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LOX/HYDROCARBON AUXILIARY PROPULSION FOR THE SPACE SHUTTLE ORBITER

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Abstract

This paper describes the completed phases in a study to evaluate LOX/Hydrocarbon (HC) auxiliary propulsion system concepts for a "second generation" Space Shuttle Orbital Maneuvering Subsystem (OMS) and Reaction Control Subsystem (RCS). The work is being performed by the McDonnell Douglas Astronautics Company-St. Louis (MDAC-STL) under a contract with the NASA Lyndon B. Johnson Space Center (JSC) - NAS9-16305. Aerojet Liquid Rocket Company (ALRC) is developing engine system data under a subcontract with MDAC-STL. The study was initiated in January 1981 and will be completed in July 1982. Ms. Joyce Seriale-Grush is the NASA Project Manager.

The overall study approach is to compare candidate LOX/HC propulsion system concepts and to evaluate major system/component design options. The study has two phases: Phase I--Preliminary System Evaluation and Phase II--In-Depth System Evaluation. Phase I was broad in scope and was structured to evaluate a large number of candidate system concepts and propellant combinations in order to identify high value concepts for detailed evaluation. In Phase II the depth of system evaluation was increased to provide greater confidence in the definition of relative advantages and limitations of the remaining concepts and to identify primary areas requiring advanced technology effort.

On the basis of the effort to date a pump-fed LOX/ethanol OMS-RCS is the most promising system concept. The LOX/ethanol propellant combination is clean burning (non-coking) and affords the highest ΔV and total impulse capability of the propellants considered.

Introduction

During the last two decades spacecraft propulsion systems have almost exclusively employed simple pressure-fed systems using earth storable propellants such as monopropellant hydrazine (N_2H_4) or hypergolic bipropellant combinations such as nitrogen tetroxide (N_2O_4) and monomethylhydrazine (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 Shuttle Orbiter.

During the early 1970's various studies[1-3] considered the use of LOX/H_2 for the Shuttle auxiliary propulsion systems. However, two inherent characteristics of liquid H_2--a low density and low storage temperature--impose severe penalties on a reusable system such as the Shuttle Orbiter in terms of dry weight and volume.

The LOX/HC propellants possess many of the desirable characteristics of LOX/H_2 while avoiding its disadvantages. They are low in toxicity, noncorrosive, and low in cost. The hydrocarbon fuels also have a high density compared to liquid H_2 which allows much lower fuel tank volumes. During evolution of the Space Shuttle design LOX/HC propellants were considered for the Orbiter OMS-RCS[4]. However, 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 schedule and develoment cost goals of the Orbiter.

This study is part of a NASA-JSC effort to identify viable propulsion designs and propellant combinations to replace N_2O_4/MMH for future spacecraft auxiliary propulsion systems and to develop the technology base for future systems development. Initial contracted efforts have been directed towards basic combustion and heat transfer processes: NAS9-15724-Photographic Combustion Characterization of LOX/HC Type Propellants[5]; and NAS9-15958-Combustion Performance and Heat Transfer Characterization of LOX/HC Type Propellants[6].

The purpose of this study is to provide overall LOX/HC propulsion system characterization. The study approach is to use the Shuttle Orbiter OMS-RCS requirements as a basis for comparing LOX/HC propulsion systems.

The technical effort is being conducted in two phases. Phase I was a preliminary evaluation to screen a large number of system concepts and propellant combinations. Phase II is an in-depth evaluation of the most promising system and propellant concepts resulting from Phase I.

The following paragraphs summarize the results from Phase I and describe the effort being conducted in Phase II.

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Phase I Evaluations and Results

The approach in Phase I was to evaluate candidate fuel and system options assuming the LOX/HC propulsion systems would be packaged within the same pod moldline as the current OMS-RCS. The current OMS and aft-RCS are packaged in pods installed on the Orbiter aft fuselage. These pods are built by McDonnell Douglas Astronautics Company in St. Louis. As shown in Figure 1 each pod contains OMS-RCS 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 MMH and N_2O_4. A forward RCS module is installed in the nose of the Orbiter which is similar in design to the aft-RCS.

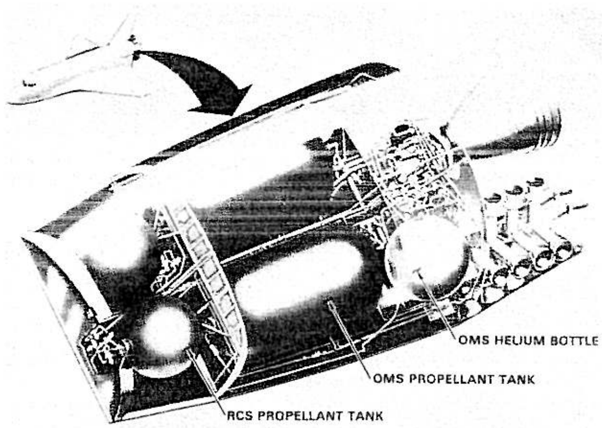

Fig. 1 Orbiter aft propulsion subsystem pod

The candidate fuels selected for the study are identified in Table I and represent each of the major propellant classes. They are low in cost and toxicity, non-corrosive, and possess a good technology base for engine development. Even though ammonia is not a hydrocarbon it was selected because it is clean burning and was used with LOX in the X-15 rocket engine system. RP-1 was not selected 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. Instead, ethanol (ethyl alcohol) was selected to represent the earth storable fuel class because it is non-coking, was used with LOX in the early Navaho, Redstone, and X-15 engine systems, and has an acceptably high vapor pressure. (The vapor presure of ethanol is greater than MMH). The final two fuel candidates, propane and methane, were selected because they were being investigated in current engine system technology contracts with NASA-JSC[5-6].

In order to limit the number of system concepts to be considered, only the key feed system and tankage options were selected for evaluation in Phase I. The overall Phase I system evaluation matrix is shown in Table II. The method of system evaluation is described below for two of the system design options--pump versus pressure fed OMS and cryogenic versus ambient propellant temperature fed RCS.

Table I Candidate fuel matrix

		FUELS SELECTED FOR PHASE I
EARTH STORABLE	(BOILING POINTS MUCH GREATER THAN AMBIENT)	
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)

Table II Phase I system evaluation matrix

DESIGN OPTIONS	CANDIDATE FUELS			
	ETHANOL	METHANE	PROPANE	AMMONIA
PUMP VS. PRESSURE FEED	√	√	√	√
NBP VS. SUBCOOLED LIQUID STORAGE			√	
CRYOGENIC VS. AMBIENT RCS FEED	√	√	√	√
DEGREE OF OMS/RCS INTEGRATION	√	√	√	√
BLOWDOWN VS. REGULATED PUMP NPSP			√	
TANK INSULATION OPTIONS FEEDLINE INSULATION OPTIONS	LOX			

Pump Versus Pressure Fed OMS

A schematic for the pump-fed OMS that incorporates the same fail operational-fail safe component redundancy as the current pressure fed OMS is shown in Figure 2. Pump net positive suction pressure (NPSP) is provided by a regulated helium pressurization system. The turbines are powered by bipropellant gas generators which are fed from liquid accumulators during start-up. Cryogenic propellants (LOX and methane) are fed to the OMS engine as liquids and are vented from the feedlines following each engine burn. The engine is fuel regeneratively cooled and employs a gaseous nitrogen valve actuation system similar to the current OMS engine.

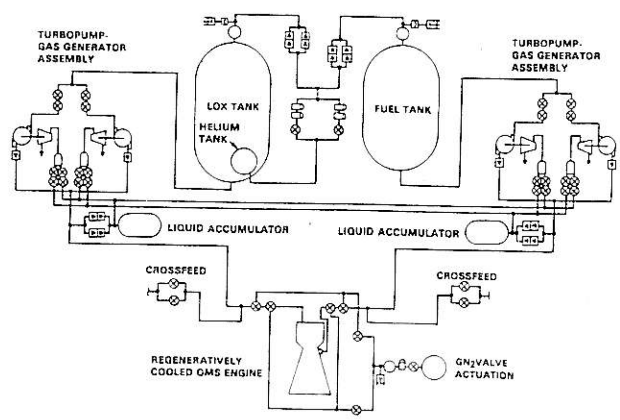

Fig. 2 LOX/HC OMS turbopump system

Comparisons of pump and pressure fed LOX/HC OMS are presented in Figure 3. Chamber pressures of 800 and 100 psia were found to be near-optimum for the pump and pressure-fed systems, respectively. Three criteria are used in the comparisons--OMS ΔV capability, OMS wet weight, and OMS dry weight. To compare ΔV capability the system volume was constrained to the current pod volume. To compare wet and dry weights the total impulse (ΔV capability) was set equal to the current OMS value. Because of their higher specific impulse the pump-fed OMS offer overriding advantages in terms of ΔV capability, wet, and dry weights. The LOX/ethanol OMS offers the highest ΔV capability since it affords the largest density - specific impulse product of the candidate hydrocarbon systems.

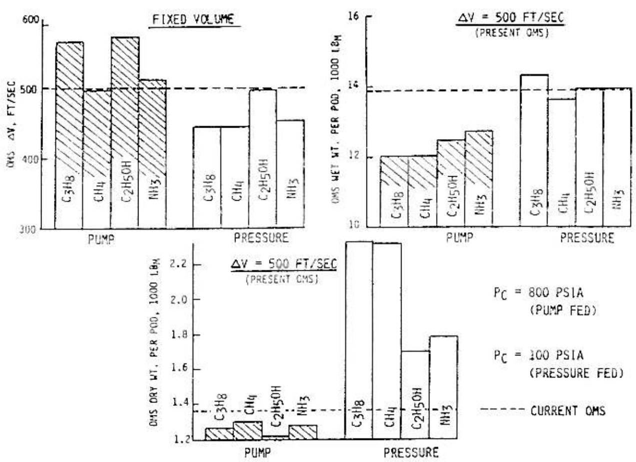

Fig. 3 Comparison of pump and pressure-fed OMS

Cryogenic Versus Ambient Fed RCS

A schematic for an ambient propellant temperature fed RCS is shown in Figure 4. This is hybrid system concept that is applicable to ethanol, propane or ammonia fuels (i.e., earth storable or space storable fuels that can be reliably distributed to the RCS thrusters in the liquid phase). As shown in Figure 4, the LOX is thermally conditioned to a superheated vapor by gas generator-turbine exhaust products. For deep cryogenic fuels such as methane both the fuel and oxidizer are thermally conditioned to a superheated vapor. These RCS concepts are categorized as ambient fed systems. The primary advantage of the ambient fed RCS is the elimination of insulation from the propellant feedlines. Ambient and cryogenic fed RCS are compared in Figure 5 using the same criteria employed for the previous OMS comparisons. A chamber pressure of 250 psia was selected because it was found to be near optimum for a pump-fed RCS. From the comparisons of Figure 5 it is seen that the ambient fed RCS provide lower total impulse capability and are substantially heavier than the cryogenic fed systems. This is because of the specific impulse penalties associated with thermally conditioning the cryogenic propellant. For the LOX/methane system, where both propellants are thermally conditioned, the specific impulse penalty is most severe. As in the case of the OMS, the LOX/ethanol RCS affords the greatest total

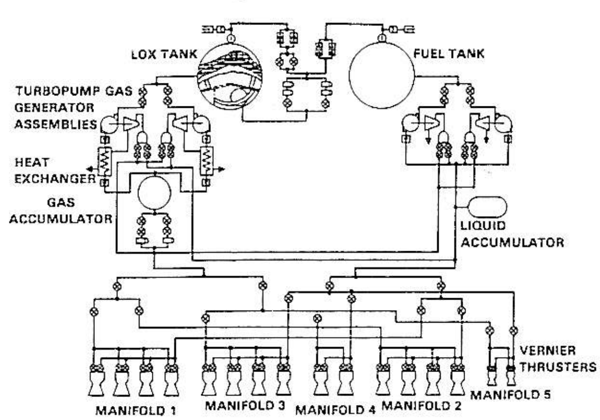

Fig. 4 LOX/HC RCS ambient feed system (hybrid)

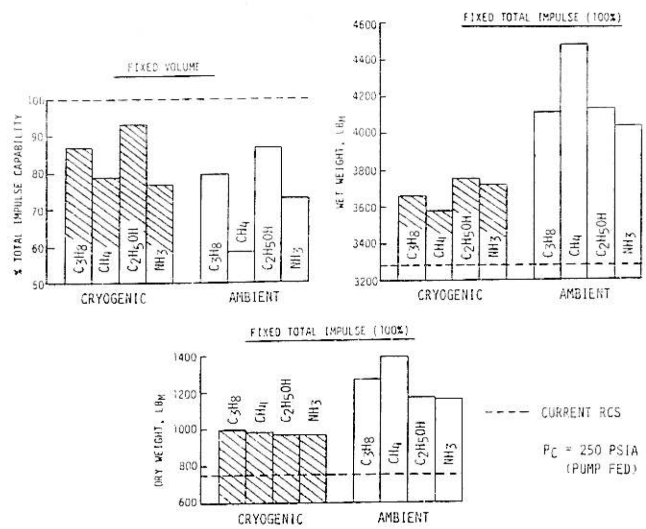

Fig. 5 Comparison of cryogenic and ambient fed RCS

impulse capability as a result of its higher density - specific impulse. For the purpose of providing higher performance capability and lower weight in a LOX/ethanol ambient fed RCS, it was decided to investigate passive LOX thermal conditioning in Phase II. Passive conditioning was judged to be feasible in the LOX/ethanol system because of its low mixture ratio (lower O_2 flow) compared to the other hydrocarbon systems.

Summary of Phase I Results and Recommendations

Similar evaluations were performed for the other system design options of Table II and the results are summarized in Table III. Ethanol and methane are considered to be the best fuel candidates as both are non-coking and offer high performance capability. Ethanol affords the highest ΔV and total impulse capability because of its high density-specific impulse product. Methane affords the lowest system wet weight (highest payload capability) when the system is sized for a fixed ΔV or total impulse requirement.

On the basis of the system evaluation results summarized in Table III, the following groundrules were established for the Phase II effort:

(1) gas generator cycle LOX/ethanol OMS
(2) expander cycle LOX/methane OMS (increased performance)
(3) single turbine driving both fuel and oxidizer pumps (fewer feed systems components)
(4) regulated helium for pump NPSP (lower weight)
(5) common OMS-aft RCS tanks with external entry propellant sumps (better packaging and total impulse capability; fewer feed system components)

Table III Summary of phase I results and recommendations

FUELS:	ETHANOL AND METHANE ARE BEST FUEL CANDIDATES
SYSTEMS:	• PUMP FED OMS PREFERRED OVER PRESSURE FED OMS. CONSIDER METHANE EXPANDER CYCLE FOR INCREASED PERFORMANCE & COLD TURBINE OPTION
	• PUMP VS. PRESSURE FED RCS REQUIRES FURTHER EVALUATION. CONSIDER ELECTRIC PUMPS FOR RCS FEED
	• AMBIENT FED LOX/METHANE RCS CONSIDERED IMPRACTICAL BECAUSE OF EXCESSIVE ENERGY REQUIREMENTS FOR THERMAL CONDITIONING
	• AMBIENT FED LOX/ETHANOL RCS WITH PASSIVE LOX THERMAL CONDITIONING REQUIRES FURTHER EVALUATION
	• COMMON OMS-AFT RCS TANKS BETTER THAN SEPARATE TANKS. POSSIBLE INTEGRATION OF FORWARD RCS WITH AFT PROPULSION SYSTEM REQUIRES FURTHER EVALUATION.
	• REGULATED HELIUM PUMP NPSP SYSTEM PREFERRED OVER BLOWDOWN SYSTEM BECAUSE OF SUBSTANTIAL WEIGHT ADVANTAGE.
	• FURTHER EVALUATIONS REUQIRED FOR TANK/FEEDLINE INSULATION MATERIALS.

The primary results obtained to date during the Phase II effort are discussed in the remaining paragraphs.

Phase II Evaluations and Results

The overall Phase II system evaluation matrix is presented in Table IV. The effort to date has concentrated on the evaluation of LOX/ethanol and LOX/methane OMS-RCS concepts in which electric pumps are used to supply RCS propellants. The use of electric pumps increases RCS specific impulse (since there are no gas generator flow penalties) and reduces the number of OMS turbopump cycles (since the turbopumps are used only for OMS burns). In order to eliminate the need for insulation on the RCS accumulators and feedlines, the LOX/ethanol system employs passive O_2 thermal conditioning to supply the RCS thrusters with gaseous oxygen (GOX) at near ambient temperatures. For the competing LOX/methane system, the thermal conditioning energy penalties for both LOX and methane are excessive, and therefore, insulated RCS accumulators and feedlines are used to maintain the propellants as cryogenic liquids throughout the mission. Results from thermal analyses to determine system feasibility and chamber pressure sensitivity evaluations to determine optimum design points are presented below for each of these systems.

Table IV Phase II system evaluation matrix

DESIGN OPTIONS	FUEL CANDIDATES: ETHANOL	FUEL CANDIDATES: METHANE
PUMP VS. PRESSURE FED-RCS	√	
CRYOGENIC VS. AMBIENT RCS FEED	√	
SEPARATE VS. COMMON FORWARD /AFT TANKS	√	
OMS ENGINE EXPANDER CYCLE		√
ELECTRIC PUMPS FOR RCS FEED	√	√
CONVENTIONAL VS. NON-CONVENTIONAL TANK SHAPES	√	
TANK/FEEDLINE INSULATION & COOLING OPTIONS	LOX & METHANE	

LOX/Ethanol OMS-RCS

A simplified schematic of the LOX/ethanol OMS-RCS is shown in Figure 6. This system differs from those evaluated in Phase I in that: (1) a single turbine is used to drive the OMS fuel and oxidizer pumps; (2) small electric pumps are used to resupply the RCS accumulators; and (3) an ethanol tank passive heat exchanger is used to thermally condition the O_2 to a superheated vapor before supplying it to the RCS accumulator. Thermal analyses were performed using specialized computer codes to assess the effectiveness of the ethanol tank heat exchanger and to determine if reasonable accumulator temperature variations could be achieved during the RCS mission.

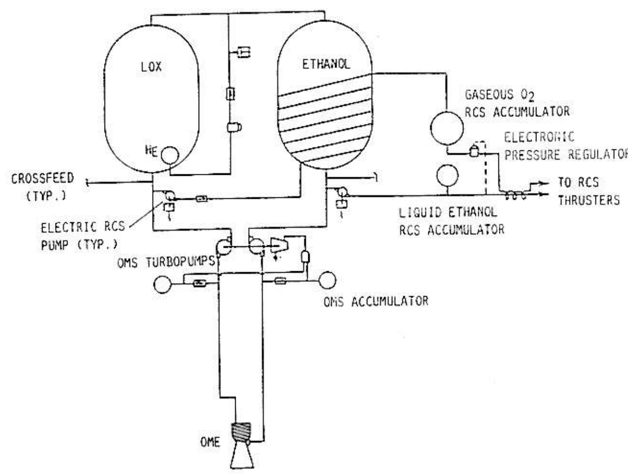

Fig. 6 Simplified LOX/ethanol OMS-RCS schematic (ambient RCS feed)

The ethanol tank heat exchanger model is illustrated in Figure 7. The O_2 heat exchanger line is attached to the outside wall of the ethanol tank and absorbs heat from the tank wall, liquid ethanol, and the environment. The heat exchanger line is divided into segments, and the energy and mass conservation equations are solved for each segment. The performance of this heat exchanger concept is shown in Figures 8 and 9. Figure 8 shows O_2 inlet and exit temperature over a 7-day OMS-RCS

• O_2 HEAT EXCHANGER LINE ABSORBS HEAT FROM THE TANK, FUEL, AND ENVIRONMENT
• LINE FLOW IS MODELED AS FULLY DEVELOPED TURBULENT FLOW WITH VARIABLE FLUID PROPERTIES.

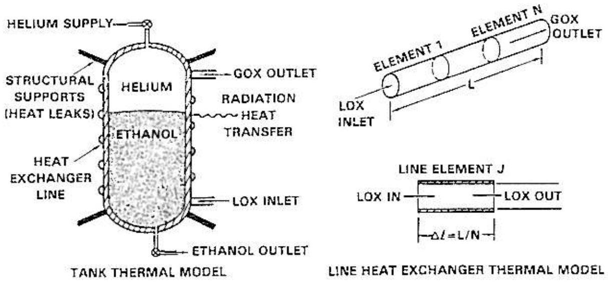

Fig. 7 Ethanol tank passive O_2 heat exchanger model

. 7-DAY MISSION
. HEAT EXCHANGER FLOWRATE = 3.3 LB_M/SEC
. HEAT EXCHANGER O_2 INLET TEMP. = 162°R

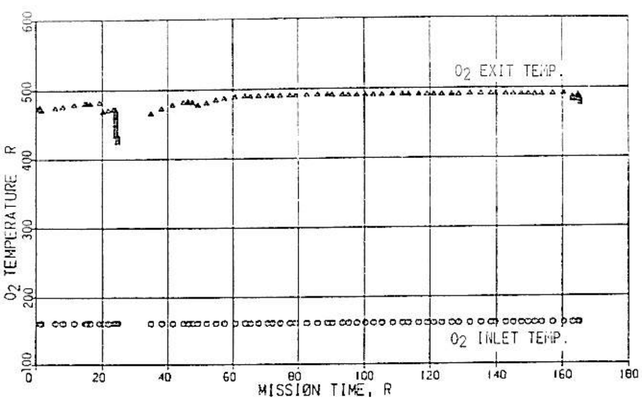

Fig. 8 Ethanol tank passive O_2 heat exchanger performance

mission duty cycle. The heat exchanger O_2 line is sized for a flowrate of 3.3 lbm/sec which is sufficient to meet the back-up RCS deorbit burn requirement for two-aft firing thrusters per pod. As shown in Figure 8, O_2 heat exchanger exit temperature is maintained near 490°R throughout the mission. The coolest exit temperature (425°R) occurs approximately 24 hours into the mission during the period of maximum RCS usage. The corresponding liquid ethanol temperature is shown in Figure 9 along with the quantity of ethanol remaining. The coolest ethanol temperature (430°R) also occurs 24 hours into the mission. These results demonstrate the feasibility of an ethanol tank heat exchanger for thermally conditioning the RCS O_2 accumulator resupply flow.

To further demonstrate the feasibility of this passive O_2 thermal conditioning approach, RCS accumulator pressure-temperature profiles were developed for a 7-day mission. The gaseous O_2 accumulator profiles are shown in Figure 10, and the liquid ethanol accumulator profiles are shown in Figure 11. For these examples the oxidizer and fuel resupply flow temperatures were set equal to

. 7-DAY MISSION
. HEAT EXCHANGER FLOWRATE = 3.3 LB_M/SEC
. HEAT EXCHANGER O_2 INLET TEMP. = 162°R

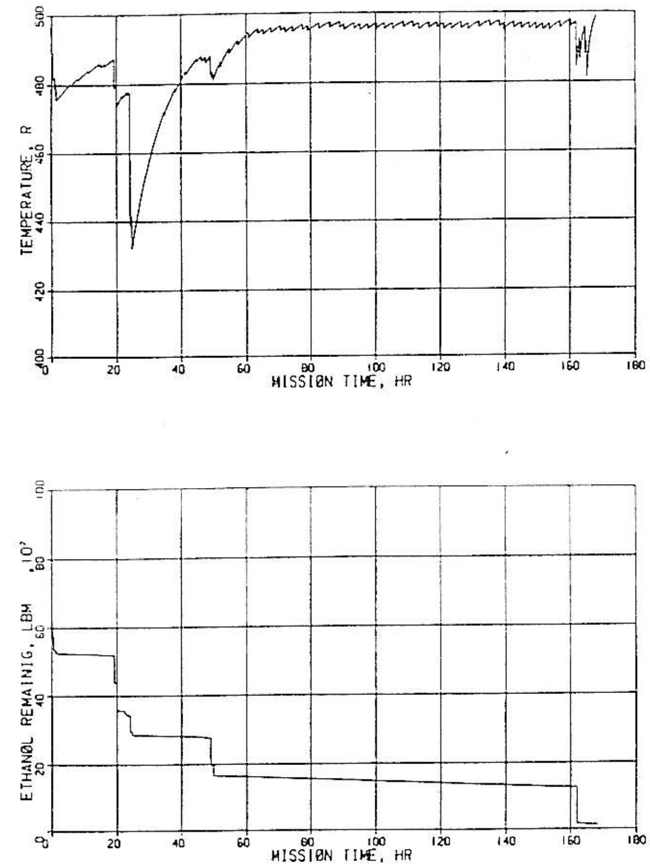

Fig. 9 Ethanol temperature and quantity remaining (passive O_2 heat exchanger concept)

their minimum values (425 and 430°R, respectively). Both accumulators were sized to provide RCS impulse for Shuttle external tank separation without resupply flow. The gaseous O_2 accumulator is charged initially to 1300 psia at ambient temperature and then blows down to 350 psia when resupply flow is initiated after external tank separation. The liquid ethanol accumulator incorporates a helium pressure pad and blows down from 500 to 350 psia before resupply is initiated. Resupply flow is terminated when the accumulator pressure recharges to 500 psia. Despite the variations in accumulator pressures and temperatures, control over RCS thruster mixture ratio is achieved through use of an electronic pressure regulator and thermally-shorted feedlines downstream of the accumulator (Figure 6). 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 thermally shorted feedlines.

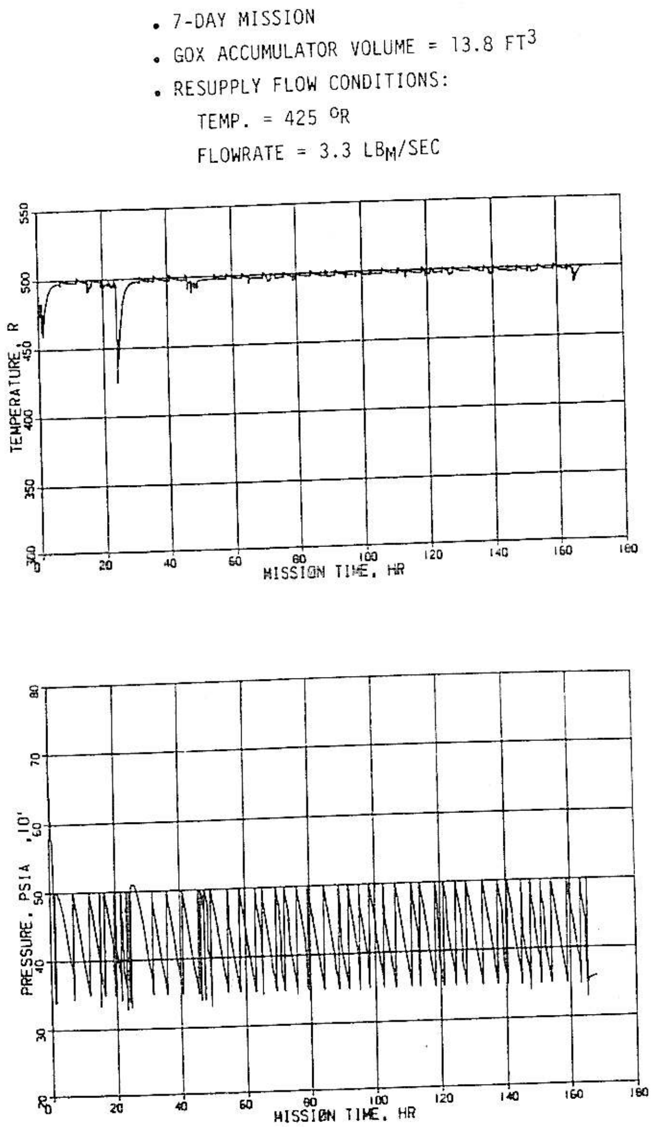

Fig. 10 GOX accumulator press.-temp. history

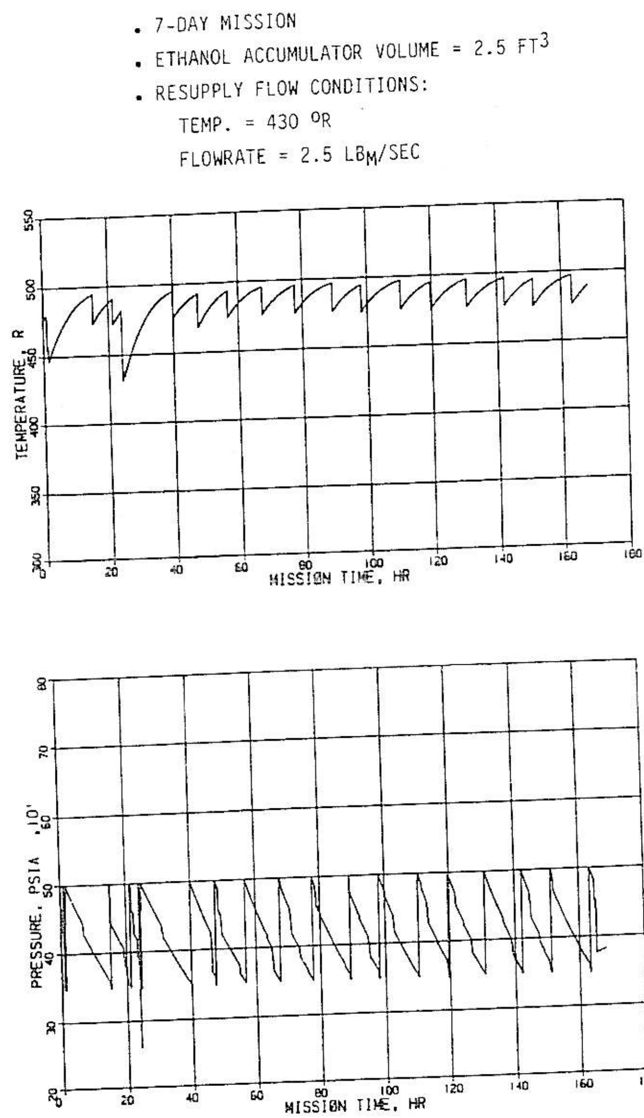

Fig. 11 Ethanol accumulator press.-temp. history

The results of Figures 10 and 11 show that reasonable temperature variations are achieved in the RCS accumulators and further 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 weight sensitivity of this LOX/ethanol system to OMS and RCS chamber pressure is presented in Figure 12. An OMS chamber presure of 600 psia was baselined for this system since it provides the best compromise between system weight and performance and engine cooling margin. An RCS chamber pressure of 100 psia was baselined to minimize electric pump weight and power requirements.

LOX/Methane OMS-RCS

A simplified schematic of the LOX/methane OMS-RCS is shown in Figure 13. This system uses an OMS engine expander cycle in which gaseous methane leaving the engine cooling jacket is expanded through a turbine to drive the pump assemblies. As in the preceeding LOX/ethanol system a single turbine is used to drive both the fuel and oxidizer pumps and electric pumps are used to resupply the RCS accumulators. Because of excessive energy requirements for propellant thermal conditioning, the LOX and methane are fed to the RCS thrusters as cryogenic liquids. As such, thermal analyses were performed using specialized tank and feedline heat transfer codes to determine the effectiveness of candidate insulation materials. The intent of these evaluations was not to develop a detailed insulation system design, but to provide trend data for determining the feasibility of candidate insulation materials.

Two candidate insulation materials were evaluated in Phase II--aluminized mylar multi-layer insulation (MLI) and TG-15000 silica fiber insulation. The TG-15000 insulation is currently employed on the Orbiter aft propulsion subsystem pod internal moldline. It is an attractive insulation material since it is easier to handle and install

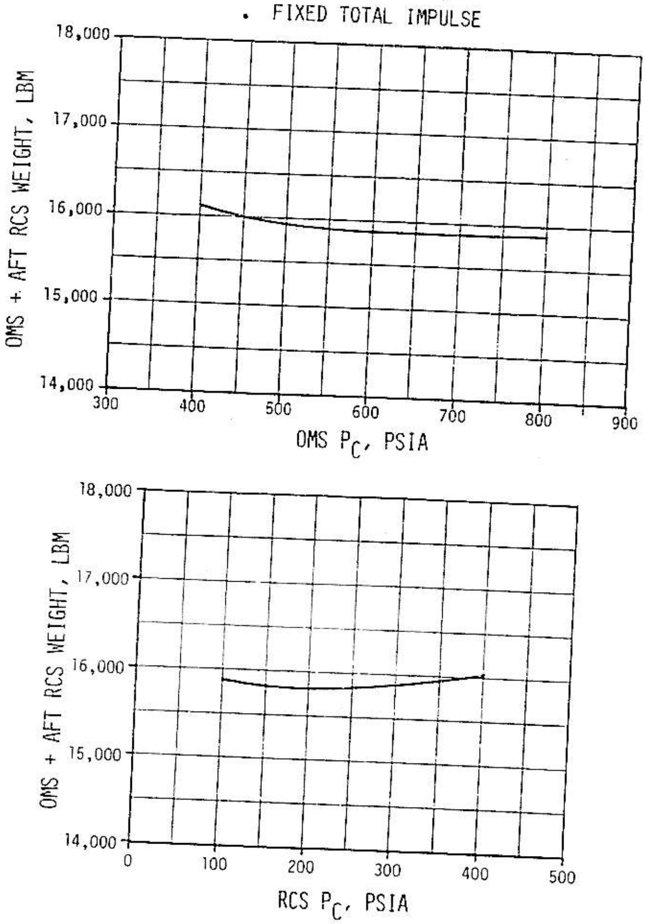

Fig. 12 LOX/ethanol system weight sensitivity to chamber pressure

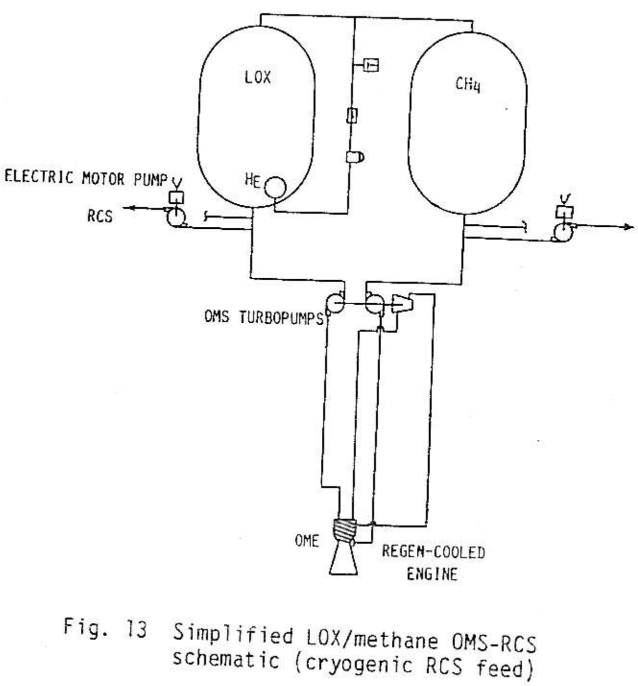

Fig. 13 Simplified LOX/methane OMS-RCS schematic (cryogenic RCS feed)

than MLI, is not as susceptable to moisture degradation (does not require a vacuum cover or jacket), and provides repeatable performance. The properties of the MLI and TG-15000 insulation are compared in Table V. The measure of tank insulation effectiveness is the amount of propellant vent loss (boil-off) that occurs during the mission, while the measure of feedline insulation effectiveness is the maximum thruster inlet propellant temperature attained during the mission.

Table V Properties of candidate insulation materials

PROPERTY		INSULATION TYPE MLI(1)	TG-15000
AMBIENT THERMAL CONDUCTIVITY, BTU/(HR-FT-°R)	(2)	0.05	0.0123
VACUUM THERMAL CONDUCTIVITY, BTU/(HR-FT-°R)	(2)	0.00075	0.000038
HEAT CAPACITY, BUT/(LBM-°R)	(2)	0.2	0.27
DENSITY, LBM/FT^3		2.0	1.14

(1) NCR-2 SINGLY ALUMINIZED MYLAR (50 LAYERS/IN WITH 5% PERFORATION)
(2) PROPERTIES EVALUATED AT A TEMPERATURE OF 180°R

To evaluate tank insulation effectiveness the thermal model shown in Figure 14 was applied. In this model a thermodynamic vent system (TVS) is employed in which a small amount of propellant flow is circulated around the tank through a cooling shroud to intercept the heat input from the environment. Figure 15 shows LOX tank total pressure for a 30-day OMS-RCS mission duty cycle. The tank total pressure is allowed to increase from an initial value of 35 psia to 60 psia before venting is initiated. LOX and methane 30-day vent losses are shown in Figure 16 for a common OMS-RCS tank installed in the aft pod. The vent losses with MLI are about one-half those of TG-15000, but vent losses for either insulation system are considered acceptable for a 30-day mission. For the more frequent 7-day missions, the LOX and methane vent losses with TG-15000 are only 35 and 16 lbm,

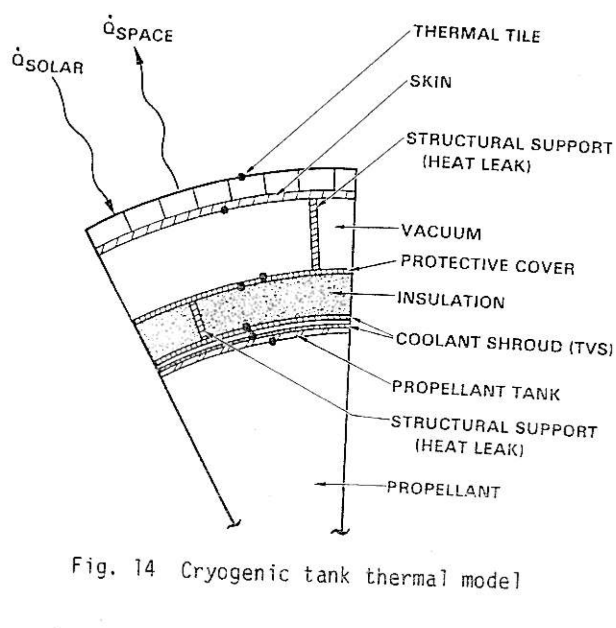

Fig. 14 Cryogenic tank thermal model

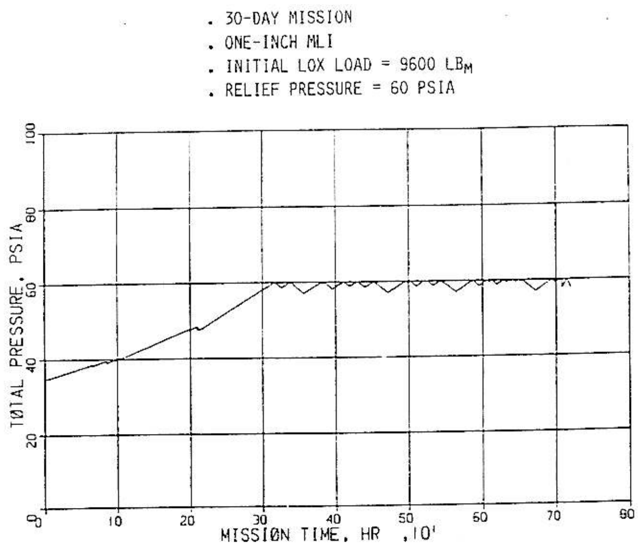

Fig. 15 Common OMS-RCS LOX tank mission pressure profile

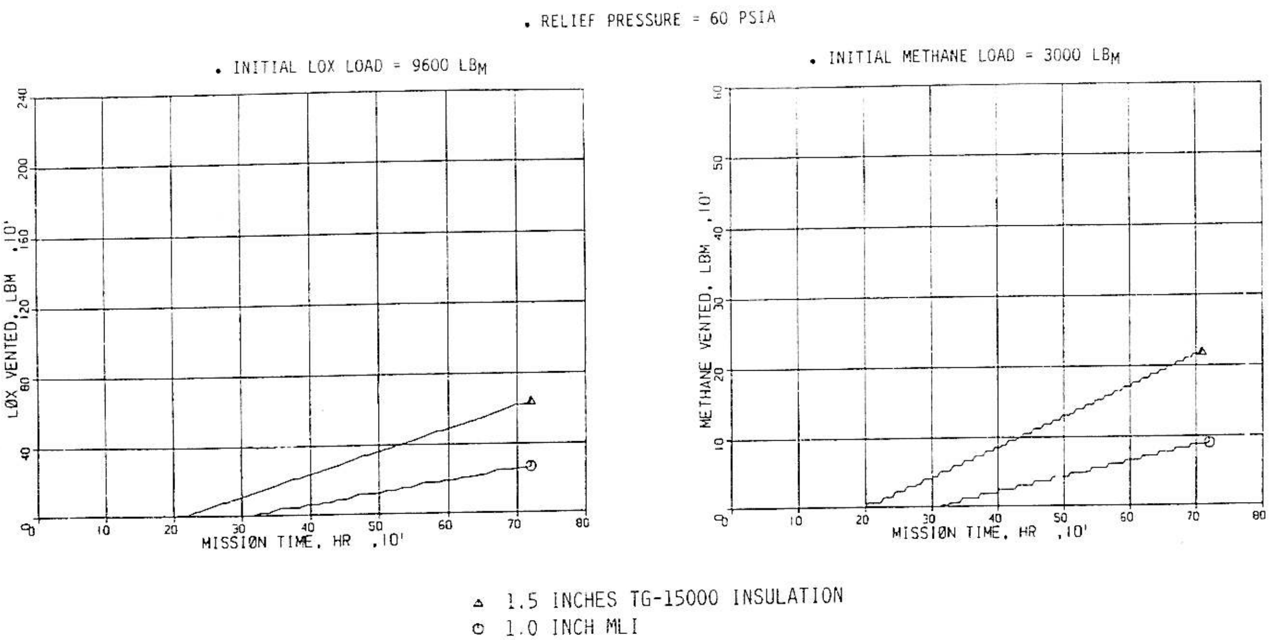

Fig. 16 Propellant vent losses for 30-day mission (Common OMS-aft RCS propellant tank)

respectively. As a result of these analyses a simple TG-15000 tank insulation system was baselined for the LOX/methane propellant tanks. Before a final tank insulation system is selected, more detailed thermal analyses would be required to assess ground-hold and transient launch heating effects.

The RCS feedline thermal model is illustrated in Figure 17. 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. LOX temperature response at the thruster valve, which is the hottest point in the feedline, is shown in Figure 18 for a 7-day mission. In this example one-inch of TG-15000 insulation was assumed on the feedline. As shown, maximum feedline temperatures are maintained below the vaporization limit of 226°R. A summary of maximum LOX feedline temperatures for both TG-15000 and MLI is presented in Figure 19. Here, LOX temperature at the thruster valve is plotted as a function of LOX usage rate

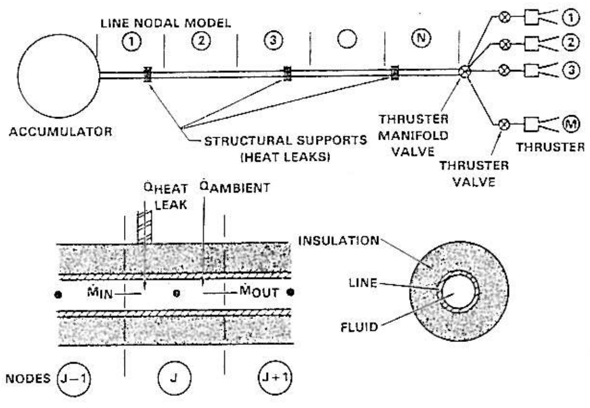

Fig. 17 RCS cryogenic feedline model

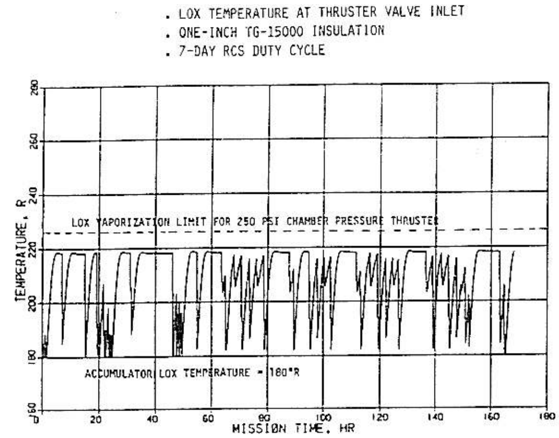

Fig. 18 RCS LOX feedline temperature response

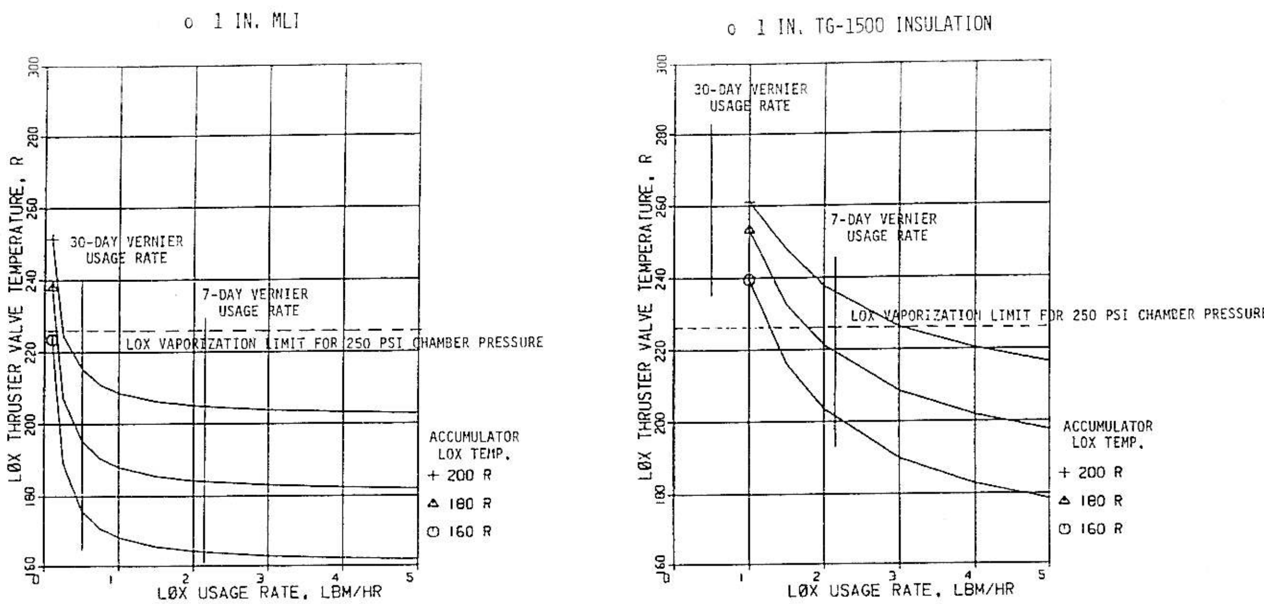

Fig. 19 RCS LOX feedline temperature summaries

and accumulator temperature. As shown, MLI is required to preclude excessive O_2 temperatures for the low usage rates associated with the 30-day mission. Similar data is presented in Figure 20 for methane, and again, the MLI is required for the 30-day mission usage rate. As a result of these analyses a vacuum jacketed MLI system was baselined for the LOX/methane RCS feedlines.

The weight sensitivity of the LOX/methane system to RCS chamber pressure is presented in Figure 21. The OMS chamber pressure was set at 400 psia which is the maximum attainable chamber pressure for achieving required engine cooling and providing sufficient energy for driving the turbine. An RCS chamber pressure of 100 psia was baselined to minimize electric motor weight and power requirements.

Summary

The LOX/ethanol and LOX/methane systems in which electric pumps are used for RCS supply are compared with the current storable OMS-RCS and a LOX/hydrogen OMS-RCS in Figure 22. From this comparison it is seen that the LOX/ethanol OMS-RCS is superior in terms of system ΔV capability and system dry weight. The LOX/ethanol system allows the use of a simple non-insulated RCS feed system, and recent testing[6] has shown that the LOX/ethanol propellant combination is clean burning (non-coking). On the basis of the evaluations performed the date, the LOX/ethanol system is the most attractive LOX/HC OMS-RCS. Because the propellants are low in cost, non-toxic, and non-corrosive, the operational costs for a LOX/ethanol

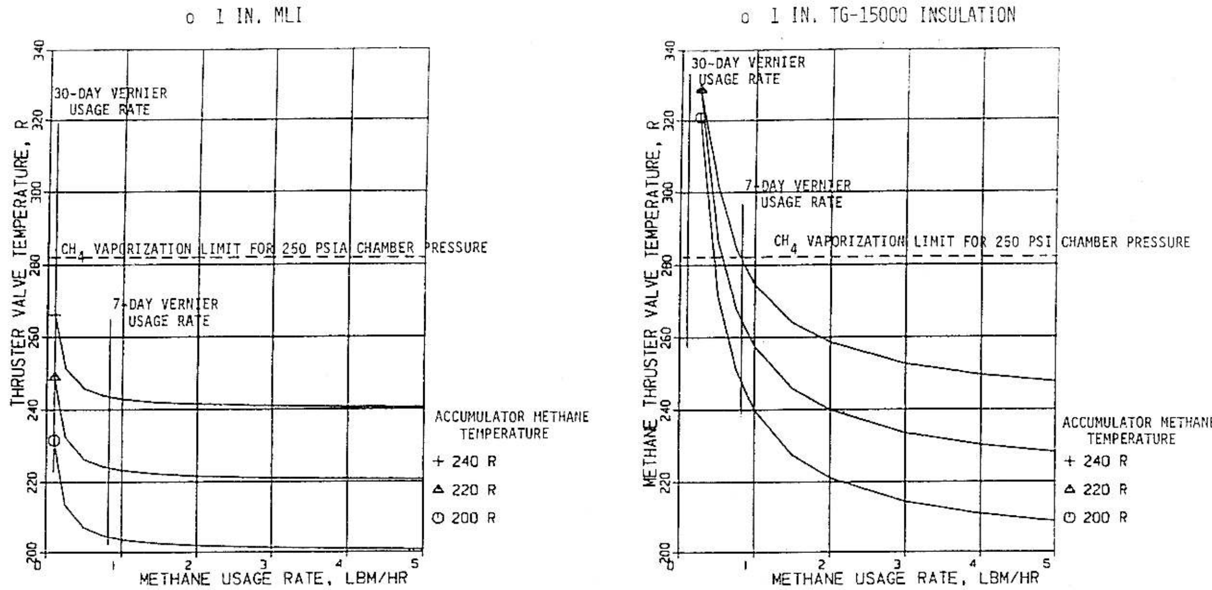

Fig. 20 RCS methane feedline temperature summaries

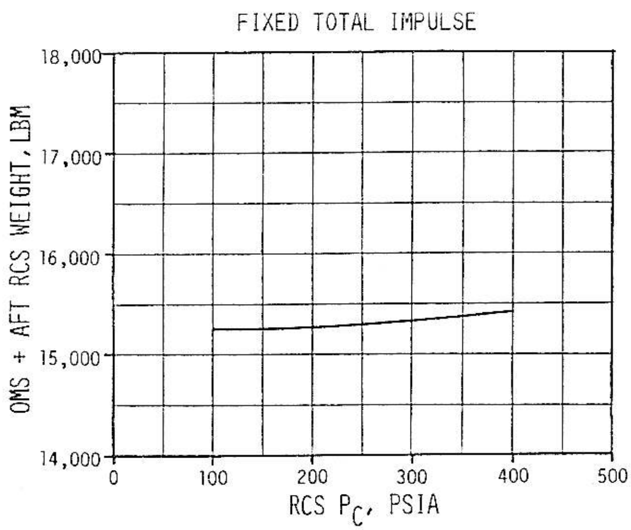

Fig. 21 LOX/methane system weight sensitivity to RCS chamber pressure

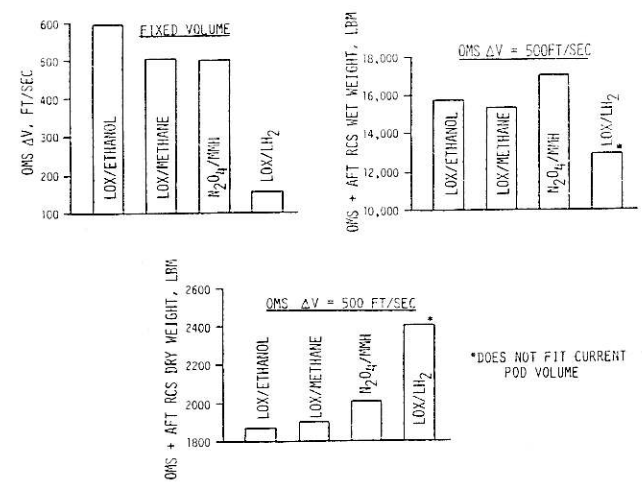

Fig. 22 Comparison of LOX/HC, N_2O_4/MMH, and LOX/LH_2 OMS-RCS

OMS-RCS would be substantially less than the current N_2O_4/MMH system. Additional evaluations are being performed to assess the degree of integration between the forward RCS and aft propulsion system and to determine the feasibility of non-conventional (conical) tank shapes for improved aft pod packaging efficiency.

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