LOX/Hydrocarbon Auxiliary Propulsion for the Space Shuttle Orbiter

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This paper describes 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 study had two phases: Phase I—Preliminary System Evaluation and Phase II—In-Depth System Evaluation. Phase I was broad in scope and structured to evaluate a large number of 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 identify the most attractive concept and define areas requiring further technology effort. On the basis of this study, a pump-fed LOX/ethanol OMS-RCS was found to be the most attractive concept. The LOX/ethanol propellant combination is clean burning (noncoking) 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 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 spacecraft 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—imposed severe penalties 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, resulting in smaller fuel tanks. During evolution of the Space Shuttle design, LOX/HC propellants were considered for the Orbiter OMS-RCS.[4] 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 development cost goals of the Orbiter.

The purpose of this study was to define the most attractive LOX/HC propulsion system concept for a second-generation Shuttle OMS and RCS. The effort was conducted in two phases. Phase I was a preliminary evaluation to screen a large number of system concepts and propellant combinations. Phase II was an in-depth evaluation of the most promising systems and propellants resulting from phase I.

The following paragraphs summarize the results from both phases of the study.

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. As shown in Fig. 1, each pod contains OMS-RCS propellant and pressurant tankage, propellant distribution networks, a 6000-lb-thrust OMS engine, 12 870-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, similar in design to the aft-RCS, is installed in the nose of the Orbiter.

The candidate fuels selected for the study are identified in Table 1 and represent each of the major propellant classes. They are low in cost and toxicity, noncorrosive, 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 noncoking, was used with LOX in the early Navaho, Redstone, and X-15 engine systems, and has an acceptably high vapor pressure. (The vapor pressure of ethanol is slightly greater than MMH.) The final two fuel candidates, propane and methane, were selected because they were being investigated in current engine technology contracts.[5,6]

In order to limit the number of concepts to be considered, only the key feed system and tankage options were selected for evaluation in phase I. The phase I system evaluation matrix is shown in Table 2. The method of evaluation is described below for one of the design options—pump- vs pressure-fed OMS.

Pump- vs Pressure-Fed OMS

A schematic for the pump-fed OMS, incorporating the same redundancy as the current pressure-fed OMS, is shown in Fig. 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 startup. Cryogenic propellants 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.

Comparisons of pump- and pressure-fed LOX/HC OMS are presented in Fig. 3. Chamber pressures of 800 and 100 psia were found to be near-optimum for the pump- and

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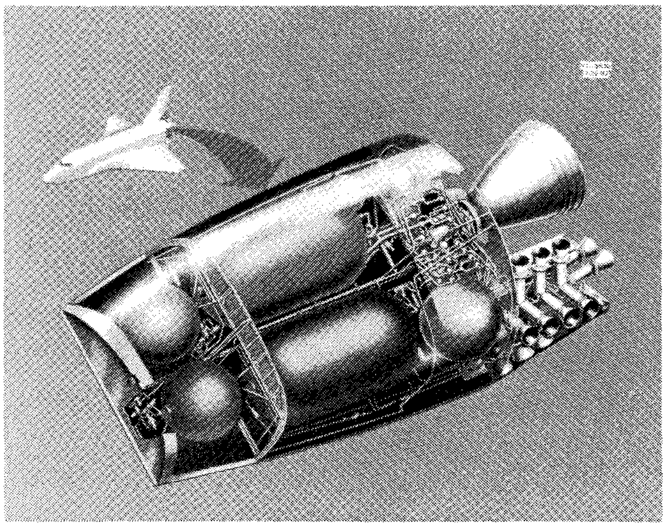

Fig. 1 Orbiter aft propulsion subsystem pod.

Table 1 Candidate fuels

	Examples	Fuels selected for phase I
Earth storable (boiling points much greater than ambient):	RP-1 Ethanol Heptane Benzene Methanol *n*-Octane	Ethanol (C_2H_5OH)
Space storable (boiling points slightly less than ambient):	Propane Butane Isobutane Propylene Ammonia	Propane (C_3H_8) Ammonia (NH_3)
Cryogenic (boiling points less than −100°F):	Ethane Methane Ethylene Cyclopentane	Methane (CH_4)

pressure-fed systems, respectively. Three criteria were 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.

Summary of Phase I Results and Recommendations

Similar evaluations were performed for the other system design options of Table 2, and the results are summarized in Table 3. Ethanol and methane were considered to be the best fuel candidates, because both are noncoking 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.

Phase II—Evaluations and Results

The phase II system evaluation matrix is presented in Table 4. The effort 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 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.

LOX/Ethanol OMS-RCS

A schematic of the LOX/ethanol OMS-RCS is shown in Fig. 4. 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 determine if reasonable accumulator temperature variations could be achieved during the RCS mission.

The ethanol tank heat exchanger model is illustrated in Fig. 5. 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 inside the tank, and the environment. The heat exchanger line was divided into segments, and the energy and mass conservation equations were solved for each segment. The performance of this heat exchanger concept is shown in Figs. 6 and 7. Figure 6 shows O_2 inlet and exit temperatures over a seven-day OMS-RCS mission. The heat exchanger O_2 line is sized for a flow rate of 3.3 lbm/s which is sufficient to meet the backup RCS deorbit burn requirement for two aft-firing thrusters per pod. As shown in Fig. 6, O_2 heat exchanger exit temperature is maintained near 490°R throughout the mission. The coolest exit temperature (425°R) occurs approximately 24 h into the mission during the period of maximum RCS usage. The corresponding liquid ethanol temperature in the propellant tank is shown in Fig. 7. Also

Table 2 Phase I system evaluation matrix

	Candidate fuels			
Design options	Ethanol	Methane	Propane	Ammonia
Pump vs pressure feed	X	X	X	X
NBP vs subcooled liquid storage			X	
Cryogenic vs ambient RCS feed	X	X	X	X
Degree of OMS/RCS integration	X	X	X	X
Blowdown vs regulated pump NPSP			X	
Tank insulation options Feedline insulation options	LOX			

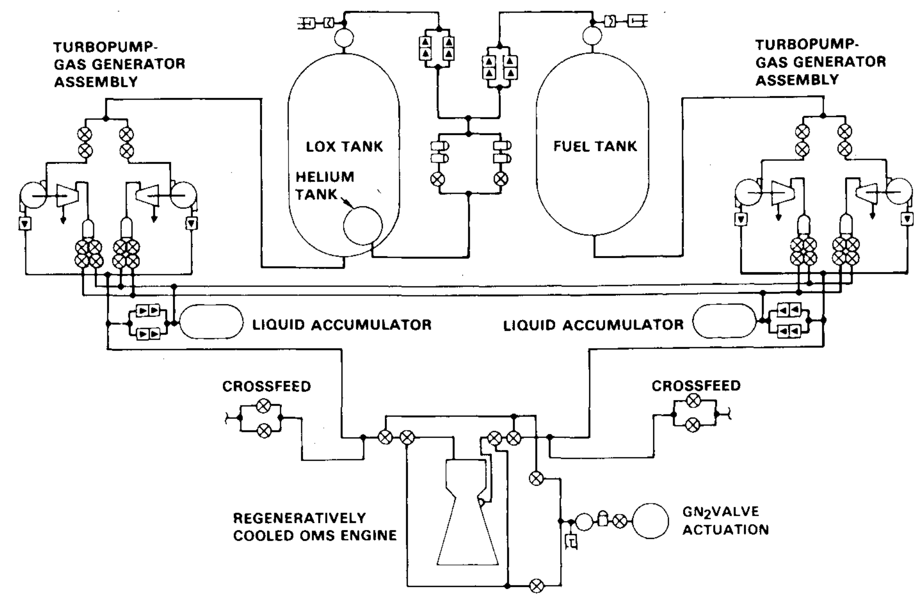

Fig. 2 LOX/HC OMS turbopump system.

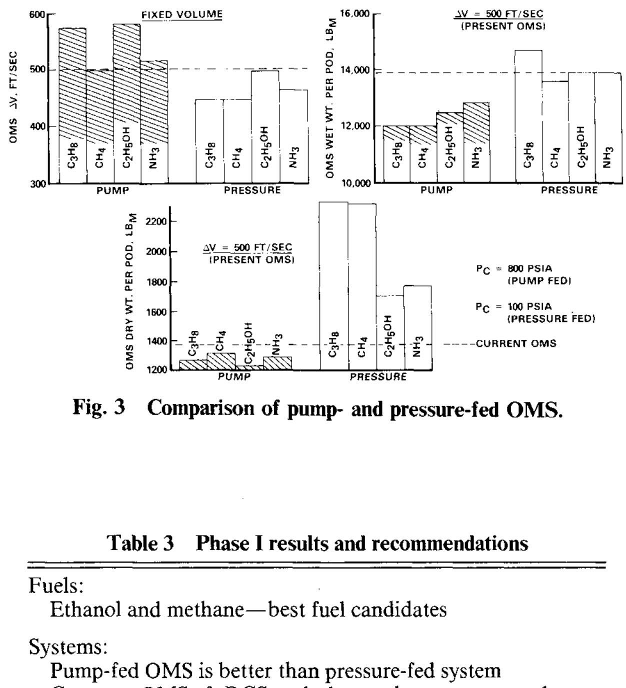

Fig. 3 Comparison of pump- and pressure-fed OMS.

Table 3 Phase I results and recommendations

Fuels:
Ethanol and methane—best fuel candidates
Systems:
Pump-fed OMS is better than pressure-fed system
Common OMS aft RCS tanks better than separate tanks
Regulated helium NPSP system preferred over blowdown
Consider methane OMS engine expander cycle in phase II
Consider electric pumps for RCS feed in phase II
Consider passive O_2 thermal conditioning for LOX/ethanol RCS

Table 4 Phase II system evaluation matrix

Design options	Fuel candidates Ethanol	Methane
Pump- vs pressure-fed RCS	X	
Cryogenic vs ambient RCS feed	X	
Separate vs common forward/aft tanks	X	
OMS Engine expander cycle		X
Electric pumps for RCS feed	X	X
Conventional vs nonconventional tank shapes	X	
Tank/feedline insulation and cooling options	LOX and methane	

shown is the quantity of liquid ethanol remaining. The coolest ethanol temperature (430°R) occurs 24 h into the mission. These results demonstrate the feasibility of an ethanol tank heat exchanger to thermally condition 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 seven-day mission. The gaseous O_2 accumulator profiles are shown in Fig. 8, and the liquid ethanol accumulator profiles are shown in Fig. 9. For these examples the oxidizer and fuel resupply flow temperatures were set equal to 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 (Fig. 4). 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.

The results of Figs. 8 and 9 show that reasonable temperature variations are achieved in the RCS accumulators and 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 Fig. 10. An OMS chamber pressure of 600 psia was baselined since it provides the best compromise between system weight 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 schematic of the LOX/methane OMS-RCS is shown in Fig. 11. This system uses an OMS engine expander cycle in which gaseous methane leaving the engine cooling jacket is

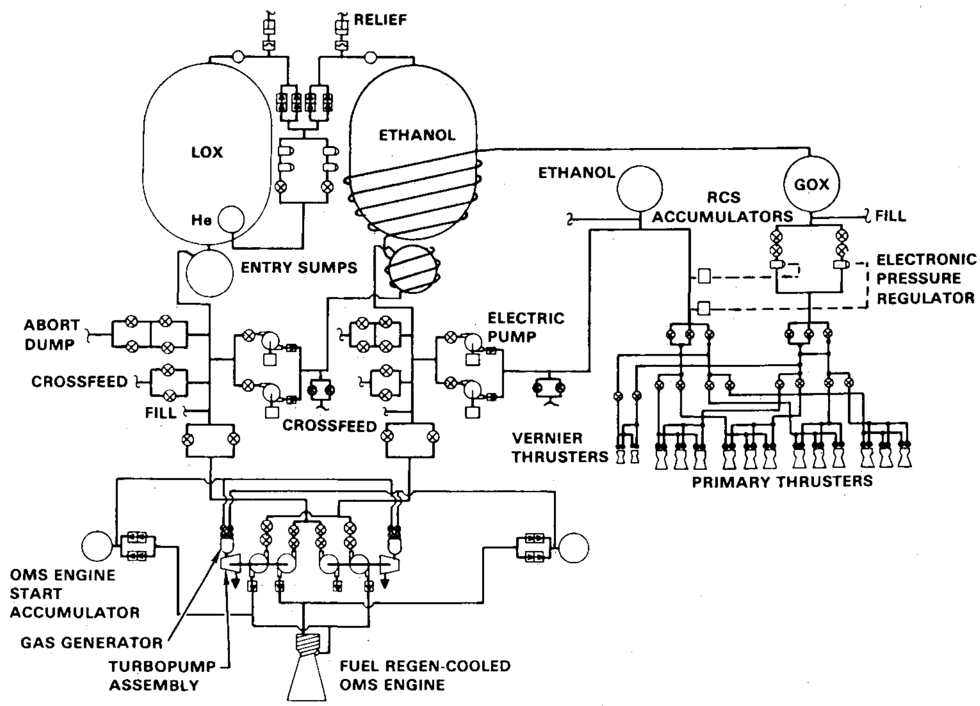

Fig. 4 LOX/ethanol OMS-RCS.

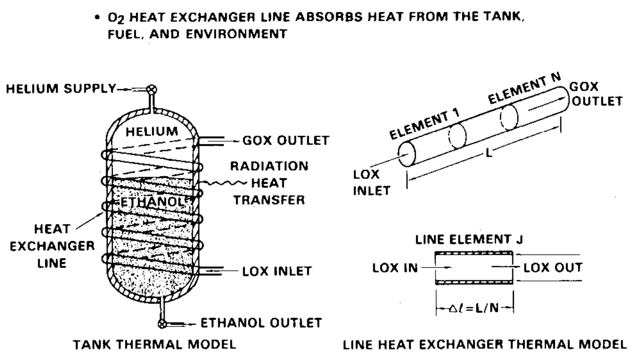

Fig. 5 Tank heat exchanger thermal model.

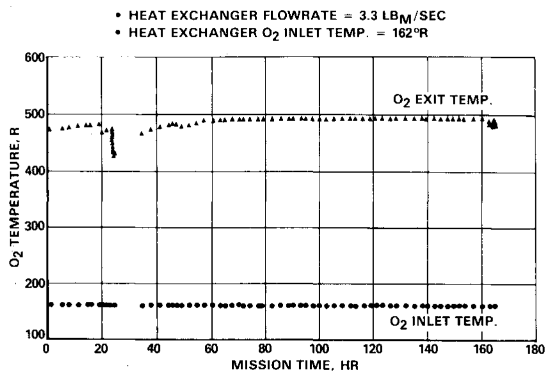

Fig. 6 Ethanol tank O_2 heat exchanger performance.

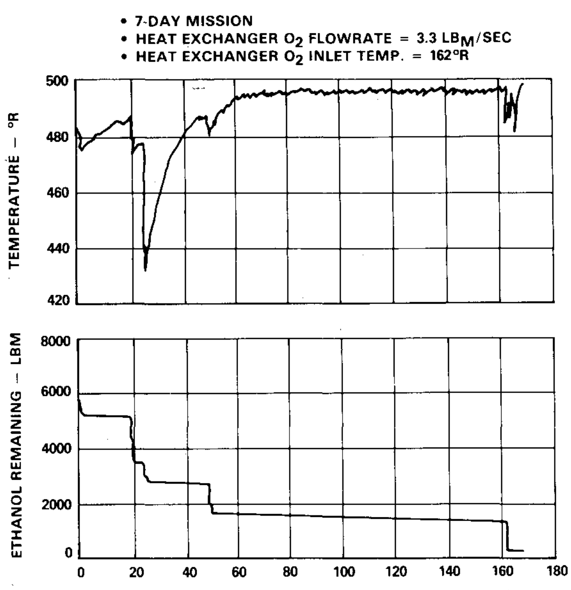

Fig. 7 Ethanol temperature and quantity remaining.

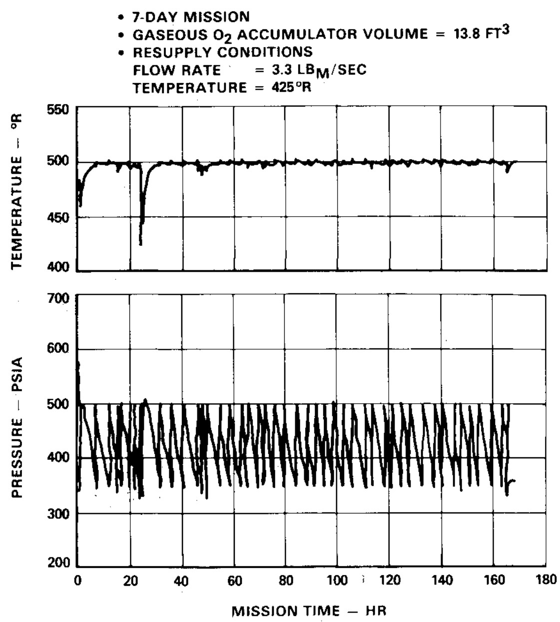

Fig. 8 RCS GOX accumulator performance.

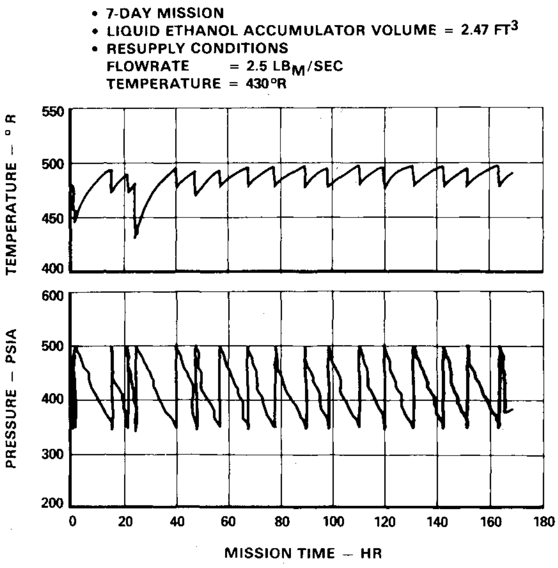

Fig. 9 RCS ethanol accumulator performance.

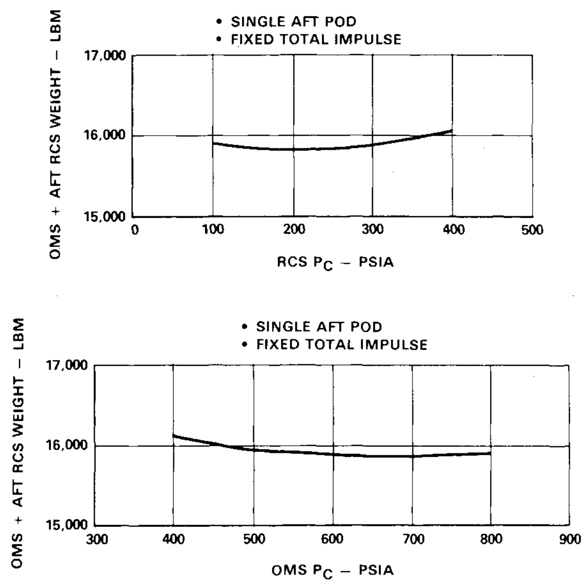

Fig. 10 LOX/ethanol system chamber pressure sensitivity.

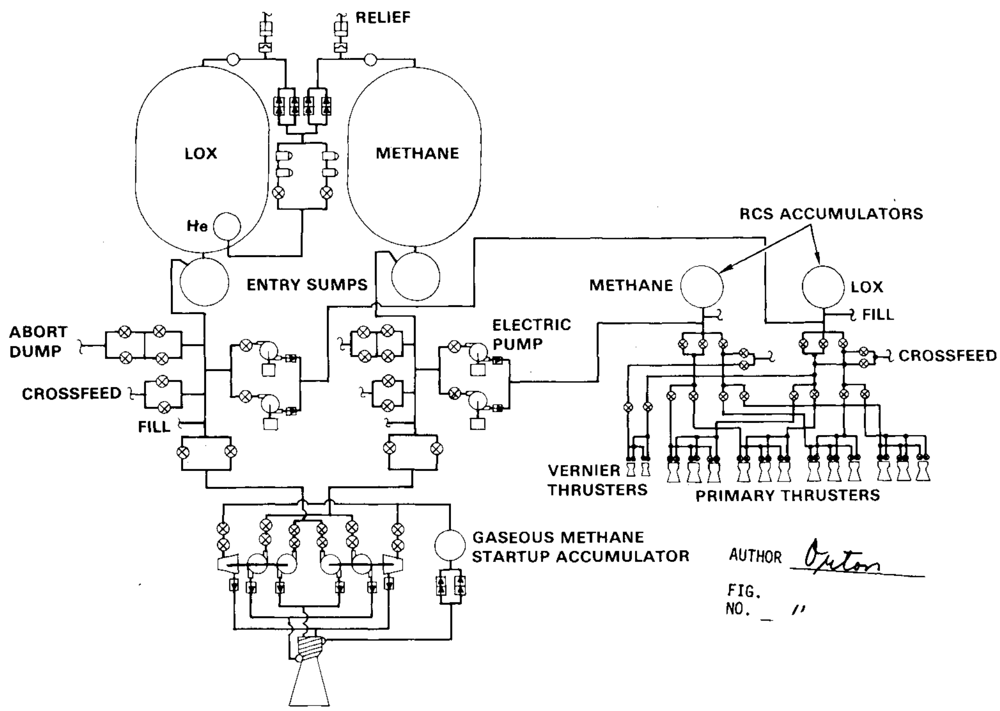

Fig. 11 LOX/methane OMS-RCS.

Table 5 Properties of candidate insulation materials

Property	Insulation type TG-15000	MLI[a]
Ambient thermal conductivity,[b] Btu/(h-ft-°R)	0.0123	0.05
Vacuum thermal conductivity,[b] Btu/(h-ft-°R)	0.00075	0.000038
Heat capacity, Btu/(lbm°R)[b]	0.2	0.27
Density, lbm/ft^2	2.0	1.14

[a]NCR-2 Singly aluminized Mylar (50 layers/in. with 5% perforation).
[b]Properties evaluated at a temperature of 180°R.

expanded through a turbine to drive the pump assemblies. As in the preceding 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 the excessive energy required to condition the propellants to the gaseous state, 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: aluminized Mylar multilayer 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 than MLI, is not as susceptible 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 5. The measure of tank insulation effectiveness is the amount of

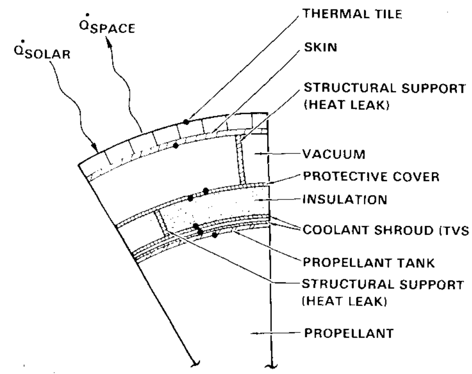

Fig. 12 Tank thermal model.

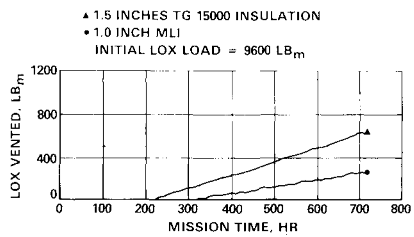

Fig. 13 LOX tank 30-day vent losses.

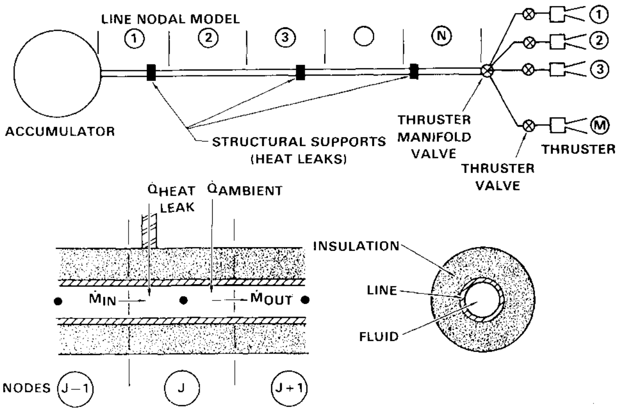

Fig. 14 Feedline thermal model.

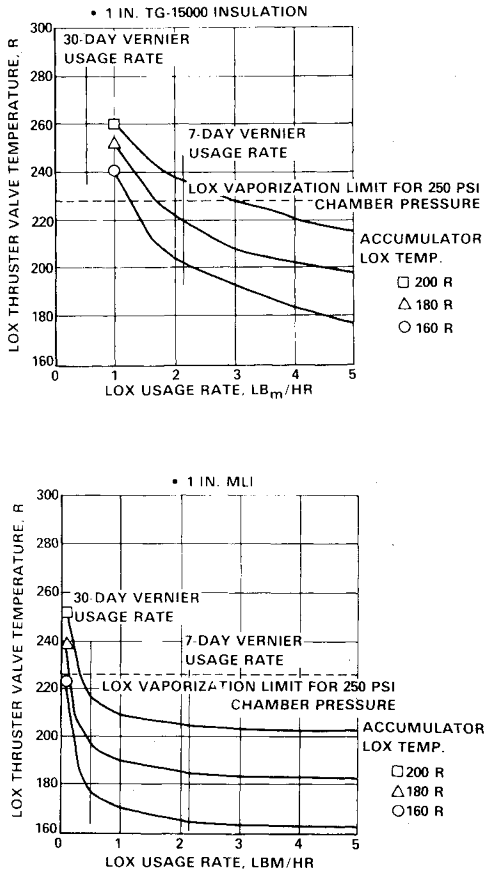

Fig. 15 RCS LOX feedline temperature summary.

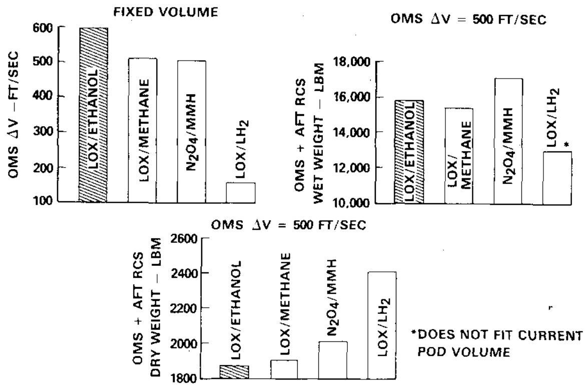

Fig. 16 Comparison of OMS-RCS systems.

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.

To evaluate tank insulation effectiveness, the thermal model shown in Fig. 12 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. LOX 30-day vent losses are shown in Fig. 13 for a common OMS-RCS tank installed in the aft pod. (The methane vent losses were less than those for LOX.) 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 seven-day missions, the LOX vent loss with TG-15000 is only 35 lbm. 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 access groundhold and transient launch heating effects.

The RCS cryogenic feedline thermal model is illustrated in Fig. 14. The feedline from the accumulator to the thruster valves was divided into segments, and the energy and mass conservation equations were solved for each segment. The analysis accounted for heat conduction through the insulation, thruster heat soakback, and major heat leaks associated with structural members such as line supports. A summary of maximum LOX feedline temperatures for both TG-15000 and MLI is presented in Fig. 15. Here, LOX temperature at the thruster valve is plotted as a function of LOX usage rate and accumulator temperature. As shown, MLI is required for the 30-day mission to avoid two-phase flow in the engine injector manifolds. Similar results were obtained for methane, and, hence, a vacuum jacketed MLI system was baselined for the LOX/methane RCS feedlines.

The weight sensitivities of the LOX/methane system to OMS and RCS chamber pressure were also developed, and the results were similar to those presented in Fig. 10 for the LOX/ethanol system. However, the LOX/methane OMS chamber pressure was set at 400 psia, which is the maximum level for meeting both engine cooling and turbine drive requirements for the engine expander cycle. An RCS chamber

Table 6 Overall study conclusions

Best fuel—ethanol
Highest ΔV and total impulse capability
Noncoking
Earth storable
Good technology base for engine development
Most attractive system concept
Pump-fed OMS with single turbine driving both fuel and oxidizer pumps
Overriding weight and performance advantages
Single turbine reduces system complexity
Common OMS/aft RCS propellant tanks
High ΔV and total impulse capability
Greater mission flexibility
Electric pumps for aft-RCS feed
Turbopumps cycled only during OMS burns
High RCS performance
Hybrid ambient temperature RCS propellant feed (GOX/liquid ethanol) (no accumulator or feedline insulation required)
Passive ethanol tank heat exchanger for O_2 thermal conditioning
No gas generators for thermal conditioning
No I_{sp} penalty (gas generator vent loss)

Table 7 New technology requirements

Feed system:
Thermal management system for cryogenic LOX tank
Insulation
Thermodynamic vent
Auxiliary cooling
Passive ethanol tank O_2 heat exchanger
Surface tension screen propellant acquisition for common OMS-aft RCS tank (cryogenic)
Improved propellant gaging approach
Electronic pressure regulator for controlling RCS GOX accumulator outlet pressure
Lithium batteries or alternate power source for electric RCS pumps
Engines:
LOX/ethanol OME
Small high-speed turbopumps
Improved heat-transfer characterizations, burnout data, and performance correlations
LOX/ethanol RCS
Improved heat-transfer characterizations
Definition of pulse mode performance capability and cycle life

pressure of 100 psia was baselined to minimize electric motor weight and power requirements.

Summary

The LOX/ethanol and LOX/methane systems are compared with the current storable OMS-RCS and a LOX/hydrogen OMS-RCS in Fig. 16. From this comparison it is seen that the LOX/ethanol system is superior in terms of ΔV capability and dry weight. The LOX/ethanol system allows use of a simple noninsulated RCS feed system, and recent testing[6] has shown that the LOX/ethanol propellant combination is clean burning (noncoking). On the basis of this comparison, the LOX/ethanol system is the most attractive LOX/HC OMS-RCS. Because the propellants are low in cost, nontoxic, and noncorrosive, the operational costs for a LOX/ethanol OMS-RCS would be less than the current N_2O_4/MMH system.

Conclusions

The overall study conclusions are summarized in Table 6, and new technology requirements for the LOX/ethanol OMS-RCS are defined in Table 7.

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