet pressure
- lithium batteries or alternate power source for electric RCS pumps

Engines

- LOX/ethanol OME
  - small high speed turbopumps
  - improved heat transfer characterizations, burn-out data, and performance correlations
- LOX/ethanol RCE
  - improved heat transfer characterizations
  - pulse mode performance and cycle life capability

TABLE XVIII

RECOMMENDATIONS FOR FURTHER FEED SYSTEM EFFORT

- definition of LOX tank thermal management system (considering ground hold, transient launch, and on-orbit heating effects)
  - tank insulation materials and thicknesses
  - thermodynamic vent system sizing
  - auxiliary cooling capability (pumps, tank supports, etc.)
- detailed evaluation of integrated forward RCS/AFT propulsion system (impact or orbiter interfaces)
- evaluation of system performance over broad mission spectrum
  - OMS-RCS mission duty cycle extremes
  - limitations of ethanol tank O_2 heat exchanger
  - realistic RCS thruster pressure/temperature boxes to begin thruster development
- definition of system controls and failure detection/isolation requirements
- Definition of component ROM costs and schedules
  - propellant tanks
  - pressure regulators
  - valves
  - accumulators
  - OME
  - RCE

REFERENCES

1. G.F. Orton, T.D. Mark, and D.D. Weber, "LOX Hydrocarbon Auxiliary Propulsion System Study Phase I Report, Volume I--Technical and Volume II--Appendices," McDonnell Douglas Corporation Report No. MDC E2479, February 1982.

2. G.F. Orton, T.D. Mark, and D.D. Weber, "LOX/Hydrocarbon Auxiliary Propulsion System Study Phase II Report," McDonnell Douglas Corporation Report No. MDC E2547, July 1982.

3. "Combustion Performance and Heat Transfer Characterization of LOX/Hydrocarbon Type Propellants", NASA JSC Contract Number NAS 9-15958.