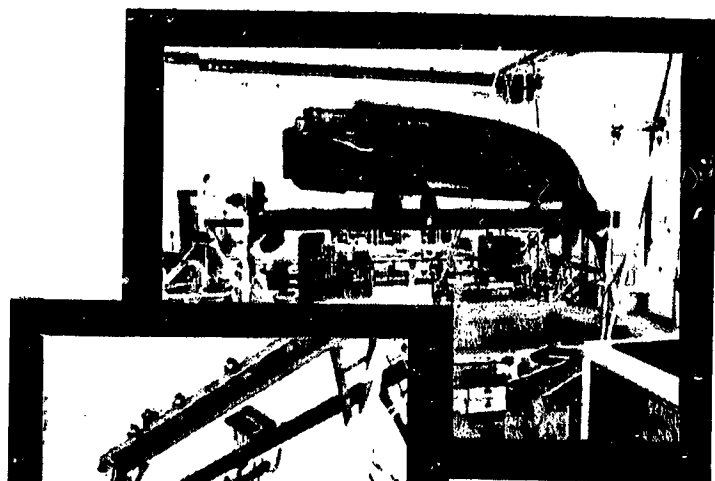


LOX/HYDROCARBON Auxiliary Propulsion System Study

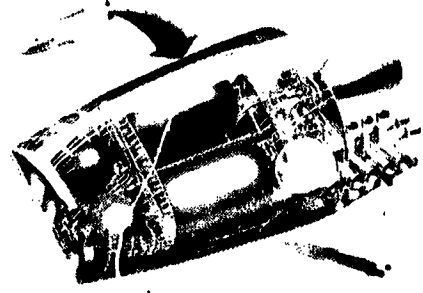


FINAL SUMMARY REPORT

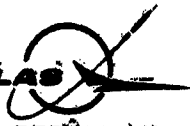
(NASA-CR-171655) LOX/HYDROCARBON AUXILIARY
PROPULSION SYSTEM STUDY Final Summary
Report (McDonnell-Douglas Astronautics Co.)
79 p HC A05/MP A01 CSCI 21H

N83-24550

G3/20 Unclass
03669



MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - ST. LOUIS DIVISION

MCDONNELL DOUGLAS

CORPORATION

LOX/HYDROCARBON Auxiliary Propulsion System Study


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

**FINAL SUMMARY 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 AERONAUTICS COMPANY-ST. LOUIS DIVISION

Box 616, Saint Louis, Missouri 63166 (314) 232-0232

MCDONNELL DOUGLAS

CORPORATION

ABSTRACT

This report summarizes the results of 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.

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**

FINAL SUMMARY REPORT-

REPORT MDC E2576
JULY 1982

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

	<u>Page</u>
1.0 Introduction.....	1
2.0 Phase I Groundrules.....	3
2.1 Propellant Candidates.....	3
2.2 System Design Options.....	6
2.3 Design Requirements.....	6
3.0 Phase I System Evaluations.....	11
3.1 Pump Versus Pressure Fed OMS.....	11
3.2 Summary of Phase I Results and Recommendations.....	14
4.0 Phase II Groundrules.....	21
5.0 Phase II Component Characterization.....	27
5.1 Weight and Performance Models.....	27
5.2 Tank Heat Transfer Models.....	31
5.3 Feedline Heat Transfer Models.....	31
6.0 Phase II System Evaluations.....	35
6.1 Tank Insulation Evaluations.....	35
6.2 RCS Feedline Insulation Evaluations.....	42
6.3 GOX/Ethanol RCS Feasibility Evaluations.....	42
6.4 LOX/Ethanol and LOX/Methane OMS-ARCS Sensitivity Analyses.....	55
6.5 Separate Versus Common FRCS/Aft Propulsion Tanks.....	59
6.6 Conventional versus Conical Propellant Tank Shapes.....	59
6.7 Pump Versus Pressure Fed FRCS.....	64
6.8 Side-by-Side OMS/ARCS Comparisons.....	64
7.0 Conclusions and Recommendations.....	67
References.....	71

LIST OF FIGURES

<u>NUMBER</u>	<u>TITLE</u>	<u>PAGE</u>
1	Current Orbiter Aft Pod OMS/RCS Packaging Arrangement.....	4
2	Pressure Fed OMS Schematic.....	12
3	Pump Fed OMS Schematic.....	13
4	Pump Fed OMS P _C Sensitivity.....	15
5	Pump and Pressure Fed OMS Comparisons.....	16
6	Passive Ethanol Feedline O ₂ Heat Exchanger Concept.....	23
7	Passive Ethanol Tank O ₂ Heat Exchanger Concept.....	23
8	LOX/Ethanol OMS Engine Specific Impulse.....	28
9	LOX Electric Motor and Pump Weight.....	29
10	Battery Weights for Electric RCS Pumps.....	30
11	Ethanol Tank O ₂ Heat Exchanger Model.....	32
12	RCS Thruster Heat Soakback Model.....	33/34
13	Methane Vent Losses for Common OMS-ARCS Tank.....	38
14	Methane Vent Losses for FRCS Tank.....	39
15	LOX Vent Losses for Common OMS-ARCS Tank.....	40
16	LOX Vent Losses for FRCS Tank.....	41
17	Effect of Methane Usage Rate on Feedline Temperature Response (TG-15000 Insulation).....	43
18	Effect of Methane Usage Rate on Feedline Temperature Response (MLI).....	44
19	Effect of LOX Usage Rate on Feedline Temperature Response (TG-15000 Insulation).....	45
20	Effect of LOX Usage Rate on Feedline Temperature Response (MLI).....	46
21	LOX/Ethanol OMS-ARCS Using OMS Turbopumps for RCS Supply.....	47
22	LOX/Ethanol OMS-ARCS Using Electric Motor Pumps for RCS Supply	49
23	O ₂ Temperature Histories for Passive Ethanol Tank Heat Exchanger.....	51
24	Ethanol Temperature And Quantity Histories for Passive Ethanol Tank Heat Exchanger.....	52
25	RCS Ethanol Accumulator Mission Response (Electric Pump Resupply).....	53
26	RCS GOX Accumulator Mission Response (Electric Pump Resupply).	54

**LOX/HYDROCARBON
Auxiliary Propulsion System Study
FINAL SUMMARY REPORT**

**REPORT MDC E2578
JULY 1982**

<u>NUMBER</u>	<u>TITLE</u>	<u>PAGE</u>
27	Baseline LOX/Ethanol OMS-ARCS.....	56
28	Baseline LOX/Methane OMS-ARCS.....	57
29	Sensitivity of LOX/Ethanol System to OMS Chamber Pressure.....	58
30 -	Sensitivity of LOX/Ethanol and LOX/Methane Systems to RCS Chamber Pressure.....	60
31	Separate versus Common FRCS/Aft Propulsion Tanks (LOX/Ethanol)	61
32	Interconnected Forward and Aft Propulsion Systems.....	62
33	Conventional Versus Conical Propellant Tank Shapes (LOX/Ethanol).....	63
34	Pump Versus Pressure-Fed FRCS (LOX/Methane).....	65/66
35	Comparison of LOX/HC, LOX/H ₂ , and N ₂ O ₄ /MMH OMS-ARCS.....	65/66

LIST OF PAGES

Title Page
ii through xi
1 through 71

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
I	Candidate Fuel Matrix.....	5
II	LOX/HC OMS-RCS Design Options.....	7
III	Options Selected for Phase I Evaluation.....	8
IV	Phase-I System Evaluation Matrix.....	9
V	Phase I Results and Recommendations.....	17
VI	Phase II Groundrules Summary.....	22
VII	Phase II Design Requirements/Constraints for Component Weight and Sizing.....	24
VIII	Phase II System Evaluation Tasks.....	36
IX	Properties of Candidate Insulation Materials.....	37
X	Overall Study Conclusions.....	68
XI	New Technology Requirements.....	69
XII	Recommendations for Further Feed System Effort.....	70

NOMENCLATURE

AE/AT	nozzle area ratio
Al	aluminum
Ag	silver
ALRC	Aerojet Liquid Rocket Company
APS	auxiliary propulsion system or aft propulsion system
ARCS	Aft Reaction Control Subsystem
BTU	British Thermal Unit
CH ₄	methane
Cu	copper
C ₂ H ₅ OH	ethanol (ethyl alcohol)
C ₃ H ₈	propane
D	diameter
F	thrust
FRCS	Forward Reaction Control Subsystem
ft	feet
ft ³	cubic feet
GG	gas generator
HC	hydrocarbon
He	helium
HR	hours
H ₂	hydrogen
in.	inches
I _{sp}	specific impulse
I _t	total impulse
JSC	Johnson Space Center
L	length
lb	pounds
lbf	pounds-force
lbm	pounds-mass
LH ₂	liquid hydrogen
Li	lithium
liq	liquid
LOX	liquid oxygen

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**

FINAL SUMMARY REPORT

REPORT MDC E2576
JULY 1982

NOMENCLATURE (Continued)

\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 ₂ H ₄	hydrazine
N ₂ O ₄	nitrogen tetroxide
OME	Orbital Maneuvering Engine
OMS	Orbital 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
°R	degrees Rankine
sec	seconds
SS	stainless steel
T	temperature
TG-15000	silica fiber insulation

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**

FINAL SUMMARY REPORT

REPORT MDC E2578
JULY 1982

NOMENCLATURE (Continued)

Ti	titanium
TPA	turbopump assembly
TVS	thermodynamic vent system
V	volume
XFEED	crossfeed
Zr	zirconium
Zn	zinc
ΔL	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.

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**

FINAL SUMMARY REPORT

REPORT MDC E2678
JULY 1982

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 the 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), while the final report was provided in Reference (3). This report presents a summary of the technical effort conducted during the study.

2.0 PHASE I GROUND RULES

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 summarized below.

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

<u>EARTH STORABLE</u> (BOILING POINTS MUCH GREATER THAN AMBIENT)	
EXAMPLES: RP-1	<u>FUELS SELECTED FOR PHASE I</u>
ETHANOL	} ETHANOL (C ₂ H ₅ OH)
HEPTANE	
BENZENE	
METHANOL	
n-OCTANE	
<u>SPACE STORABLE</u> (BOILING POINTS SLIGHTLY LESS THAN AMBIENT)	
EXAMPLES: PROPANE	PROPANE (C₃H₈)
BUTANE	} AMMONIA (NH ₃)
ISOBUTANE	
PROPYLENE	
AMMONIA	
<u>CRYOGENIC</u> (BOILING POINTS LESS THAN - 100°F)	
EXAMPLES: ETHANE	METHANE (CH₄)
METHANE	}
ETHYLENE	
CYCLOPENTANE	

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. Combining the design options of Table III with the four propellant candidates resulted in the Phase I system evaluation matrix presented in Table IV. The rationale for this matrix is described in detail in Reference (3).

2.3 Design Requirements

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

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 shape
 - 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

B
 Y

ORIGINAL PAGE IS
 OF POOR QUALITY

TABLE IV
 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				

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**

**REPORT MDC E2576
JULY 1982**

FINAL SUMMARY REPORT

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 were presented in Reference (1).

3.0 PHASE I SYSTEM EVALUATIONS

The system design options established in Task I.1 (Table IV) were evaluated in this task applying the computer codes described in Reference (1). To illustrate the scope of effort results from evaluations of pump and pressure fed OMS concepts are presented in detail followed by a summary of results for the remaining evaluations.

3.1 Pump Versus Pressure Fed OMS

Schematics for the pressure and pump fed OMS concepts are shown in Figures 2 and 3. As shown in Figure 2 the pressure fed LOX/HC OMS is similar to the current storable OMS except that the helium bottle is stored inside the LOX tank to minimize its volume. The pump fed OMS, shown in Figure 3, 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 are fed to the engine at cryogenic temperatures and then vented from the OMS feedlines 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 ($165^{\circ}R$), and the propellant tanks can be extended 11.5 inches aft. The corresponding increase in available propellant tank volume 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.

ORIGINAL PAGE IS
OF POOR QUALITY

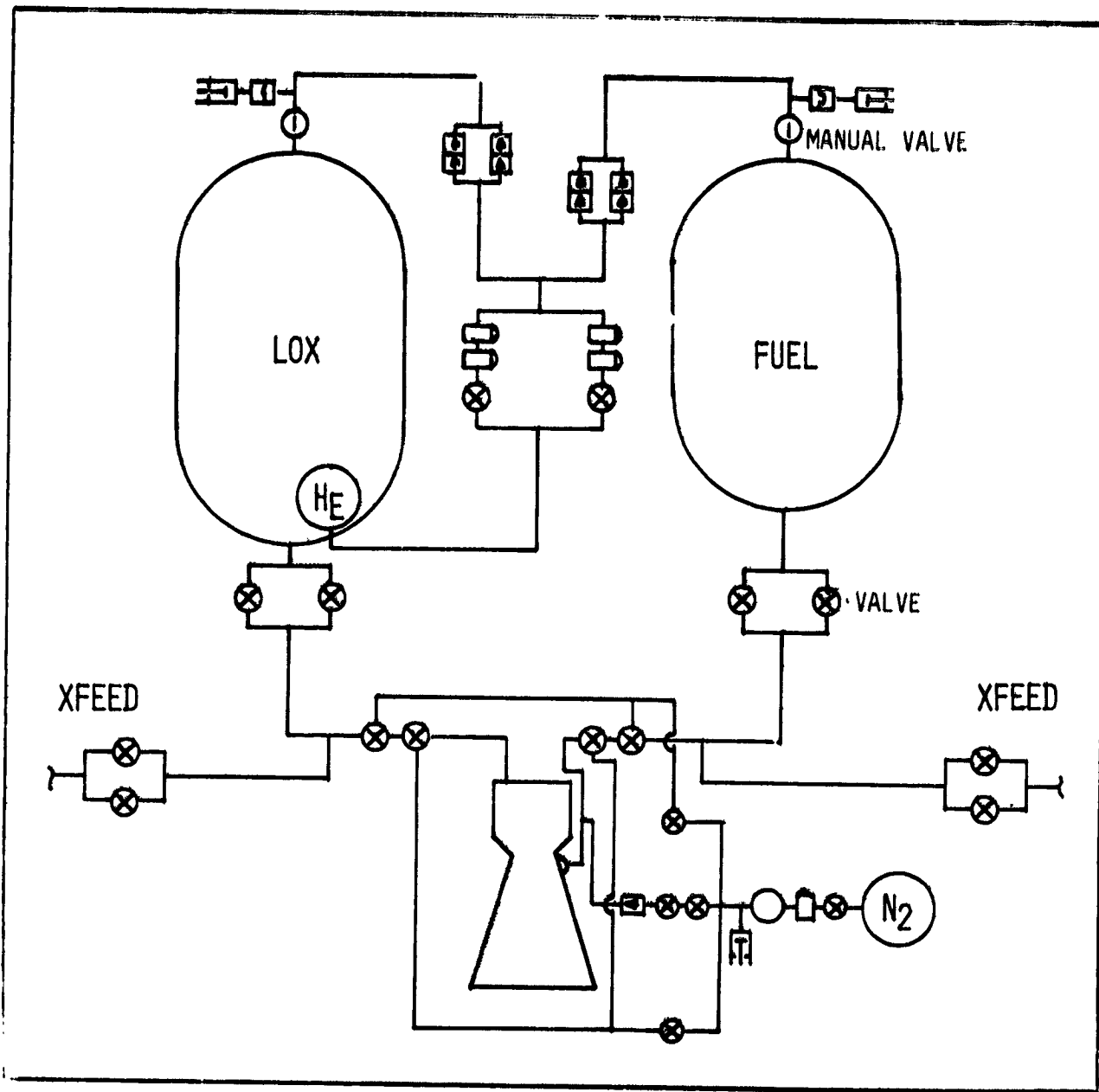


FIGURE 2 PRESSURE FED OMS SCHEMATIC

ORIGINAL FILED
OF RECORD OFFICE

S
Y.

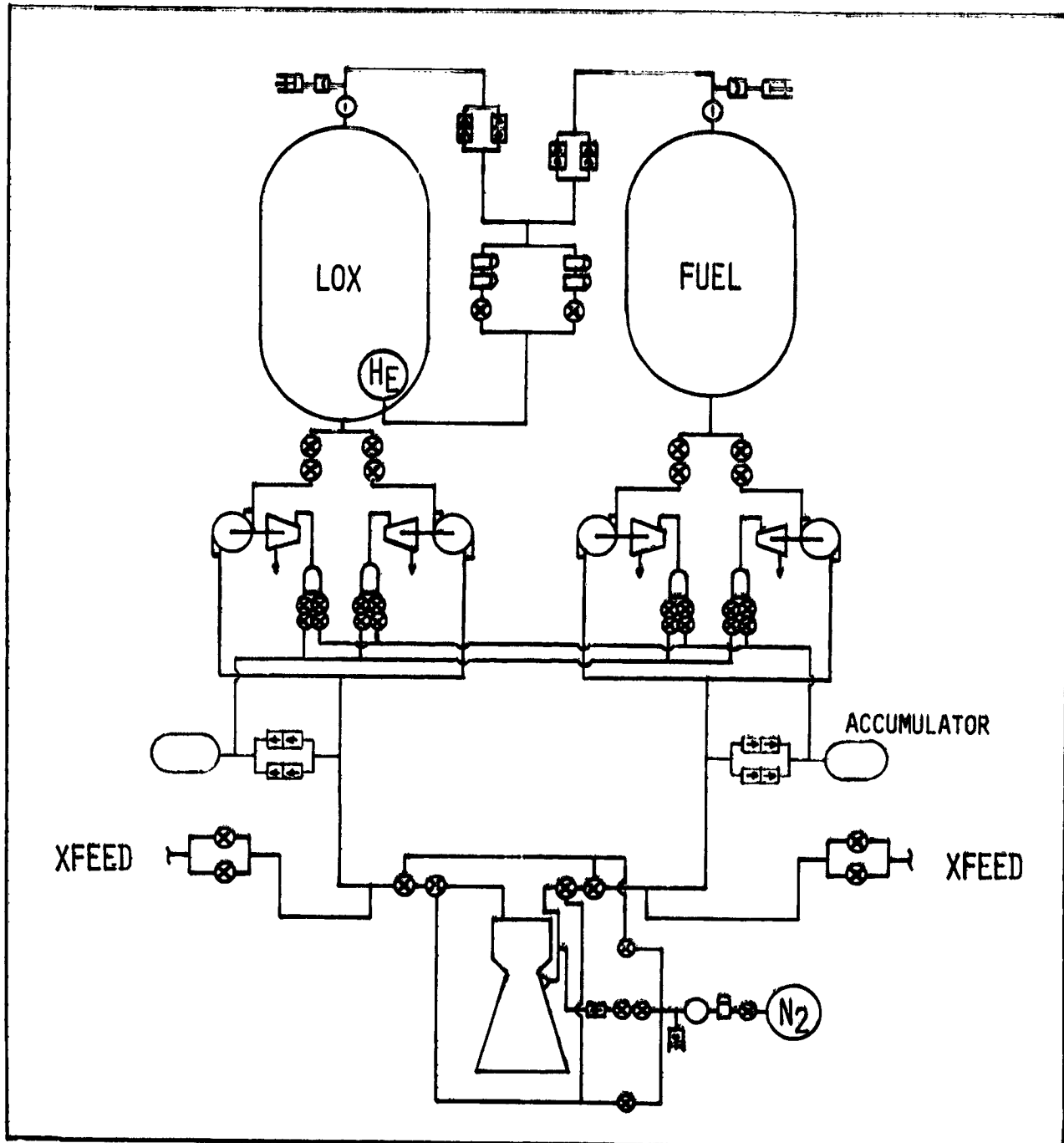


FIGURE 3 PUMP FED OMS SCHEMATIC

Based on the sensitivity data of Figure 4 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 5 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 5 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 5, 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 baselined for Phase II. For both aft pods the pump fed OMS offers a 3000-4000 lb weight advantage over the pressure fed system.

3.2 Summary of Phase I Results and Recommendations

A summary of Phase I results and recommendations is presented in Table V.

Ethanol and methane were recommended as the best fuel candidates as both are non-coking and offer high performance capability. Ethanol affords the highest ΔV and total impulse capability when sized to the current pod envelope because of its high density-specific impulse product. Methane affords the lowest system wet

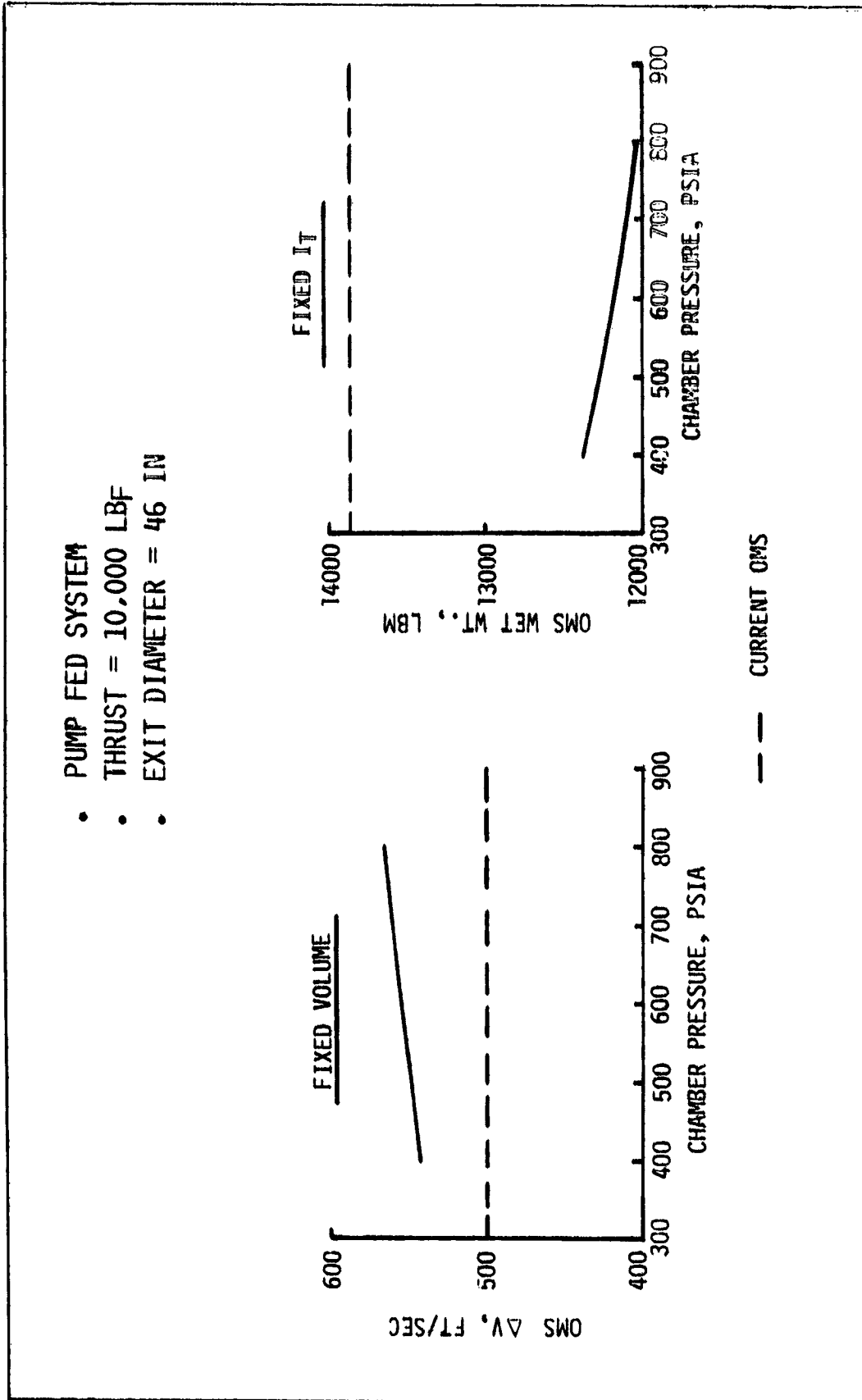


FIGURE 4 PUMP FED OMS PC SENSITIVITY

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**

FINAL SUMMARY REPORT

ORIGINAL EQUIPMENT
OF POOR QUALITY

REPORT MDC E2678
JULY 1982

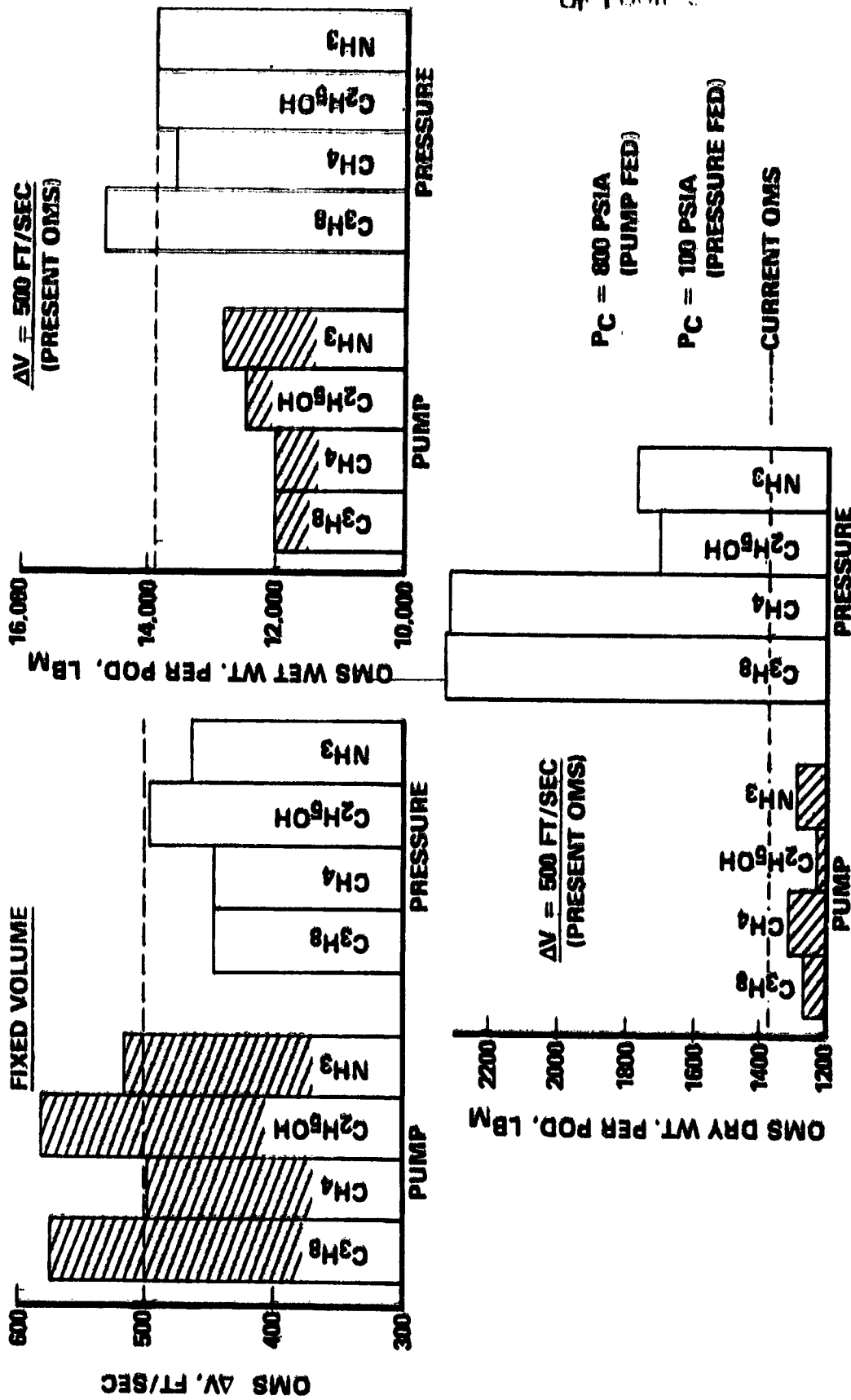


FIGURE 5 PUMP AND PRESSURE FED OMS COMPARISONS

TABLE V
PHASE I RESULTS AND RECOMMENDATIONS

1. Fuels:

- Ethanol and methane are best fuel candidates
 - non-coking
 - high performance capability
- Consider both ethanol and methane in Phase II

2. Systems:

- Pump versus Pressure Fed:
 - Pump fed OMS provides overriding weight and performance advantages over pressure fed OMS. Baseline pump fed OMS for Phase II. Consider methane expander cycle for increasing LOX/methane engine performance. Consider single turbine drive for both fuel and oxidizer pumps to reduce system complexity.
 - Pump and pressure fed RCS are comparable in terms of weight and performance. Consider battery powered electric pumps for RCS feed in Phase II to reduce pump feed system complexity and eliminate gas generator vent losses (I_{sp} penalty).
- NBP versus Subcooled Fuel Storage:
 - Subcooled propane storage (at LOX temperatures) provides 25% increase in OMS ΔV capability.
 - Do not consider further in Phase II due to recommendation of ethanol and methane as best fuel candidates.
- Cryogenic versus Ambient Temperature RCS Propellant Feed:
 - Energy requirement for ambient temperature RCS propellant feed is lowest for LOX/ethanol combination (low mixture ratio requirement).
 - Use of gas generator supplied active heat exchangers for propellant thermal conditioning imposes high I_{sp} penalties.
 - Consider passive LOX thermal conditioning for LOX/ethanol system in Phase II to eliminate I_{sp} penalty.

TABLE V (Continued)
PHASE I RESULTS AND RECOMMENDATIONS

- Common versus Separate OMS/RCS Tanks:
 - Common OMS/aft RCS tanks provide weight and performance advantages over separate tanks. They also provide greater flexibility in the use of OMS-aft RCS propellants and reduce the number of feed system components. Baseline common OMS/aft RCS tanks for Phase II.
 - Further evaluation is required in Phase II for common OMS/aft RCS/forward RCS tanks. Consider conical shaped tanks to provide improved aft pod packaging.
- Tank Insulation Options:
 - MLI is best performing tank insulation material.
 - TG-15000 is easier to handle and install than MLI, does not require dewar-type tank, but allows twice the LOX vent loss as MLI.
 - Consider both MLI and TG-15000 as candidate methane tank insulation materials in Phase II.
- Feedline Insulation Options:
 - MLI is required to prevent excessive RCS LOX feedline temperatures for 30-day missions.
 - Re-evaluate feedline insulation options for both LOX and methane in Phase II using updated thruster heat soakback model.

weight (highest payload capability) when sized to a fixed ΔV requirement because of its high engine specific impulse.

A pump fed OMS was baselined for Phase II because it offers overriding weight and performance advantages compared to a pressure fed system. A single turbine drive for both the fuel and oxidizer pumps was recommended to reduce system complexity, and an expander engine cycle was recommended for LOX/methane to increase OMS engine performance.

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 pump and pressure fed RCS were recommended for further evaluation in Phase II considering battery powered electric pumps for RCS supply to eliminate the I_{sp} penalty associated with turbopumps and reduce feed system complexity.

Because of the lower energy requirement for LOX thermal conditioning (lower oxidizer flowrate) an ambient propellant temperature LOX/ethanol RCS feed system was recommended for further evaluation in Phase II. In addition passive LOX thermal conditioning was recommended to eliminate the I_{sp} penalty associated with gas generator supplied heat exchangers and increase feed system reliability. One approach is the use of a passive ethanol tank heat exchanger to supply the energy required for gasifying the RCS oxygen supply.

Common OMS/aft-RCS tanks were baselined for Phase II because they offer improved propellant packaging in the aft pods (higher OMS ΔV and RCS total impulse capability), provide greater flexibility in the utilization of OMS-aft RCS propellants, and reduce feed system weight. Fully integrated tankage systems for the OMS, aft RCS, and forward RCS propellants were recommended for further evaluation in Phase II considering the use of conical propellant tanks for improved aft-pod packaging.

Finally, it was recommended that evaluation of candidate tank and feedline insulation materials be expanded in Phase II to include the methane feed system.

4.0 PHASE II GROUNDRULES

The results from the Phase I effort, described above, formed the groundrules for the Phase II effort. These groundrules are summarized in Table VI. As indicated in Table VI 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 6) the fuel flow is pre-heated using a hot gas heat exchanger, and then the fuel flow is used to vaporize the O₂ flow in a passive feedline heat exchanger. This approach was selected as a safety consideration since it precludes the use of fuel-rich gas generator products in an O₂ heat exchanger. In the second concept (Figure 7) the oxygen flow is circulated through a heat exchanger coiled around the outside of the ethanol tank where it absorbs heat from the environment, tank wall, and ethanol within the tank.

The system design requirements and constraints for component weight and sizing were similar to those established in Phase I and are summarized in Table VII. The three notable differences between Phase I and Phase II were:

- During an abort propellants were assumed to be burned in the OMS and RCS engines for Phase I. This approach is employed in the current OMS/RCS, but necessitated sizing the turbopumps and feedlines for abort flow demands. In Phase II an overboard dump system was assumed which allowed sizing the turbopumps and feedlines for engine flow demands.
- In Phase I tank minimum gage wall thicknesses were set at 0.03 and 0.02 inches for aluminum and titanium, respectively. In Phase II these were increased to 0.06 inches to provide resistance against handling loads.
- In Phase I the RCS accumulators were sized for 50 cycles per mission whereas in Phase II they were sized to provide the Shuttle External Tank separation impulse without resupply.

TABLE VI
PHASE II GROUND RULES 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)
 - cryogenic 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 O₂ 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)

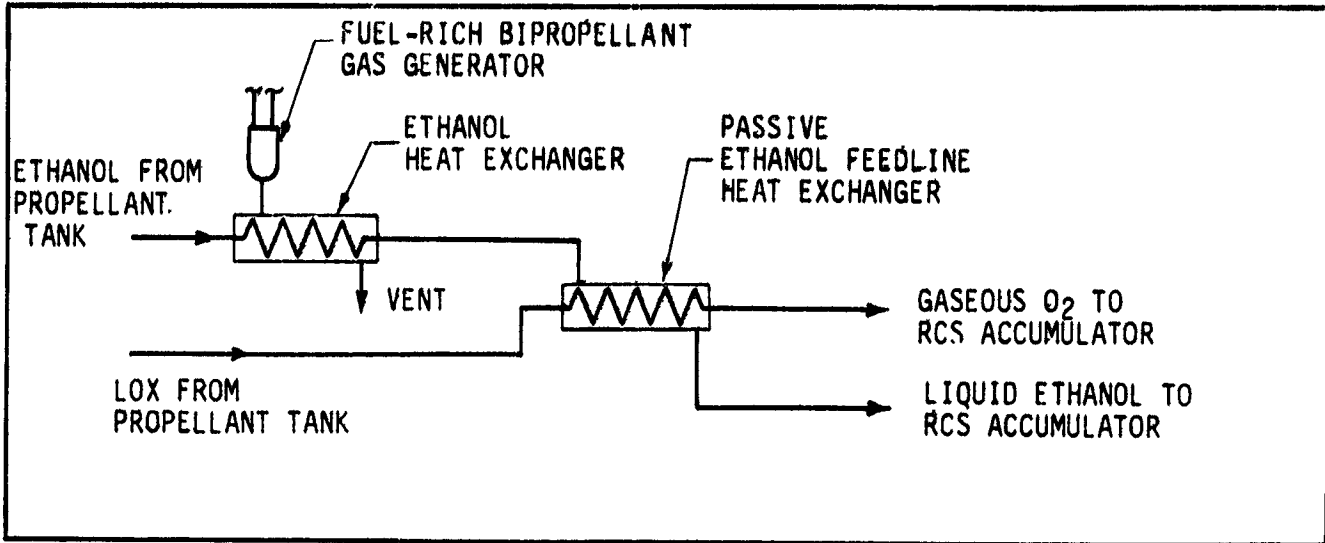


FIGURE 6 PASSIVE ETHANOL FEEDLINE O₂ HEAT EXCHANGER CONCEPT

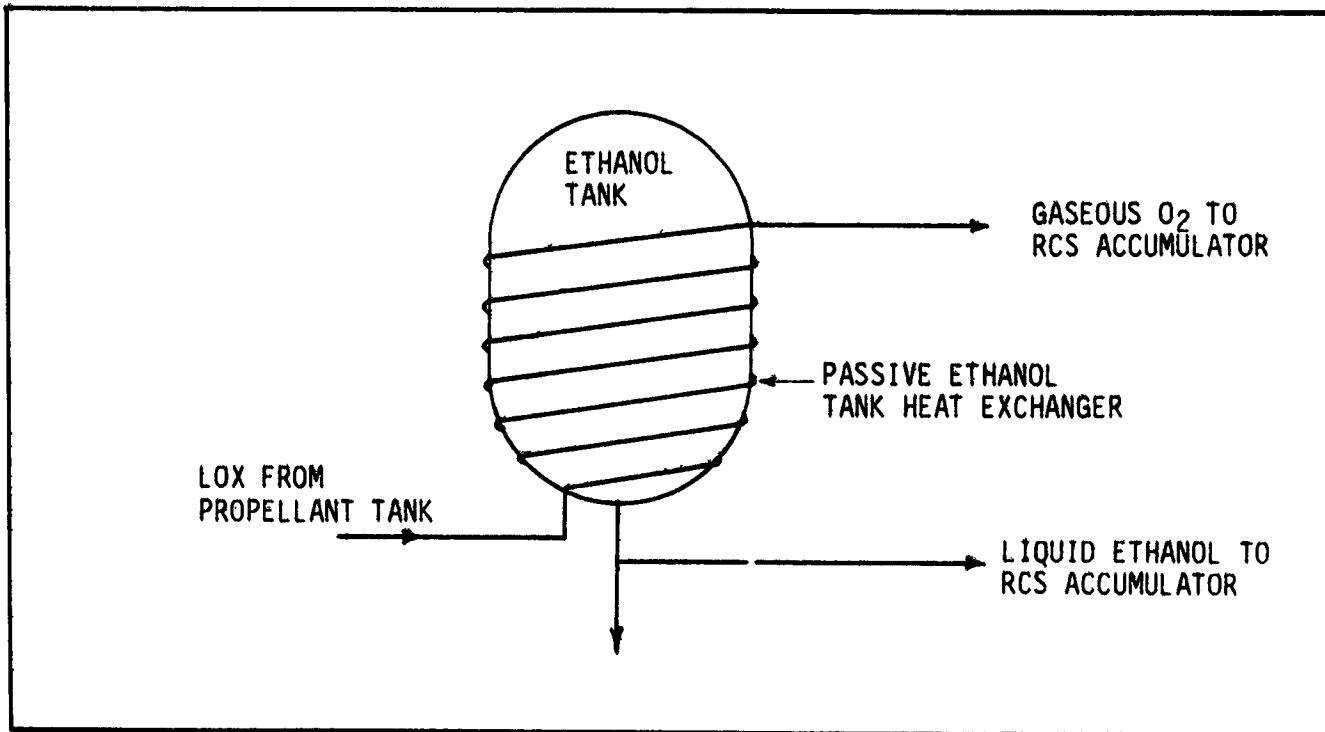


FIGURE 7 PASSIVE ETHANOL TANK O₂ HEAT EXCHANGER CONCEPT

TABLE VII

PHASE II DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

- I. Helium Pressurization System
- o common helium supply for fuel and oxidizer tanks
 - o current OMS/RCS line lengths
 - o line Mach number = 0.1 (Maximum)
 - o real gas effects
 - o solubility effects
 - o propellant vapor pressure effects
 - o line material: 304L stainless steel (SS)
 - o polytropic exponent = 1.0 (helium bottle inside LOX tank)
 - o regulator pressure ratio = 0.7 (outlet/minimum inlet)
 - o tank shape: spherical
 - o tank material: 2219-T87 aluminum (Al)
 - o storage pressure: 3000 psia
 - o ultimate factor of safety for helium tank = 1.5
- II. Propellant Tanks
- o propellant dumped overboard during an abort
 - o 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 loss (LOX and methane)
 - 5% ullage volume at storage temperature
 - o Common OMS/ARCS tank shape
 - cylindrical with oblate spheroid end domes, or
 - conical with oblate spheroid end domes
 - o Common OMS/ARCS tanks are constrained to equal lengths to permit attachment to common aft pod bulkhead
 - o FRCS tank and entry sump shape: spherical

TABLE VII (CONTINUED)

PHASE II DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

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

III. RCS Accumulators

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

IV. Propellant Feedlines

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

TABLE VII (CONTINUED)

PHASE II DESIGN REQUIREMENTS/CONSTRAINTS FOR COMPONENT WEIGHT AND SIZING

- o Darcy friction factor
 - o isenthalpic expansion process
 - o material: 2219-T87 AL
 - o minimum gage = 0.028 in.
 - o ultimate factor of safety:
 - 4.0 for diameters < 1.5 in.
 - 1.5 for diameters \geq 1.5 in.
 - o linear and angular compensation joints
 - o insulation options for RCS feedlines (LOX and methane)
 - aluminized mylar MLI
 - TG-15000 silica fiber insulation
- V. Gas Generator Exhaust Vent Line
- o line Mach number = 0.3 (maximum)
 - o Fanno line analysis
 - o line length: 20 ft
 - o exhaust nozzle area ratio = 2.0
 - o propulsive vent for OMS; nonpropulsive vent for RCS
 - o line material: 304L SS
 - o minimum gage and ultimate factor of safety: same as feedlines

5.0 PHASE II COMPONENT CHARACTERIZATION

The computer codes described in Reference (1) were upgraded in this task. The weight and performance code was modified to incorporate new engine weight and performance models for LOX/ethanol and LOX/methane and new electric pump weight models for the RCS. The tank heat transfer code was modified to incorporate a new ethanol tank O₂ heat exchanger model, while the feedline heat transfer code was modified to incorporate an improved thruster heat soakback model. These modifications are described below.

5.1 Weight and Performance Models

Revised OMS and RCS engine models were developed by ALRC and were provided in the Reference (2) appendices. The OMS engine models assumed fuel regenerative cooling, whereas the RCS engine models assumed fuel film cooling. The OMS engine model was based on a single turbine driving both the fuel and oxidizer pumps. A gas generator cycle was selected for the LOX/ethanol OMS, while an expander cycle was selected for the LOX/methane OMS. 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 avoiding the vent loss associated with the gas generator cycle. Parametric weight and performance data were generated as a function of chamber pressure as illustrated in Figure 8 for the LOX/ethanol OMS engine. In this example the nickel (Ni) chamber provides lower performance than the Zirconium-Copper (Zr-Cu) chamber because of high supplementary film cooling losses. As a result a Zr-Cu chamber was baselined for the OMS engine to provide maximum performance.

Electric motor operated RCS pump weights were also generated by ALRC (Reference (2) appendices) for incorporation into the APSDS code. These were based on an alternating current design, and typical parametric data are presented in Figure 9 for LOX. Corresponding battery weights for meeting the RCS total impulse requirement were developed by NASA-JSC and are shown in Figure 10 for both silver-zinc (Ag-Zn) and lithium batteries. The lithium batteries require new technology development but were baselined for the study because of their low weight.

ORIGINAL PAGE 107
OF POOR QUALITY

THRUST = 6000 LBF

○ ZR-CU CHAMBER
△ NI CHAMBER

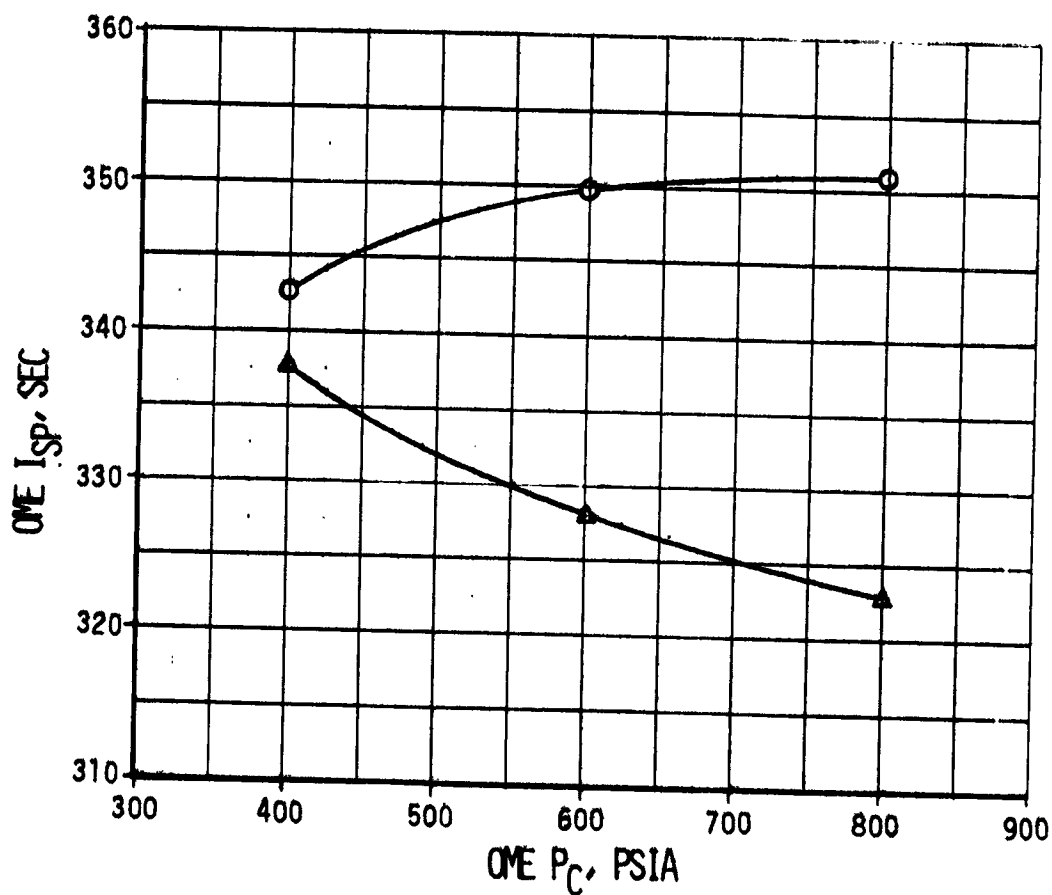


FIGURE 8 LOX/ETHANOL OMS ENGINE SPECIFIC IMPULSE

ORIGINAL BASES
OF POOR QUALITY

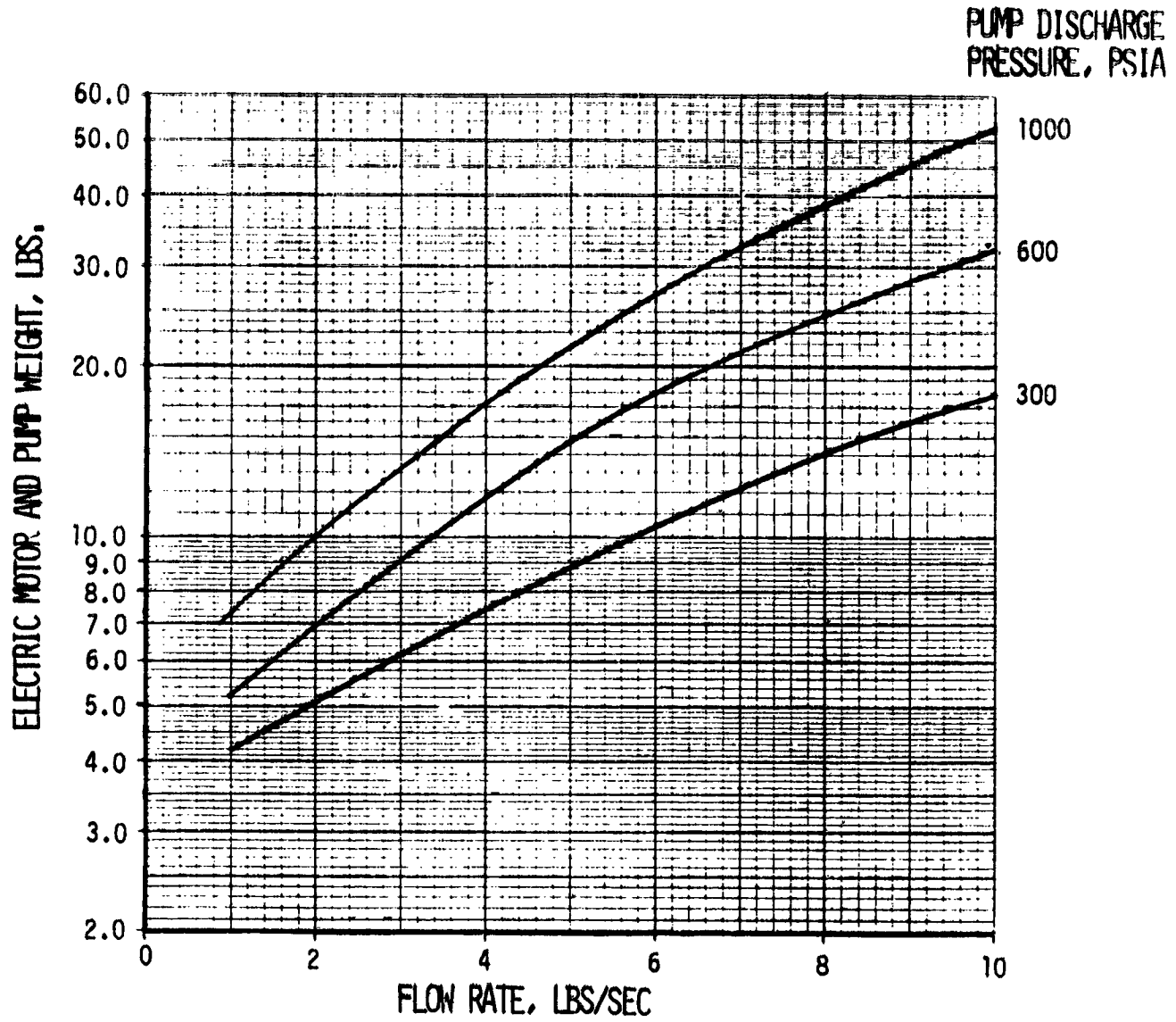


FIGURE 9 LOX ELECTRIC MOTOR AND PUMP WEIGHT

- △ METHANE
- OXYGEN
- ETHANOL

ORIGINAL SOURCE OF DATA
 OF 100% QUALITY

(REDUNDANT BATTERIES)

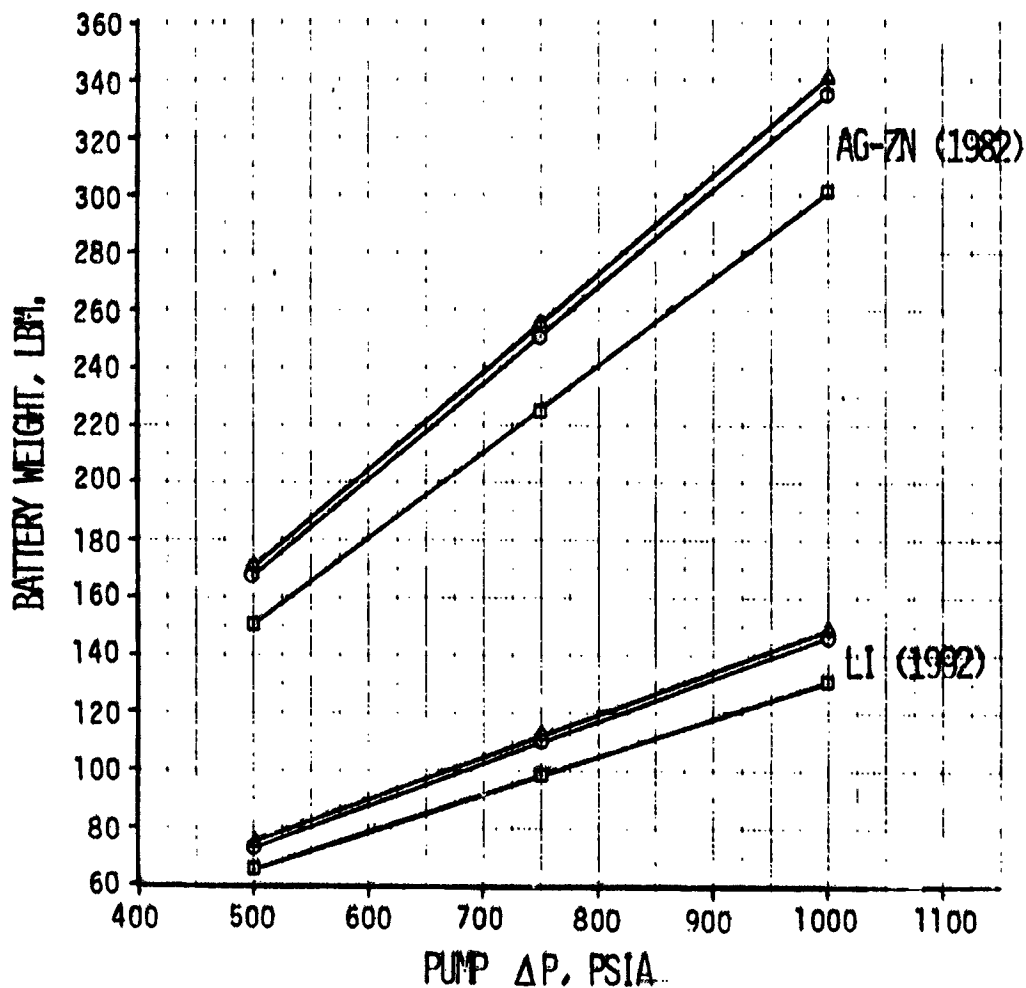


FIGURE 10 BATTERY WEIGHTS FOR ELECTRIC RCS PUMPS

5.2 Tank Heat Transfer Models

The tank heat transfer code was modified in Phase II to include the capability to analyze methane and to provide a new subroutine for evaluating a passive ethanol tank O₂ heat exchanger. The ethanol tank O₂ heat exchanger model is shown in Figure 11. The O₂ heat exchanger is coiled around the outside wall of the ethanol tank where it absorbs heat from the tank wall, the environment, and liquid ethanol within the tank. The O₂ 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 O₂ 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.

5.3 Feedline Heat Transfer Models

The feedline heat transfer code was modified to incorporate the thruster heat soakback model shown in Figure 12. In this model the heat soakback is calculated based on the thermal resistance between the injector and valve and the temperature difference provided by Figure 12. The computer code maintains an inventory of thruster pulses and the time between firings and then applies the injector-valve temperature difference given by Figure 12 to compute thruster heat soakback.

ORIGINAL QUALITY
OF POOR QUALITY

- O₂ HEAT EXCHANGER LINE ABSORBS HEAT FROM THE TANK, FUEL, AND ENVIRONMENT

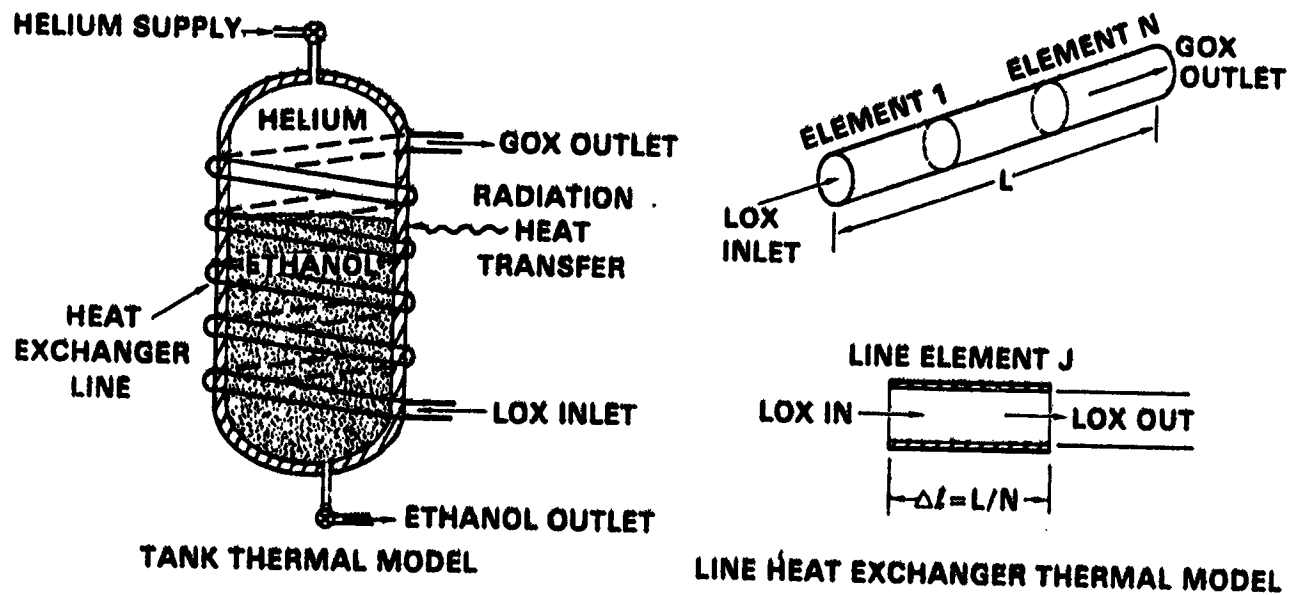


FIGURE 11 ETHANOL TANK O₂ HEAT EXCHANGER MODEL

ORIGINAL PAGE IS
 OF POOR QUALITY

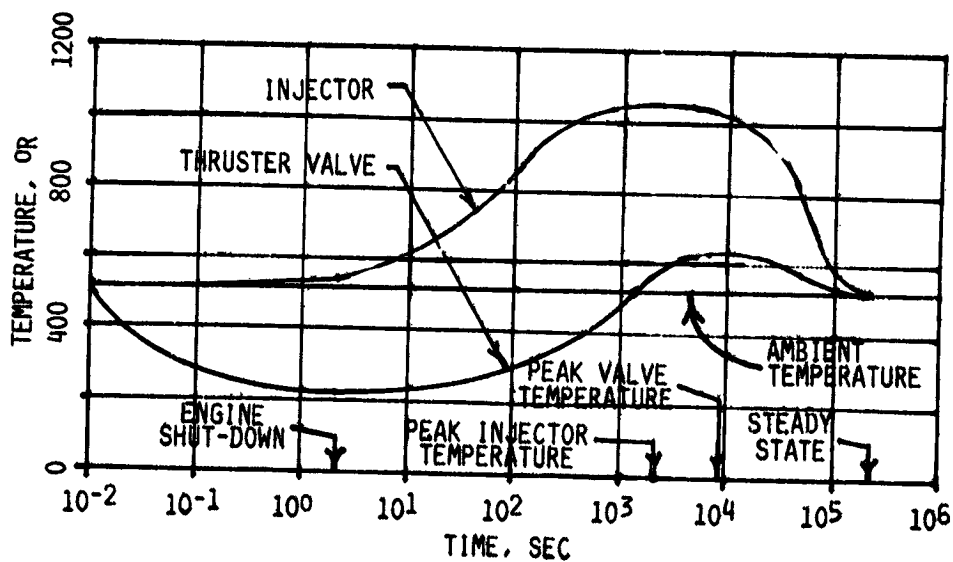
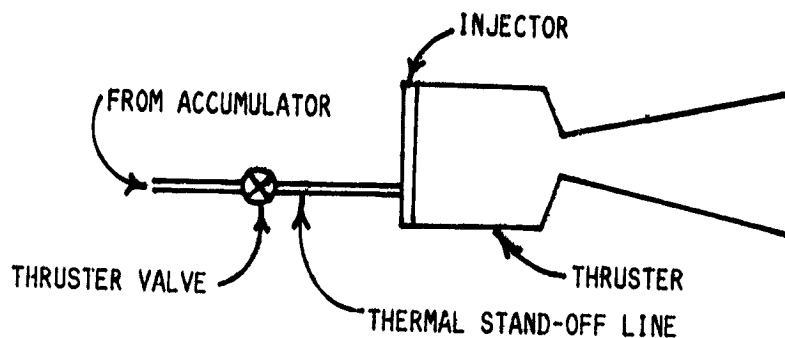


FIGURE 12 RCS THRUSTER HEAT SOAKBACK MODEL

6.0 TASK II.3--PHASE II SYSTEM EVALUATIONS

The evaluations performed in this task are summarized in Table VIII. They include the Phase II design options identified previously in Section 4.0 (Table VI), design point sensitivity analyses, and side-by-side comparisons of the most attractive LOX/HC systems with a LOX/H₂ system and the current storable propellant OMS/RCS. System weight and performance data generated to support these evaluations were provided in the Reference (2) appendices. The following paragraphs summarize the results and conclusions derived from these evaluations.

6.1 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 are shown in Table IX. The MLI exhibits the lowest vacuum thermal conductivity but requires a vacuum cover (dewar-type tank) to prevent moisture degradation. The TG-15000 insulation is currently employed on the Shuttle aft pod internal moldline. It is attractive because it is easier to handle and install than MLI and is not susceptible to moisture degradation (does not require a vacuum cover). Its disadvantage is a higher vacuum thermal conductivity compared to MLI. The tank insulation evaluations were performed using the tank heat transfer code (Reference (3)) applying representative OMS-RCS engine firing cycles for a 30-day mission.

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 13 through 16 for a common OMS-ARCS tank and a separate FRCS tank. Results for methane are presented in Figures 13 and 14, whereas results for oxygen are presented in Figures 15 and 16. 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.

TABLE VIII
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 O₂ heat exchanger
 - Electric pump RCS propellant feed with ethanol tank O₂ 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. Conventional versus Conical ; _pellant Tank Shapes
7. Pump versus Pressure Fed FRCS
8. Side-by-Side OMS/ARCS Comparisons
 - LOX/ethanol
 - LOX/methane
 - LOX/H₂
 - Current N₂O₄/MMH

ORIGINAL PAGE IS
 OF POOR QUALITY

TABLE IX
 PROPERTIES OF CANDIDATE INSULATION MATERIALS

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

ORIGINAL PAGE IS
OF POOR QUALITY.

- 30 DAY MISSION
 - INITIAL METHANE LOAD = 3005 LBM
 - RELIEF PRESSURE = 60 PSIA
 - ENVIRONMENTAL TEMPERATURE = 500°R
-
- ▲ 1.5 INCHES TG-15000 INSULATION
 - 1.0 INCH MLI

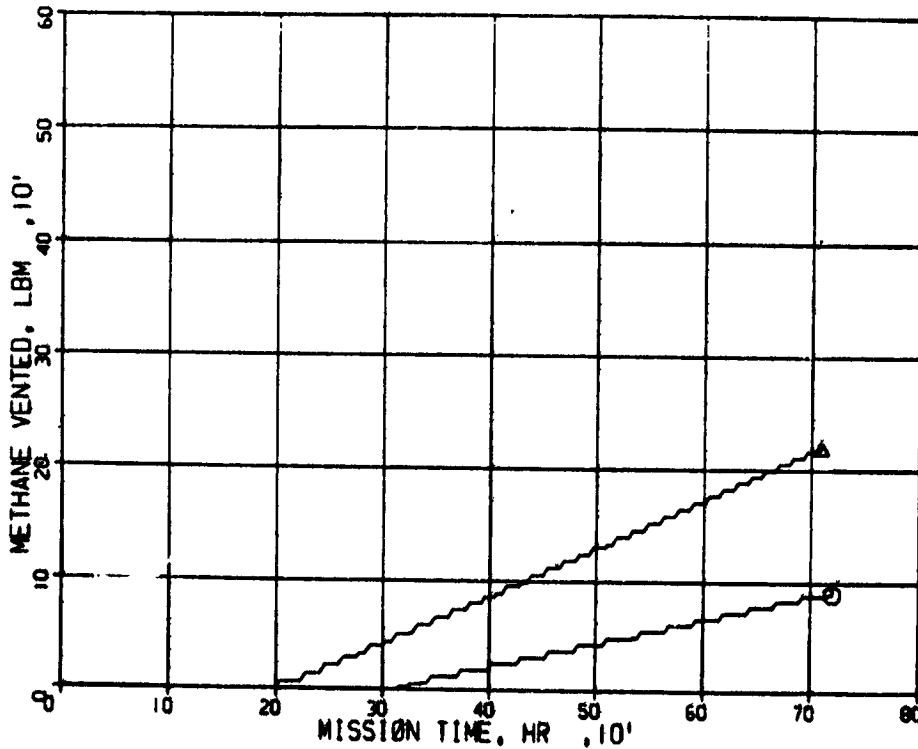


FIGURE 13 METHANE VENT LOSSES FOR COMMON OMS-ARCS TANK

ORIGINAL PAGE IS
OF POOR QUALITY

9
Y

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

△ 1.5 INCHES TG-15000 INSULATION

○ 1.0 INCH MLI

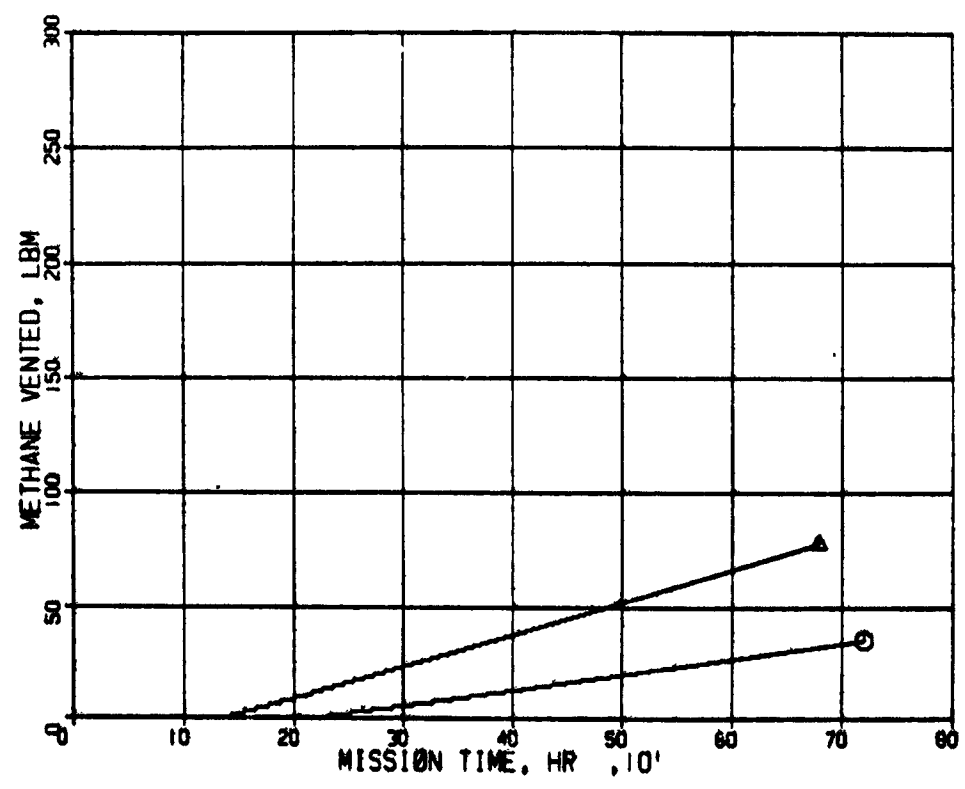


FIGURE 14 METHANE VENT LOSSES FOR FRCS TANK

ORIGINAL PAGE IS
OF POOR QUALITY

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

- ▲ 1.5 INCHES TG-15000 INSULATION
- 1.0 INCH MLI

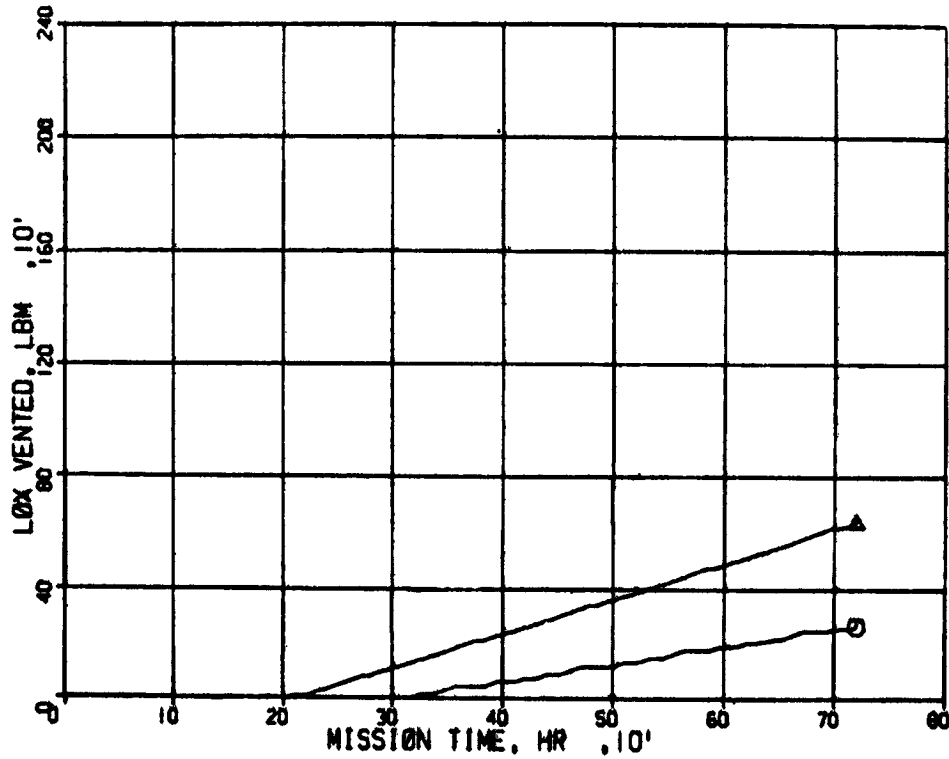


FIGURE 15 LOX VENT LOSSES FOR COMMON OMS-ARCS TANK

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**
FINAL SUMMARY REPORT

REPORT MDC E2576
JULY 1982

ORIGINAL PROPERTY
OF ROCKWELL

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

- ▲ 1.5 INCHES TG-15000 INSULATION
- 1.0 INCH MLI

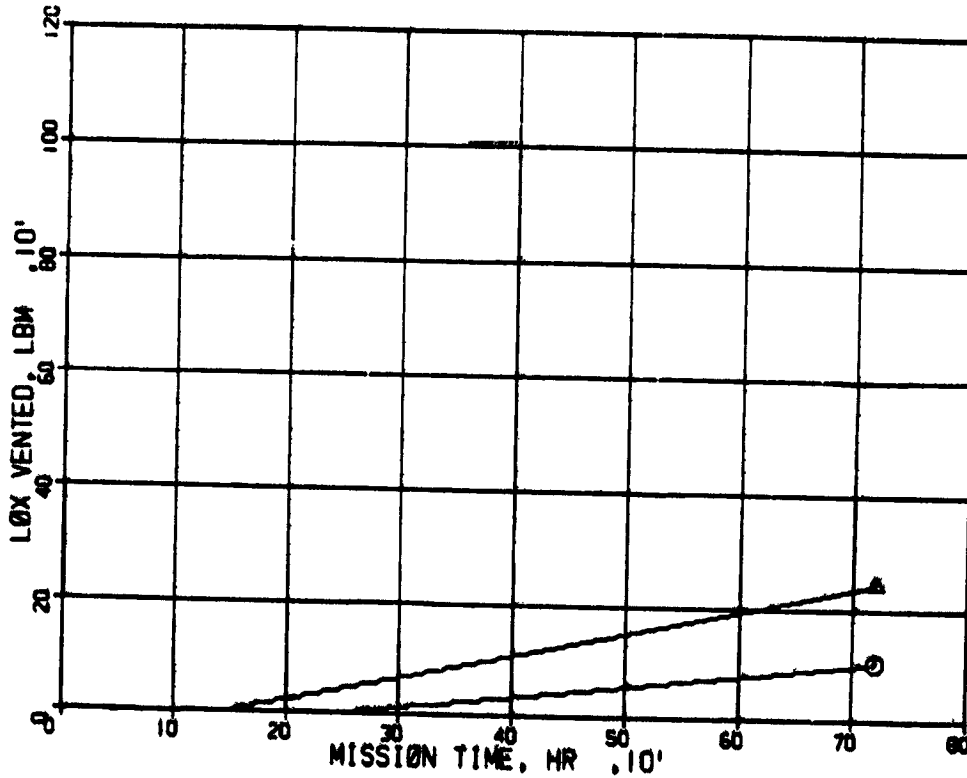


FIGURE 16 LOX VENT LOSSES FOR FRCS TANK

6.2 RCS Feedline Insulation Evaluations

MLI and TG-15000 insulation materials were also evaluated for cryogenic methane and LOX RCS feedlines. These evaluations were performed using the feedline heat transfer code (Reference (3)) and employed the thruster heat soakback model described in Section 5.3. 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.)

Summary plots of maximum methane feedline temperature as a function of accumulator temperature and usage rate are presented in Figures 17 and 18 for TG-15000 and MLI, respectively. As shown in Figure 17 for TG-15000 insulation methane feedline temperatures are maintained below the vaporization limit for the 7-day thruster usage rates but exceed the vaporization limit for the lower 30-day usage rates. However, with MLI (Figure 18) methane feedline temperatures are maintained well below the vaporization limit for both the 7 and 30-day usage rates. Similar trends are evident for LOX feedline temperatures as shown by Figures 19 and 20. As a result of these evaluations one-inch of MLI was baselined for the cryogenic methane and LOX RCS feedlines.

6.3 GOX/Ethanol RCS Feasibility Evaluations

Two feed system approaches were evaluated to determine the feasibility of gaseous O₂ (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 21. This approach uses two heat exchangers

ORIGINAL DRAWING
OF POOR QUALITY

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

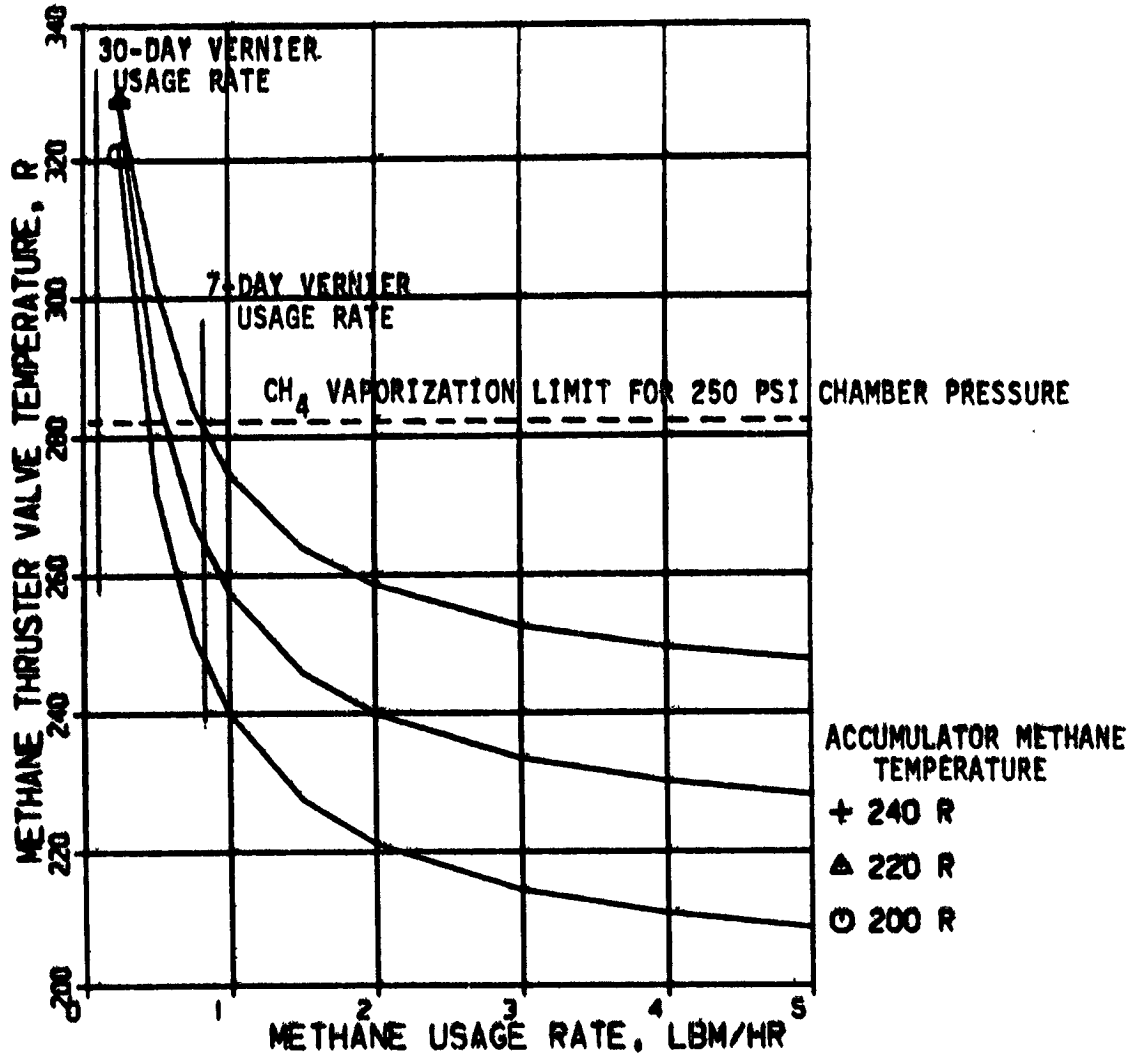


FIGURE 17 EFFECT OF METHANE USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (TG-15000 INSULATION)

- o 1 IN. MLI
- o PRESSURE = 500 PSIA

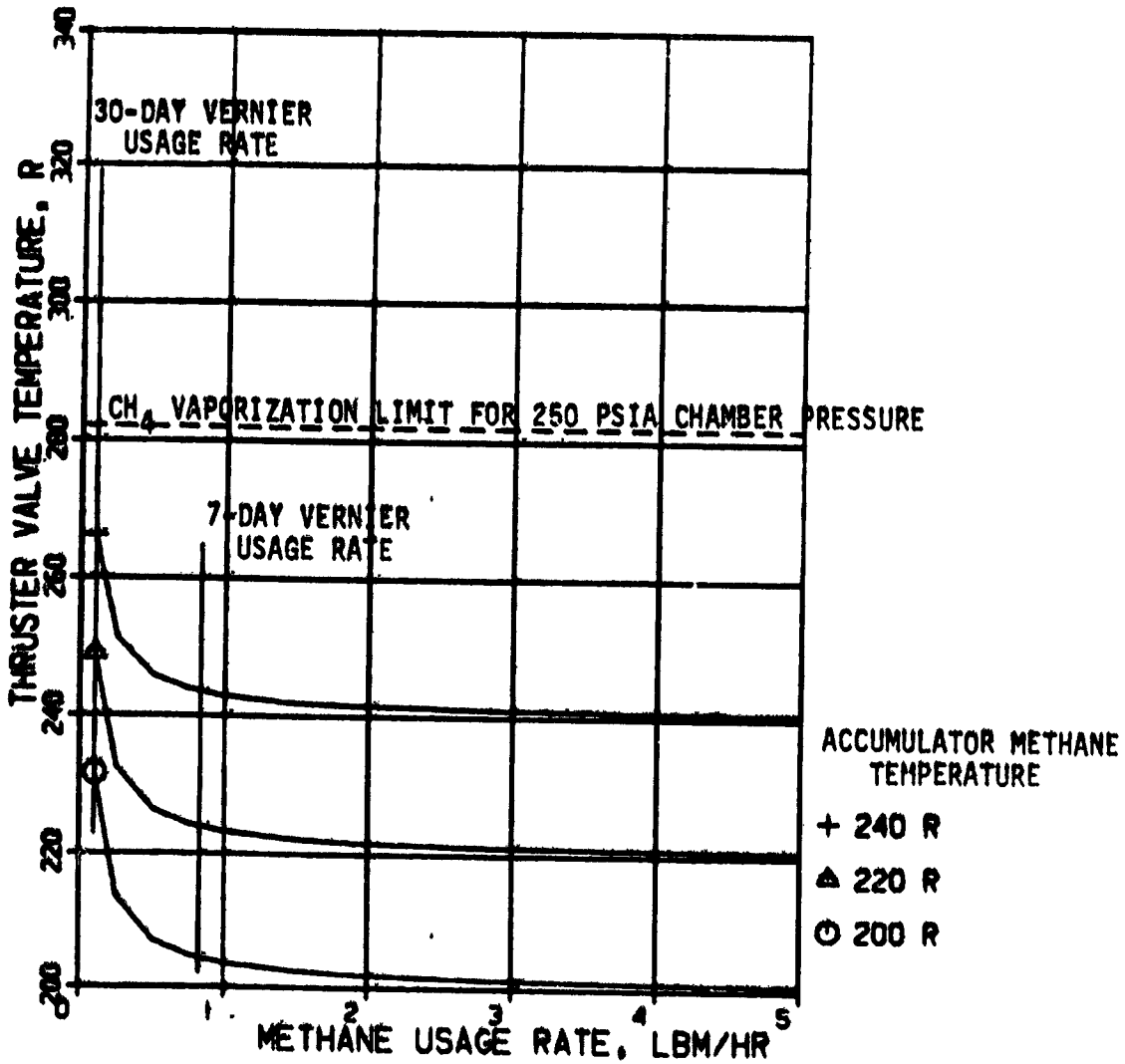


FIGURE 18 EFFECT OF METHANE USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (MLI)

ORIGINAL PAGE IS
 OF POOR QUALITY

- o 1 IN. TG-1500 INSULATION ..
- o PRESSURE = 500 PSIA

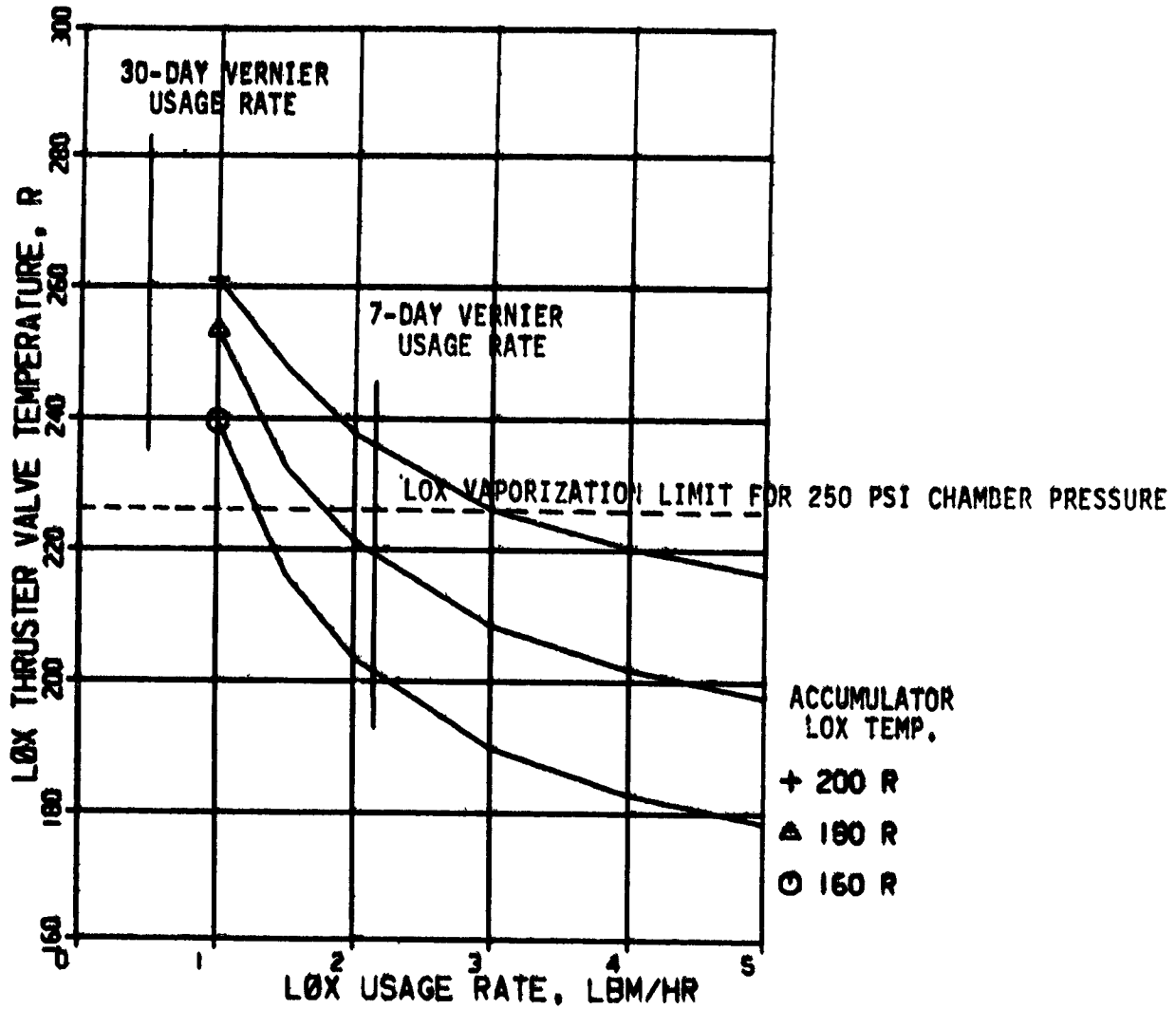


FIGURE 19 EFFECT OF LOX USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (TG-15000 INSULATION)

ORIGINAL PAGE 13
 OF POOR QUALITY

- o 1 IN. MLI
- o PRESSURE = 500 PSIA

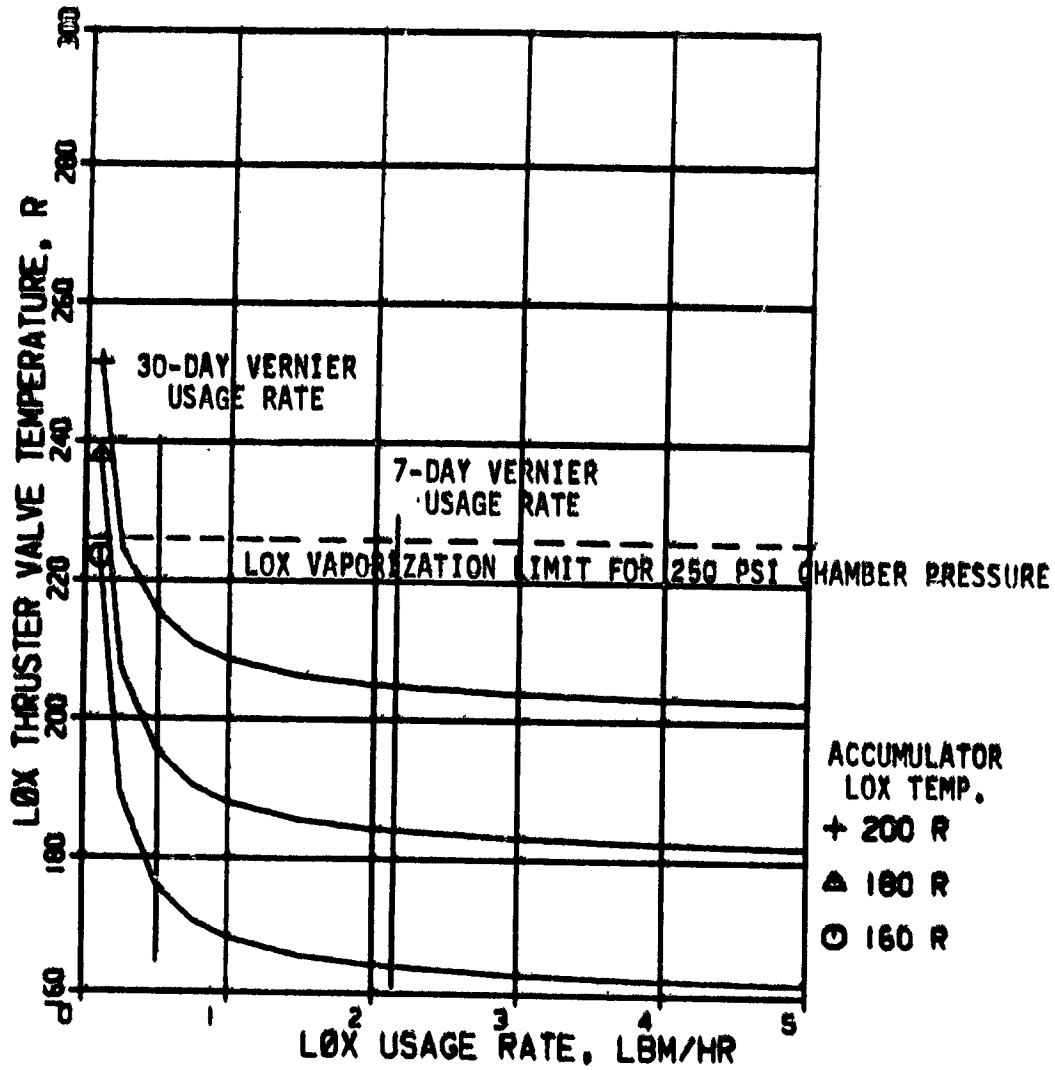


FIGURE 20 EFFECT OF LOX USAGE RATE ON FEEDLINE TEMPERATURE RESPONSE (MLI)

ORIGINAL ENGINEERING
OF PROPOSED QUALITY

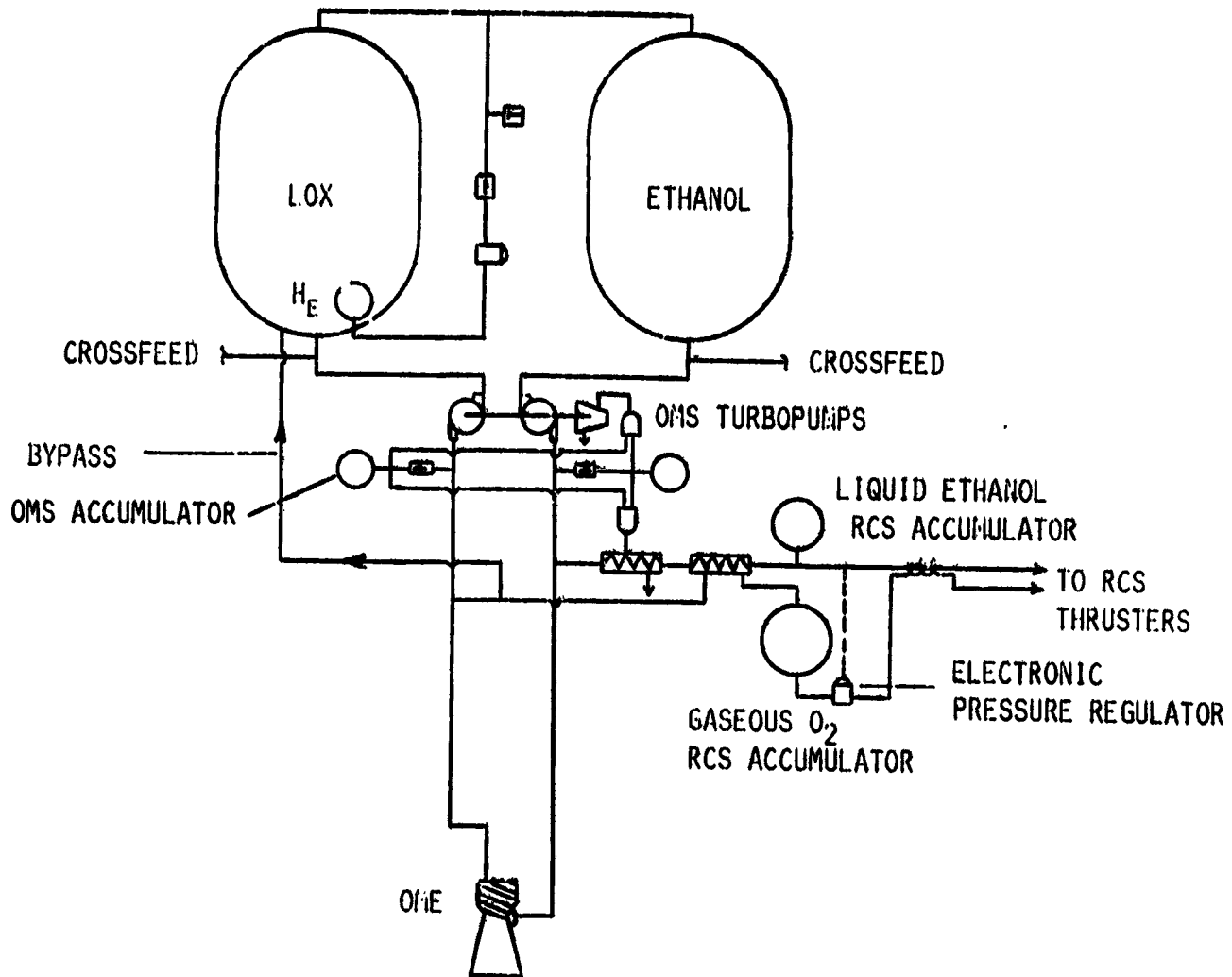


FIGURE 21 LOX/ETHANOL OMS-ARCS USING OMS TURBOPUMPS FOR RCS SUPPLY

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**

FINAL SUMMARY REPORT

REPORT MDC 62576
JULY 1982

upstream of the RCS accumulators to thermally condition the RCS O₂ supply and avoid the use of fuel-rich gas generator products in an O₂ heat exchanger. During RCS accumulator resupply fuel leaving the OMS turbopump is first preheated to 660°R in a heat exchanger by reaction products from a separate fuel-rich gas generator. The hot fuel is then used to thermally condition the O₂ resupply flow from 165 to 370°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 O₂ heating 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 O₂ flow is routed back to the LOX tank by-passing the heat exchanger.

The ethanol and GOX 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. Despite variations in accumulator pressures and temperatures during the mission control over RCS thruster mixture ratio is achieved through the use of an electronic pressure regulator and thermally shorted feedlines downstream of the accumulators. The O₂ accumulator outlet pressure is controlled in response to ethanol accumulator pressure with the electronic pressure regulator, while O₂ and ethanol fluid temperatures are equalized with the thermally shorted feedlines.

Evaluations using the tank heat transfer code showed that reasonable accumulator pressures and temperatures could be maintained with this feed system approach. However, the approach has the following disadvantages:

- large number of turbopump cycles (50 per mission)
- complexity associated with the use of an O₂ heat exchanger bypass 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 22. In this approach O₂

ORIGINAL FILED IN
 DE LOX/ETHANOL

5
 Y

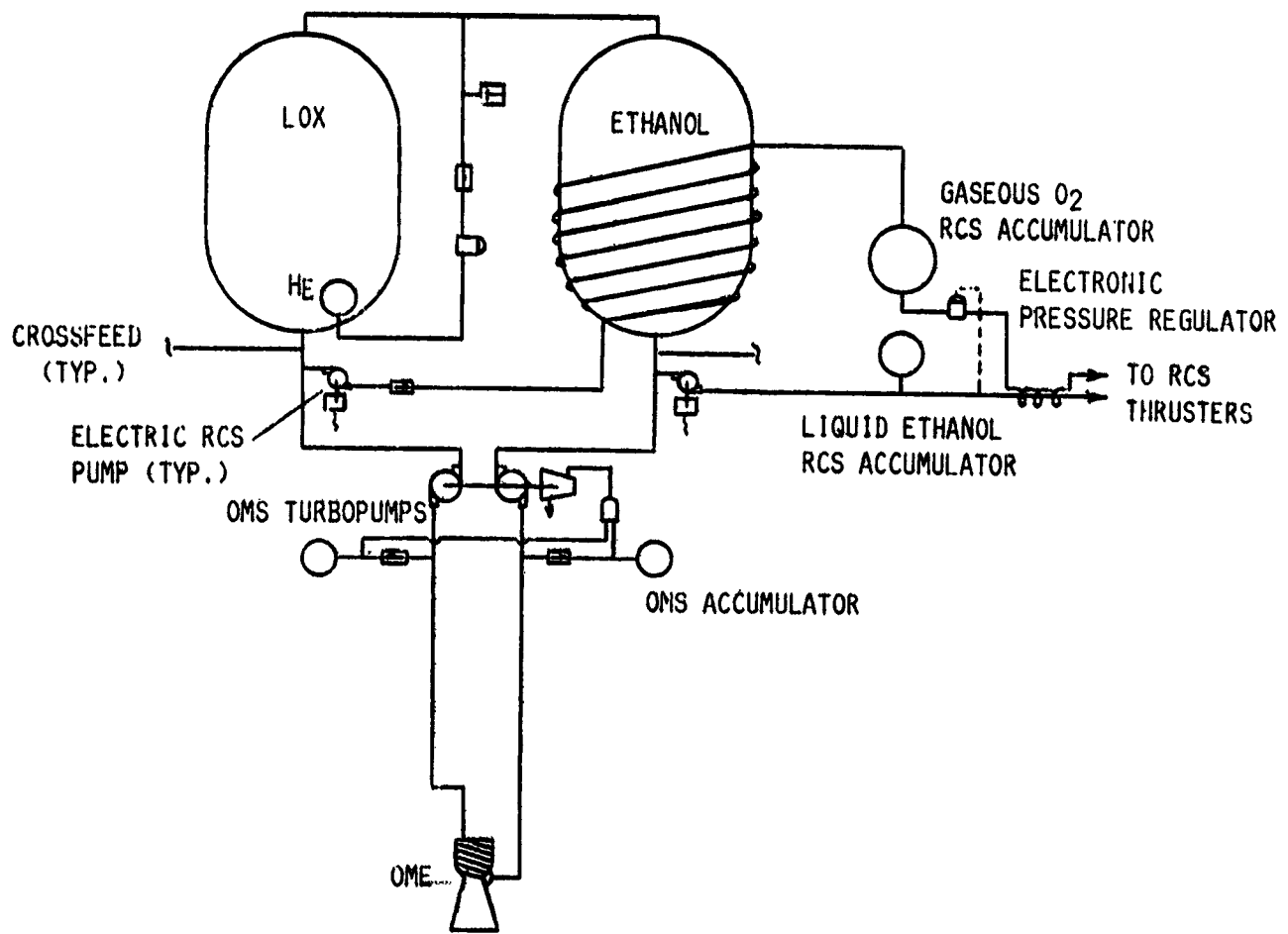


FIGURE 22 LOX/ETHANOL OMS-ARCS USING ELECTRIC MOTOR PUMPS FOR RCS SUPPLY

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 23 and 24 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 23 shows the O_2 inlet and outlet temperature histories over the 7-day period. The coldest O_2 outlet temperature is $425^{\circ}R$ and occurs 24 hours into the mission during the period of maximum RCS usage. Figure 24 shows the corresponding temperature and quantity of ethanol remaining as a function of mission time. The coldest ethanol temperature ($430^{\circ}R$) also occurs at the 24 hour point.

Examples of RCS accumulator temperature-pressure response with the electric pump resupply approach are shown in Figures 25 and 26. Figure 25 shows the response of the liquid ethanol accumulator, while Figure 26 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 ($430^{\circ}R$ and $425^{\circ}R$, respectively). In order to minimize electric motor weight and power requirements pump discharge pressures were set at 500 psia. Unlike the preceding 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 preceding concept an electronic pressure regulator and thermally shorted feedlines are employed downstream of the accumulators to control RCS thruster mixture ratio (Figure 22).

The results of Figures 23 through 26 demonstrate the feasibility of a hybrid RCS feed system (gaseous O_2 and liquid ethanol) in which electric pumps are used for accumulator resupply 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 exchanger assembly or bypass 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

ORIGINAL PAGE IS
OF POOR QUALITY

B
Y

- 7-DAY OMS-RCS MISSION DUTY CYCLE
 - HEAT EXCHANGER O₂ FLOWRATE = 3.3 LBM/SEC
 - HEAT EXCHANGER INLET TEMP. = 162°R
 - HEAT EXCHANGER INLET PRESS. = 500 PSIA
- } DURING RE-SUPPLY

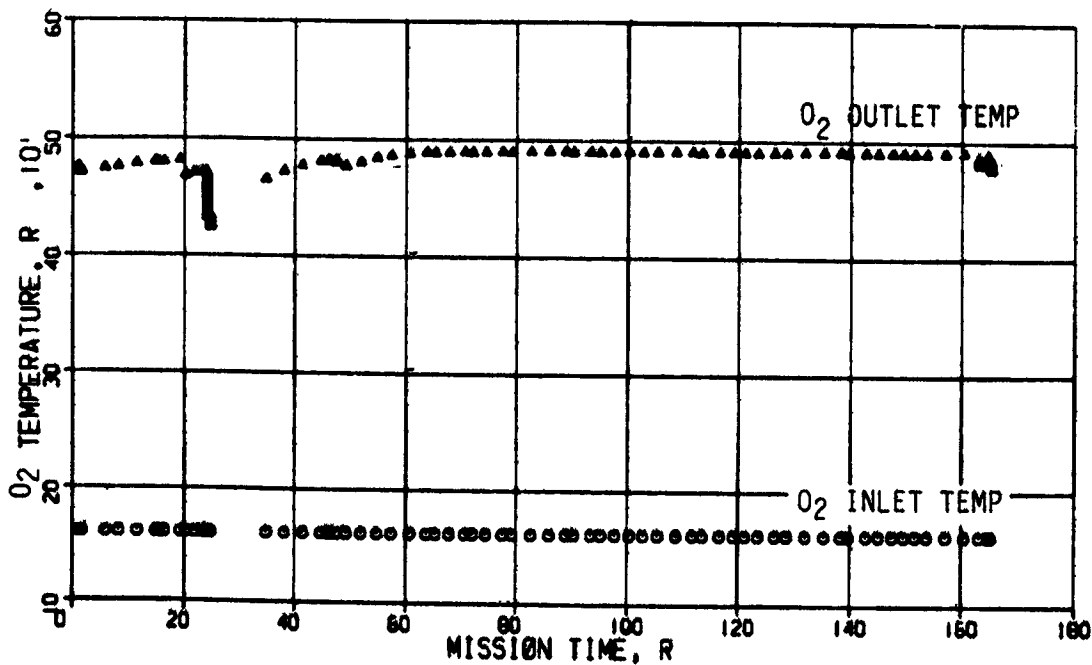


FIGURE 23 O₂ TEMPERATURE HISTORIES FOR PASSIVE ETHANOL TANK HEAT EXCHANGER

- 7-DAY OMS-RCS MISSION DUTY CYCLE
 - HEAT EXCHANGER O₂ FLOWRATE = 3.3 LB_M/SEC
 - HEAT EXCHANGER O₂ INLET TEMP. = 162°R
 - HEAT EXCHANGER O₂ INLET PRESS. = 500 PSIA
- } DURING RE-SUPPLY

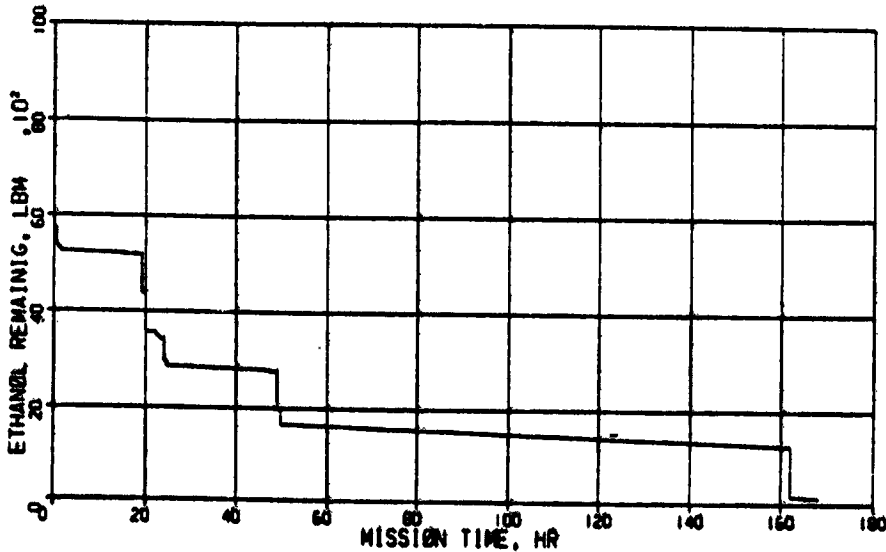
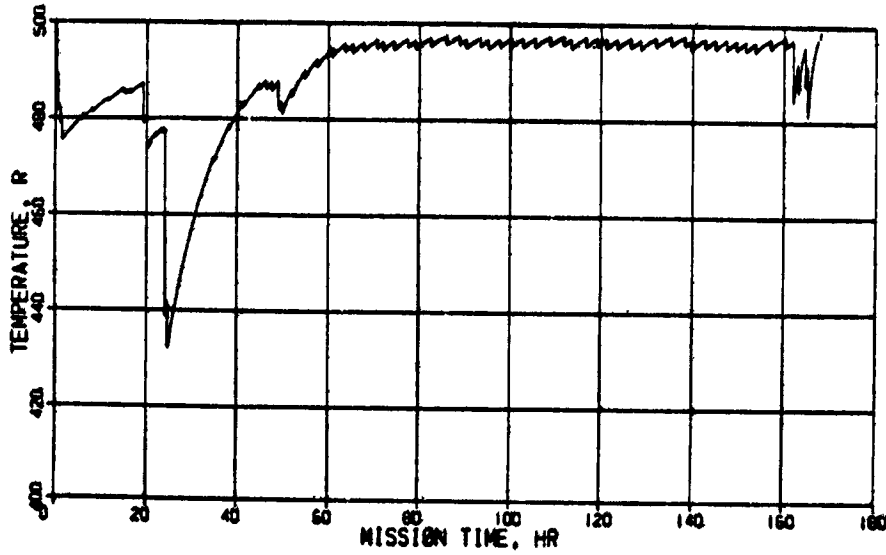


FIGURE 24 ETHANOL TEMPERATURE AND QUANTITY HISTORIES FOR PASSIVE ETHANOL TANK HEAT EXCHANGER

LOX/HYDROCARBON
Auxiliary Propulsion System Study
FINAL SUMMARY REPORT

ORIGINAL PAGE IS
OF POOR QUALITY

REPORT MDC E2578
JULY 1982

- 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

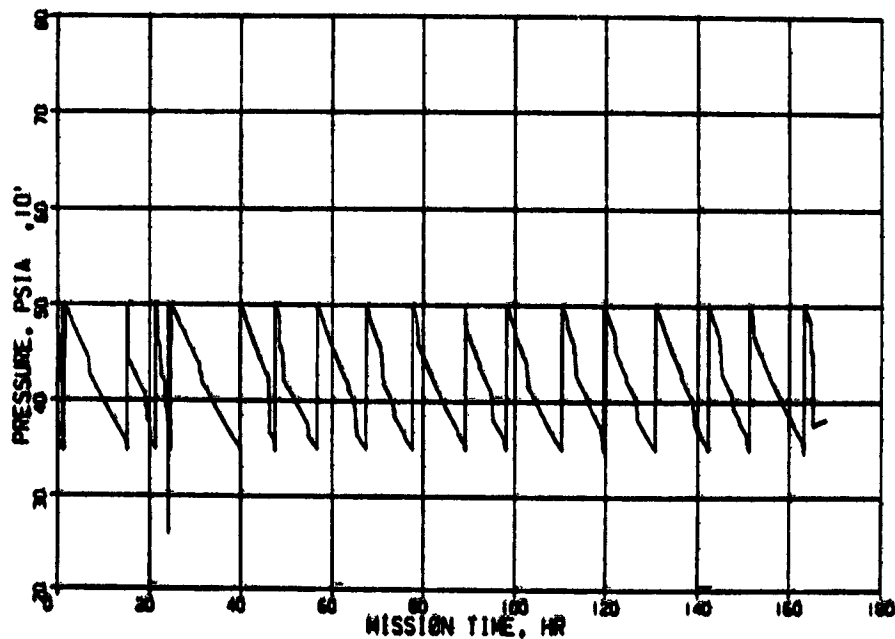
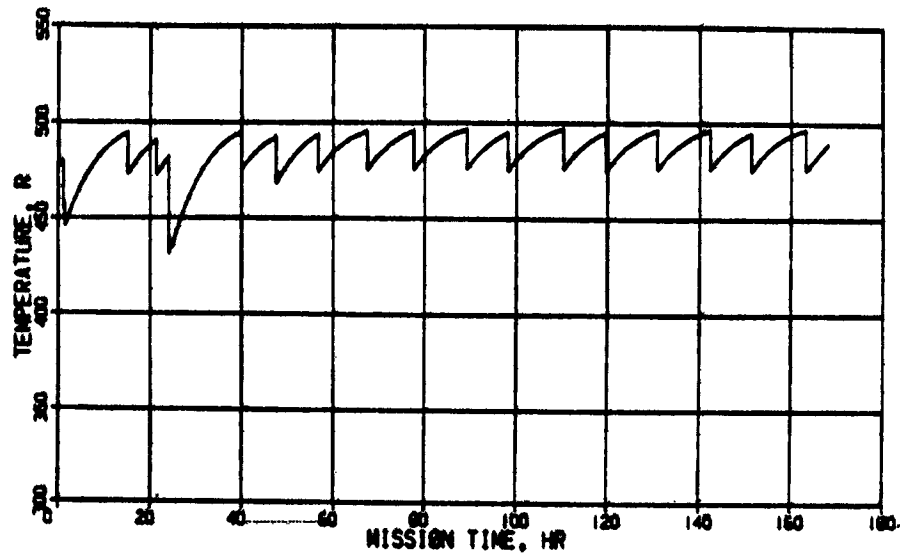


FIGURE 25 RCS ETHANOL ACCUMULATOR MISSION RESPONSE
(ELECTRIC PUMP RE-SUPPLY)

LOX/HYDROCARBON
Auxiliary Propulsion System Study
FINAL SUMMARY REPORT

ORIGINAL DOCUMENT
OF PROGRAM REPORT

REPORT MDG E2576
JULY 1982

- ELECTRIC PUMPS USED TO RE-SUPPLY RCS ACCUMULATORS
- GASEOUS O₂ ACCUMULATOR VOLUME = 13.8 FT³
- RE-SUPPLY CONDITIONS
 - FLOWRATE = 3.3 LBM/SEC
 - TEMPERATURE = 425°R
 - PRESSURE = 500 PSIA
- ACCUMULATOR RE-SUPPLY SWITCHING PRESSURES
 - INITIATION = 350 PSIA
 - CUT-OFF = 500 PSIA

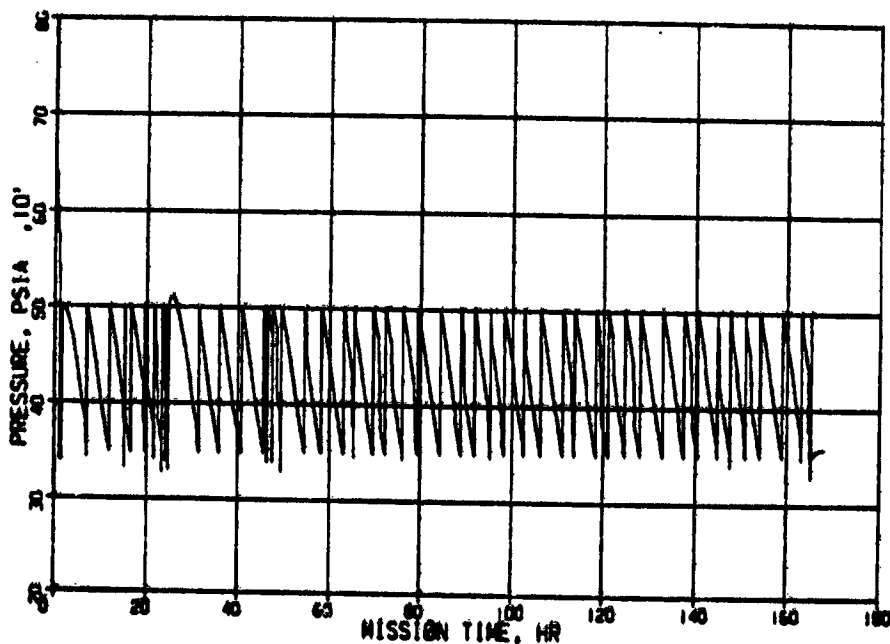
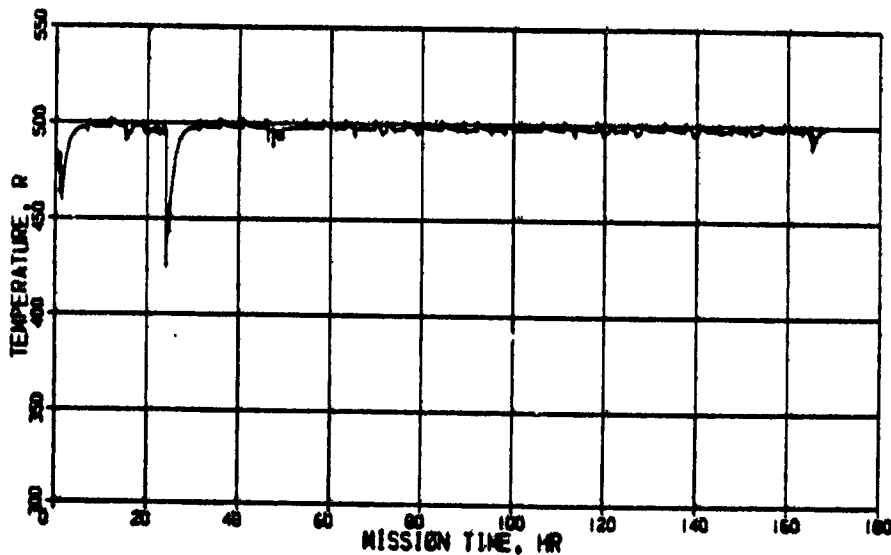


FIGURE 26 RCS GOX ACCUMULATOR MISSION RESPONSE
(ELECTRIC PUMP RESUPPLY)

O₂ 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 6 which eliminates the use of hot, fuel-rich gas generator products to thermally condition the O₂.

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

The selected baseline feed systems for LOX/ethanol and LOX/methane are shown in Figures 27 and 28, 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 O₂ and liquid ethanol to the thrusters through uninsulated accumulators and feedlines. The O₂ 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 sensitivity analyses are presented in Reference (2), however, the chamber pressure optimizations are summarized in the following paragraphs.

The weight sensitivity of the LOX/ethanol system to OMS engine chamber pressure is shown in Figure 29. 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

ORIGINAL FILED IN
 OF POOR QUALITY

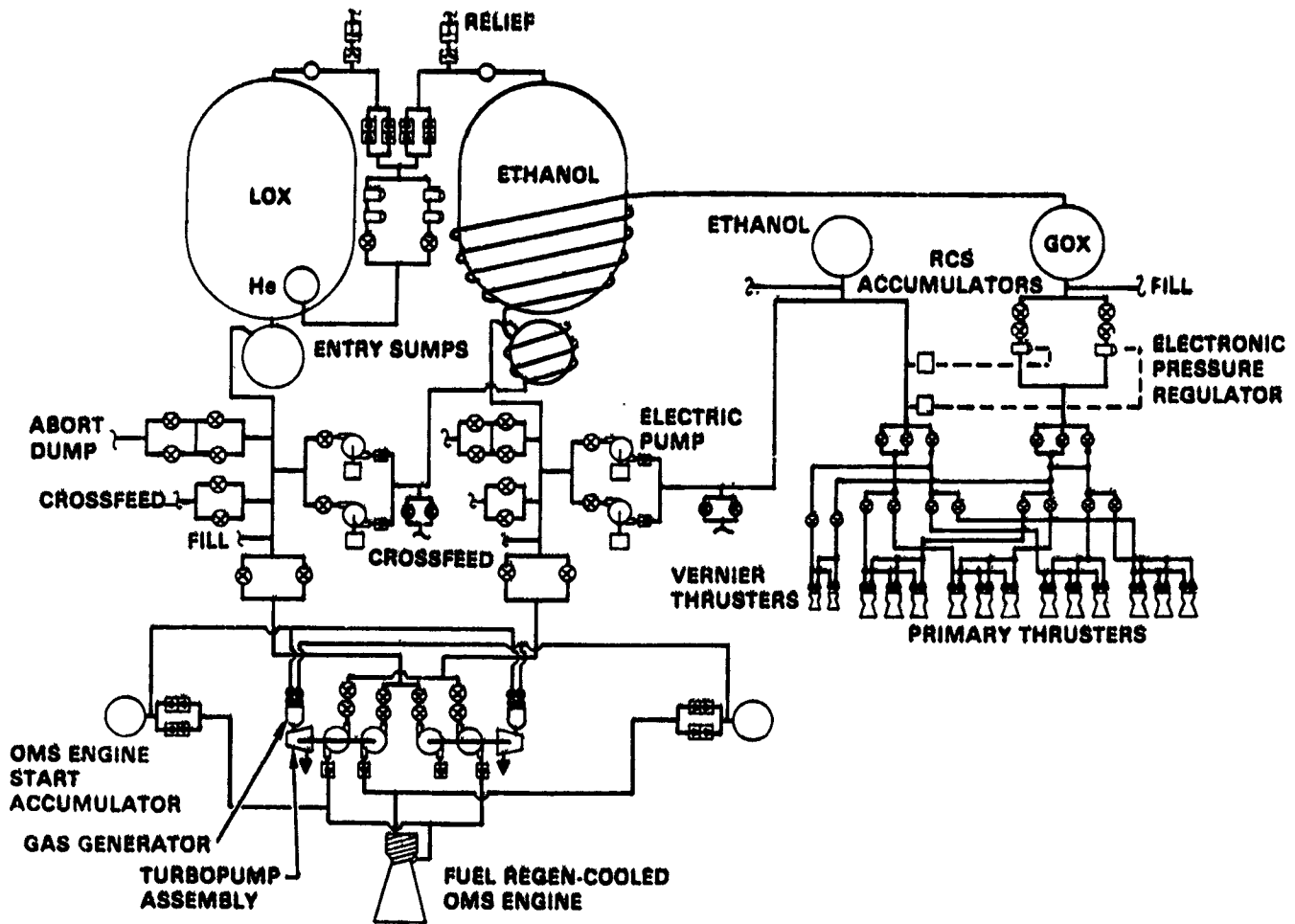


FIGURE 27 BASELINE LOX/ETHANOL OMS-ARCS

ORIGINAL DRAWING
OF POOR QUALITY

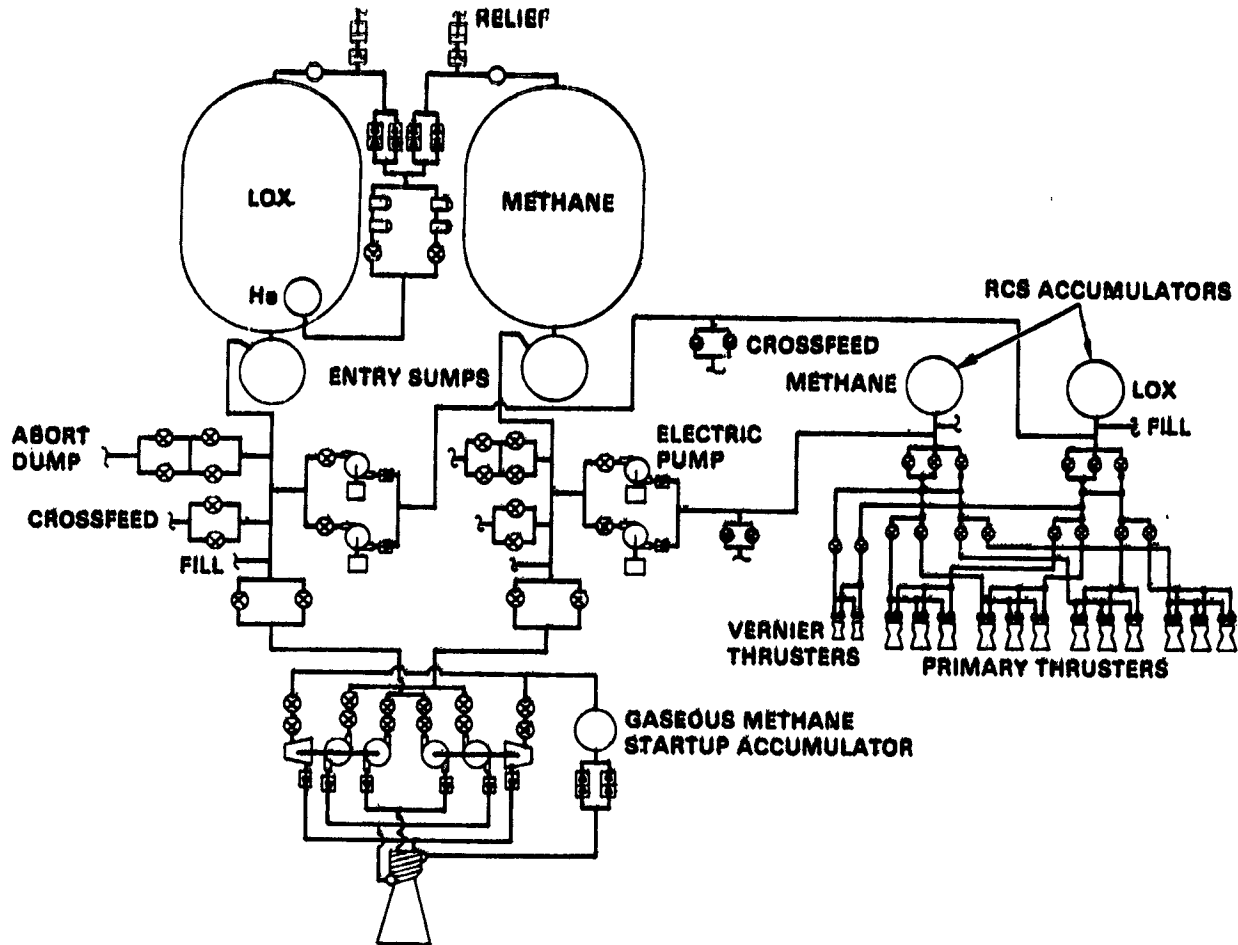


FIGURE 28 BASELINE LOX/METHANE OMS-ARCS

**ORIGINAL PAGE IS
OF POOR QUALITY**

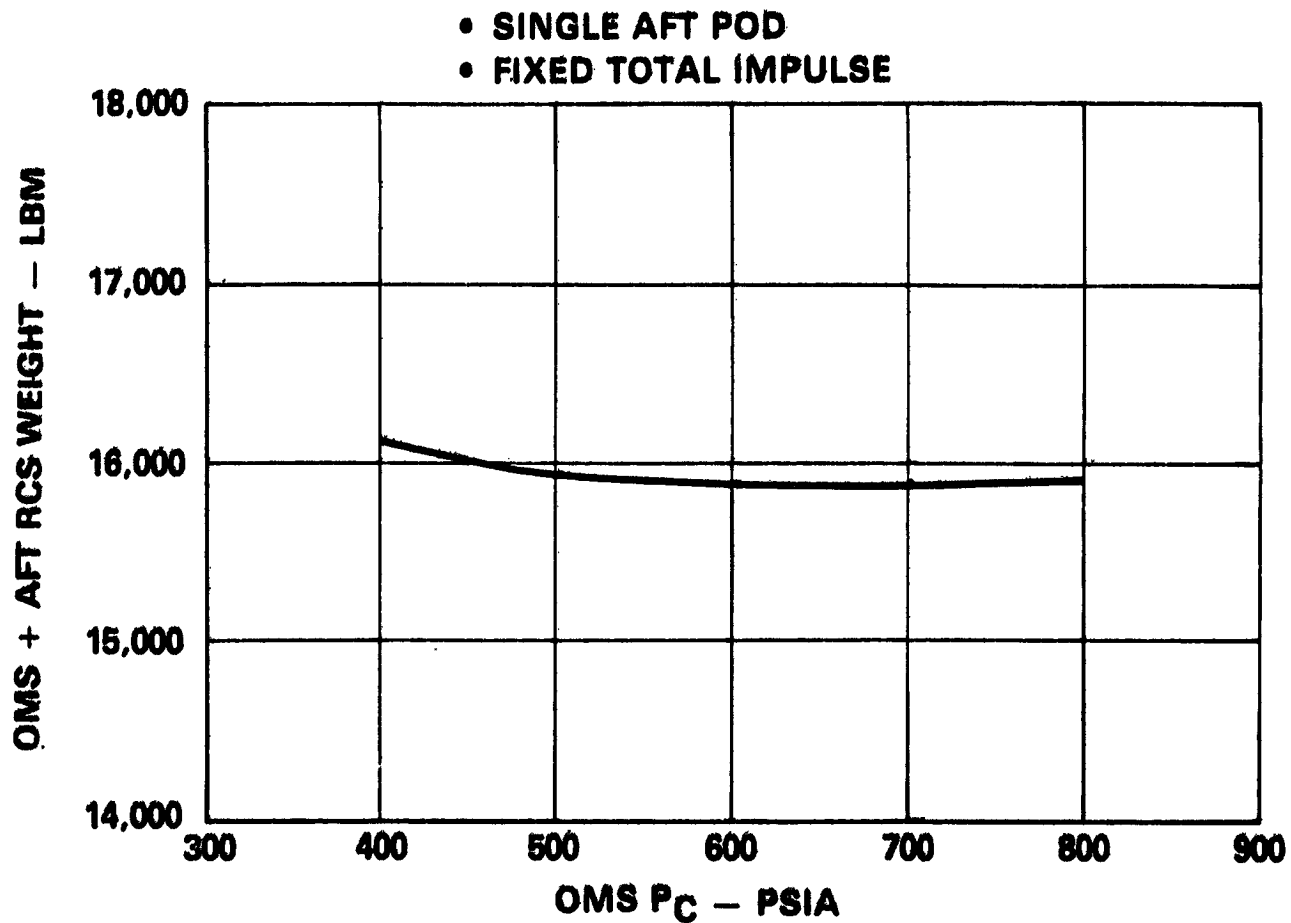


FIGURE 29 SENSITIVITY OF LOX/ETHANOL SYSTEM TO OMS CHAMBER PRESSURE

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 30. 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.

6.5 Separate versus Common FRCS/Aft Propulsion Tanks

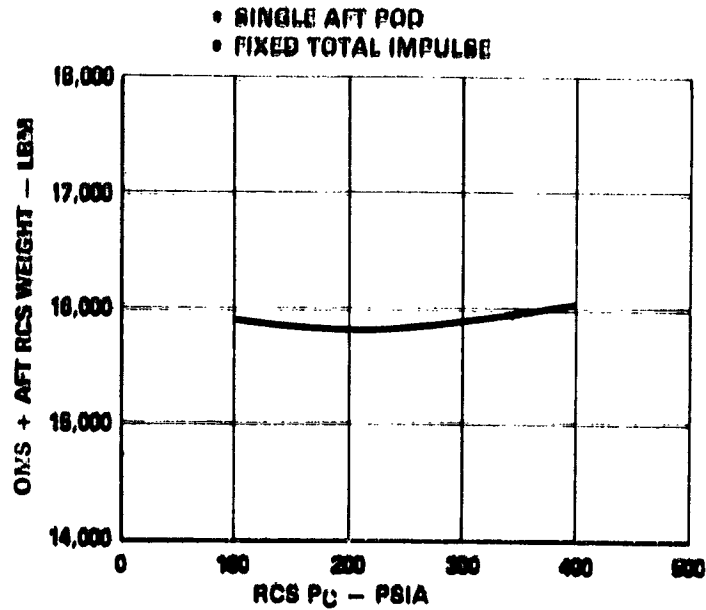
Comparisons of separate versus common propellant tanks for the FRCS and aft propulsion pods are shown in Figure 31. These comparisons were performed for LOX/ethanol with the pod volume constrained to the current dimensions. For the common system feedlines are routed along the length of the Orbiter to interconnect the forward and aft pods (Figure 32). As shown in Figure 31 the common system provides lower OMS ΔV capability due to 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.

6.6 Conventional versus Conical Propellant Tank Shapes

Comparisons of OMS ΔV capability for conventional and conical shaped propellant tanks are presented in Figure 33. 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 33 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

ORIGINAL PAGE 19
OF POOR QUALITY

LOX/ETHANOL



LOX/METHANE

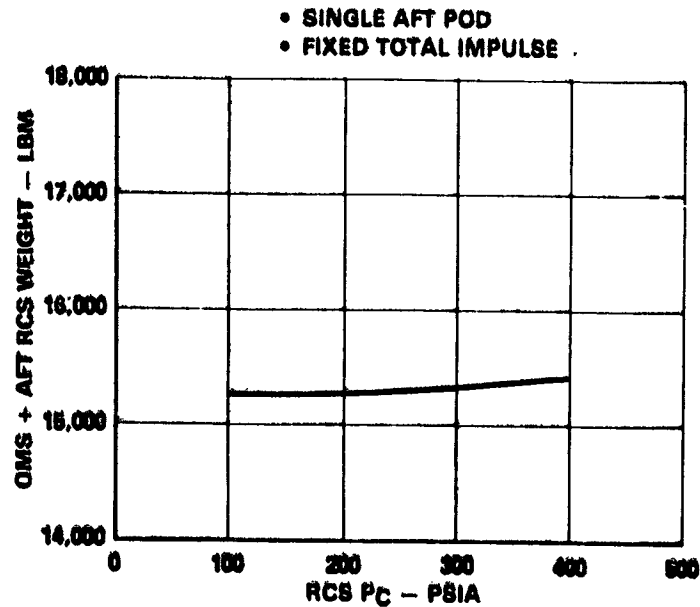


FIGURE 30 SENSITIVITY OF LOX/ETHANOL AND LOX/METHANE SYSTEMS TO RCS CHAMBER PRESSURE

CONFIDENTIAL
CLASSIFIED

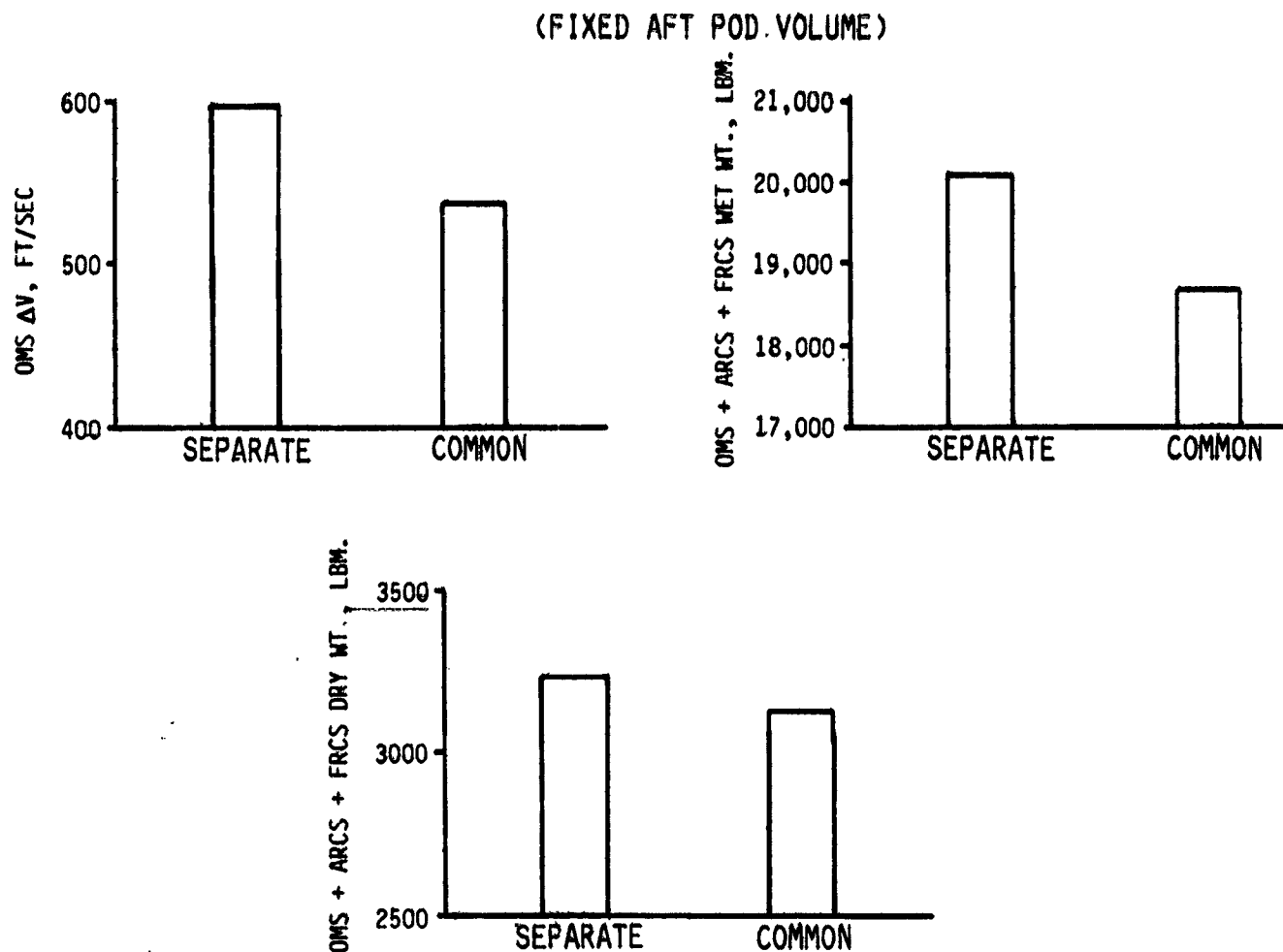


FIGURE 31 SEPARATE VS. COMMON FRCS/AFT PROPULSION TANKS
(LOX/ETHANOL)

**ORIGINAL PAGE 16
OF POOR QUALITY**

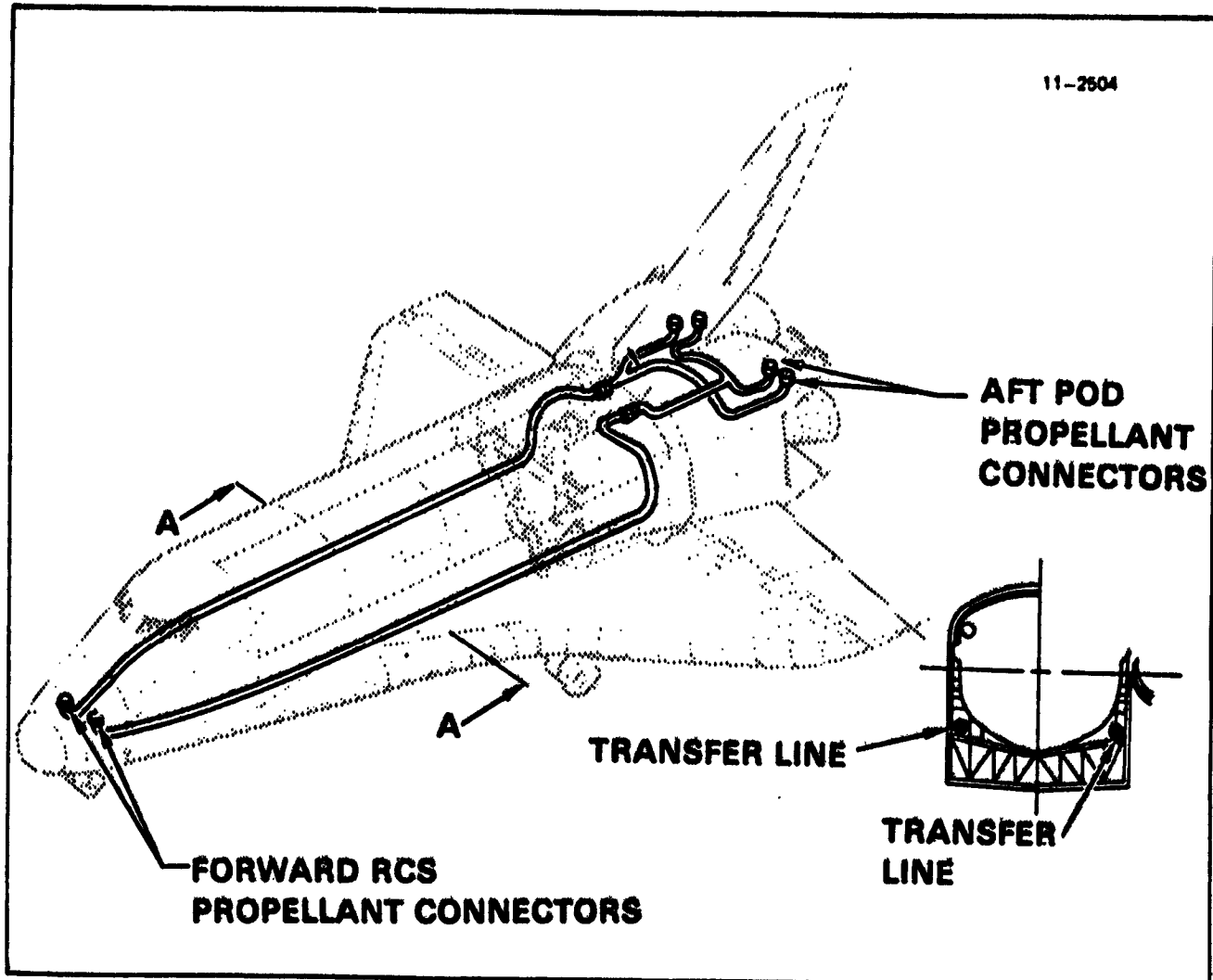


FIGURE 32 INTERCONNECTED FORWARD AND AFT PROPULSION SYSTEMS

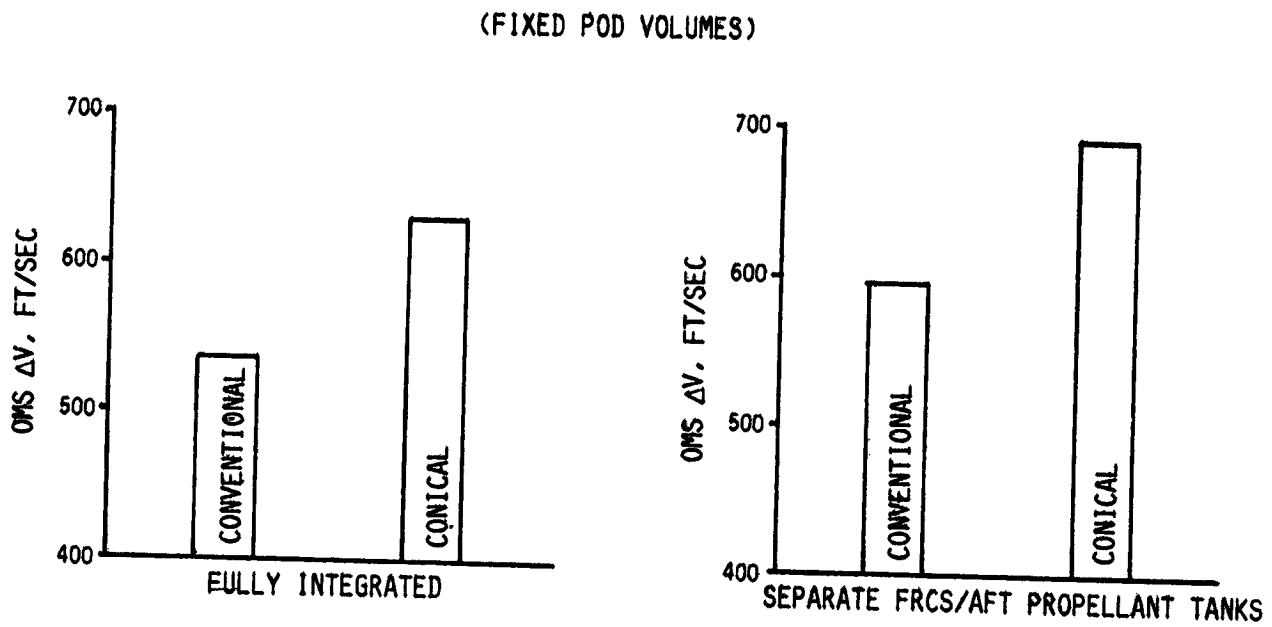


FIGURE 33 CONVENTIONAL VS. CONICAL PROPELLANT TANK SHAPES
(LOX/ETHANOL)

**LOX/HYDROCARBON
Auxiliary Propulsion System Study**

FINAL SUMMARY REPORT

REPORT MDC E2576
JULY 1982

690 ft/sec could be achieved. On the basis of this evaluation it was concluded that a conical propellant tank can provide a substantial increase in ΔV and total impulse capability for a pump fed system.

6.7 Pump versus Pressure Fed FRCS

Comparisons of pressure and electric pump fed FRCS are presented in Figure 34. 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 34 the pressure fed FRCS has lower wet and dry weights. As such a pressure fed system 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.

6.8 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/H₂ system, as well as the current storable OMS-ARCS. The resulting weight and performance comparisons are presented in Figure 35. The LOX/H₂ system was configured to the same groundrules as the LOX/methane OMS-ARCS (Figure 28) 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 O₂ supply to a superheated vapor (Figure 27).

(FIXED TOTAL IMPULSE)
CHAMBER PRESSURE = 100 PSIA

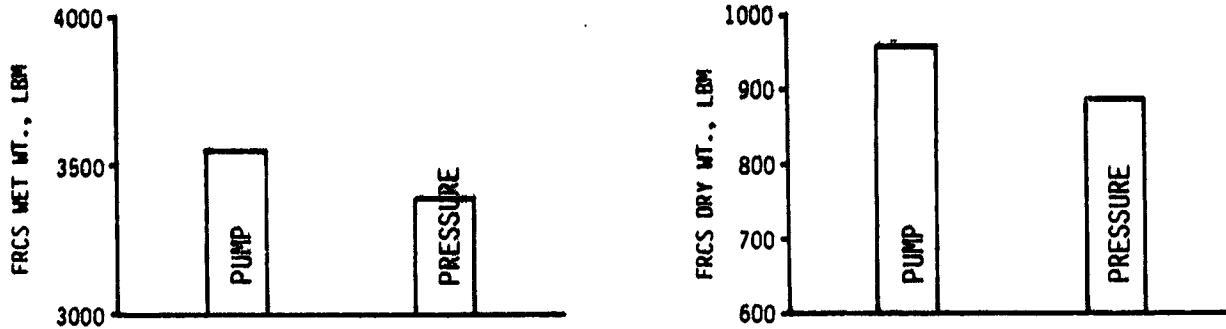


FIGURE 34 PUMP VS. PRESSURE FED FRCS (LOX/METHANE)

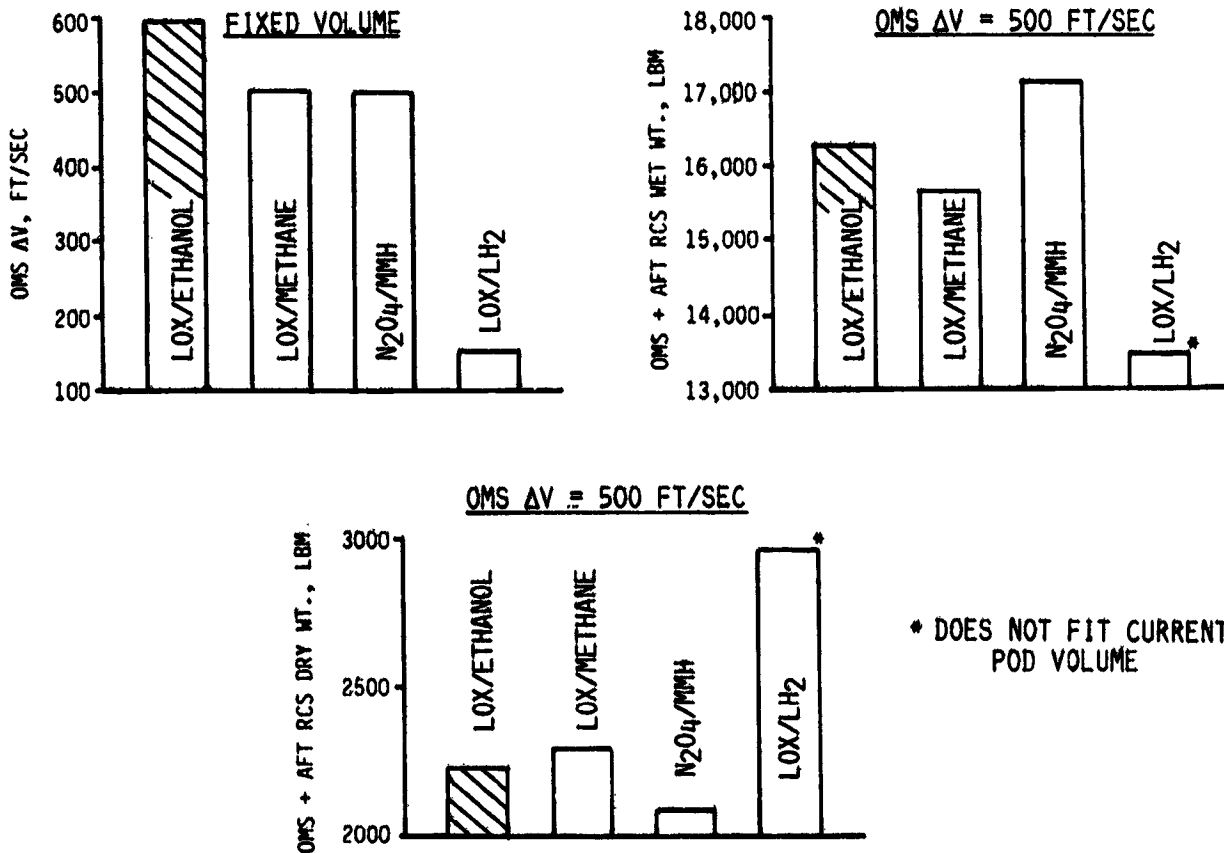


FIGURE 35 COMPARISON OF LOX/HC, LOX/H₂, AND N₂O₄/MMH OMS+ARCS

7.0 CONCLUSIONS AND RECOMMENDATIONS

The overall study conclusions are summarized in Table X. An integrated LOX/ethanol OMS-ARCS (Figure 27) 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 (4)--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 XI, while recommendations for future feed system studies are summarized in Table XII.

TABLE X
OVERALL STUDY CONCLUSIONS

BEST FUEL - ETHANOL

- HIGHEST ΔV & 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 & OXID PUMPS
 - OVERRIDING WEIGHT & PERFORMANCE 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 FT³ MORE PROPELLANT VOLUME THAN SEPARATE TANKS)
 - HIGH ΔV & 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 SEC. HIGHER THAN TURBOPUMP RCS I_{sp})
- HYBRID AMBIENT TEMPERATURE RCS PROPELLANT FEED (GOX/LIQUID ETHANOL) (NO ACCUMULATOR OR FEEDLINE INSULATION REQUIRED)
- PASSIVE ETHANOL TANK HEAT EXCHANGER FOR O₂ THERMAL CONDITIONING
 - LOW FEED SYSTEM COMPLEXITY (NO GAS GENERATORS FOR THERMAL CONDITIONING)
 - NO I_{sp} PENALTY (GAS GENERATOR VENT LOSS)

TABLE XI
NEW TECHNOLOGY REQUIREMENTS

FEED SYSTEM

- THERMAL MANAGEMENT SYSTEM FOR CRYOGENIC LOX TANK
 - INSULATION
 - THERMODYNAMIC VENT
 - AUXILIARY COOLING
- PASSIVE ETHANOL TANK O₂ 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, & PERFORMANCE CORRELATIONS
- LOX/ETHANOL RCE
 - IMPROVED HEAT TRANSFER CHARACTERIZATIONS
 - PULSE MODE PERFORMANCE CAPABILITY & CYCLE LIFE

TABLE XII
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 & 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 O₂ HEAT EXCHANGER
 - REALISTIC RCS THRUSTER PRESS./TEMP. BOXES TO BEGIN THRUSTER DEVELOP.
- DEFINITION OF SYSTEM CONTROLS & FAILURE DETECTION/ISOLATION REQUIREMENTS
- DEFINITION OF COMPONENT ROM COSTS & 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. G.F. Orton, T.D. Mark, and D.D. Weber, "LOX/Hydrocarbon Auxiliary Propulsion System Study Final Report," McDonnell Douglas Corporation Report No. MDC E2548, July 1982.
4. "Combustion Performance and Heat Transfer Characterization of LOX/Hydrocarbon Type Propellants," NASA JSC Contract Number NAS 9-15958.