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AN ANALYSIS OF POTENTIAL ORBITAL PROPELLANT STORAGE REQUIREMENTS AND MODES OF OPERATION

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Program Development

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This report attempts to indicate the current status with respect to orbital propellant storage requirements and modes of operation. The problems connected with long-term storage and orbital propellant transfer are discussed and some tentative recommendations are presented.

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TABLE OF CONTENTS

		Page
SUMMARY		1
I.	INTRODUCTION AND BACKGROUND	1
II.	ORBITAL PROPELLANT REQUIREMENTS	2
III.	PROPELLANT DEPOT CONCEPTS	4
IV.	OPERATIONAL CONCEPTS	4
V.	TECHNOLOGY	8
	A. Launch Pad Operations	11
	B. Space Shuttle Internal Slush Facilities	11
	C. Orbital Propellant Depot Spacecraft	13
VI.	CONCLUSIONS AND RECOMMENDATIONS	17
REFERENCES		19

LIST OF ILLUSTRATIONS

Figure		Page
1.	Propellant depot concepts (using rotational acceleration for transfer)	5
2.	Propellant depot concept (linear acceleration transfer)	6
3.	Integral tank delivery of propellant to the orbital storage facility	9
4.	Space Shuttle propellant tank transfer concept	9
5.	Two-stage Space Shuttle	10
6.	Factors influencing propellant transfer	14

LIST OF TABLES

Table		Page
1.	Space Hardware — Possible Time Phasing	3
2.	LH_2 Cargo — Shuttle Payload Capacity Utilization	7

TECHNICAL MEMORANDUM X-64538

AN ANALYSIS OF POTENTIAL ORBITAL PROPELLANT STORAGE REQUIREMENTS AND MODES OF OPERATION

SUMMARY

The recent developments and proposals with respect to potential orbital propellant storage requirements and modes of operation have been reviewed and analyzed. This report is thus intended to serve as a starting point, a point of departure, for the in-house and contracted studies of orbital propellant storage systems to be initiated in the near future.

The problems related to propellant transfer and storage in conjunction with the use of the Space Shuttle, a Space Tug, the Lunar Shuttle, and other proposed space oriented vehicles are discussed. The interplay of the various proposed missions for these vehicles is analyzed from a propellant use point of view and some tentative recommendations are presented.

No statements made herein should be interpreted as positive statements with respect to the programs mentioned, the direction of future efforts, or intended methods of operation. The document reflects the view of the author, following analysis of the data available, and should not be construed to be an official recommendation.

I. INTRODUCTION AND BACKGROUND

During the past year, NASA has developed a tentative, overall plan for the various programs now expected to be conducted in space during the next 15 to 20 years. This plan [1], presently referred to as the "Integrated Space Program — 1970-1990," encompasses a multitude of space operations, including the possibility of in-orbit propellant storage and resupply near the end of this decade. This orbital storage and transfer of propellant is currently considered a vital part of the implementation process for this Integrated Space Program (ISP).

As now envisioned, the operations during the next 20 years of space exploration may involve such diverse hardware elements as an earth-to-earth orbit personnel and cargo delivery system — the Space Shuttle, a 12-man Space Station (which may well develop into a 50-man Space Base), a Space Tug (for operations in earth orbit and for transfer of payloads to other near-vicinity orbits), a Lunar Shuttle (for transfer of items to lunar orbit and possibly earth synchronous orbits), a lunar orbit station, a lunar surface base, and unmanned probes to Mars and other planets.

Within the program currently envisioned, the Lunar Shuttle will probably be the largest consumer of propellants. Over the 10-year span, starting near the end of this decade, it is considered possible for this portion of the program to require as many as 10 round trips (earth orbit - lunar orbit - earth orbit) per year. In addition to the Lunar Shuttle, large quantities of liquid hydrogen (LH_2) and liquid oxygen (LO_2) may be consumed by the Space Tug and the Space Station, although these usage rates would be comparatively small.

It is currently planned for the Space Shuttle, with a possible gross capacity of about 25 000 pounds, to be the prime earth-surface to earth-orbit transportation vehicle of the ISP. However, larger payload vehicles, such as a Saturn V, Intermediate 21, or Hybrid Shuttle, could possibly be potential propellant transport vehicles in view of the large consumption rates currently being considered.

II. ORBITAL PROPELLANT REQUIREMENTS

The current estimate for start dates of the four major facets (Space Shuttle, Space Station, Space Tug, and Lunar Shuttle) of the ISP is very fluid. The total proposed NASA program is now being reworked and rescheduled and the start dates will not "settle" until after this task is completed. An indication of the time phasing being considered for these programs is noted in Table 1.

On this basis the orbital propellant requirements could possibly develop as follows:

a. Space Tug — The Space Tug's use of LO_2 and LH_2 will, of course, depend on the manner in which it is used. However, for the purpose of this analysis, it was assumed that it would engage in operations essentially equivalent to:

TABLE 1. SPACE HARDWARE — POSSIBLE TIME PHASING

Hardware Unit	Initial Operation — Time Phasing								
	75	76	77	78	79	80	81	82	83
Space Station					IOC				
Space Shuttle					IOC				
Space Tug					IOC				
Lunar Shuttle								IOC	
Space Shuttle — Planetary Probes							PPL'S		

1. The movement of one large payload (120 000 pounds) through a round-trip orbit altitude change of 170 nautical miles at least once per month. This would require about 36 000 pounds of propellants (LO_2/LH_2 combined) per quarter.

2. The placement of one satellite in earth synchronous orbit once per quarter. This would require about 90 000 pounds of propellants (LO_2/LH_2 combined).

3. Initial planetary probe launches requiring the expenditure of 90 000 pounds of propellants (LO_2/LH_2) per quarter.

The Space Tug operations would thus require about 216 000 pounds of cryogenic propellants (LO_2/LH_2) per quarter, or 864 000 pounds annually. If it is assumed that transfer and boiloff losses can be kept to a maximum of 10 percent, then the yearly requirement becomes about 950 000 pounds.

b. Planetary Probe Launching — The introduction of major planetary probe launchings within one or two years after initiation of Space Tug operations could possibly raise the propellant requirements by as much as 50 percent, that is by about 500 000 pounds per year.

c. Lunar Shuttle — The initiation of Lunar Shuttle operations (using nuclear propulsion) between earth orbit and lunar orbit will require the expenditure of about 350 000 pounds of LH_2 per trip. Thus, one trip per quarter would essentially double the orbital propellant requirements — from about 1 200 000 to 1 500 000 pounds per year to about 2 400 000 to 2 700 000 pounds per year. With propellant delivery by the Space Shuttle, as described above, this would necessitate about 95 to 100 flights per year. The lunar program with 10 Lunar Shuttle flights per year would require delivery to earth orbit of about 3 500 000 pounds of propellant. This would make the total requirements on the order of 4 700 000 to 5 000 000 pounds per year.

d. Space Station — The Space Station program, as currently envisioned, would probably make use of the propellant facility only in emergencies or periods of abnormal operations as the EC/LS systems are planned to operate closed loop using water as their primary input and require very small quantities relative to those discussed above.

III. PROPELLANT DEPOT CONCEPTS

Over the past several months, several concepts for the potential orbital propellant depot have been developed. These concepts fall into two basic categories: (a) those using rotational acceleration for liquid/gas interface control, and (b) those using linear acceleration for liquid/gas interface control. Figure 1 presents three potential configurations using rotational acceleration. Figure 2 presents one possible configuration using linear acceleration.

Preliminary studies have indicated that a propellant depot with a capacity of about 150 000 cubic feet for LH_2 may be desirable to improve the efficiency of the overall space program, to handle fluctuations in refill requirements, and to facilitate flexibility in the scheduling of Space Shuttle flights for propellant delivery. It is currently envisioned that a 1000-cubic-foot capacity for LO_2 should prove quite adequate.

If the Space Shuttle is the depot delivery vehicle, then the depot must be constructed of parts that will fit the Shuttle cargo hold; i. e., units which have a diameter of not more than 15 feet and a length of not more than 60 feet.

IV. OPERATIONAL CONCEPTS

Delivery of propellants to the orbital storage unit, or directly to any one of the major operational elements of the ISP, could be accomplished by direct

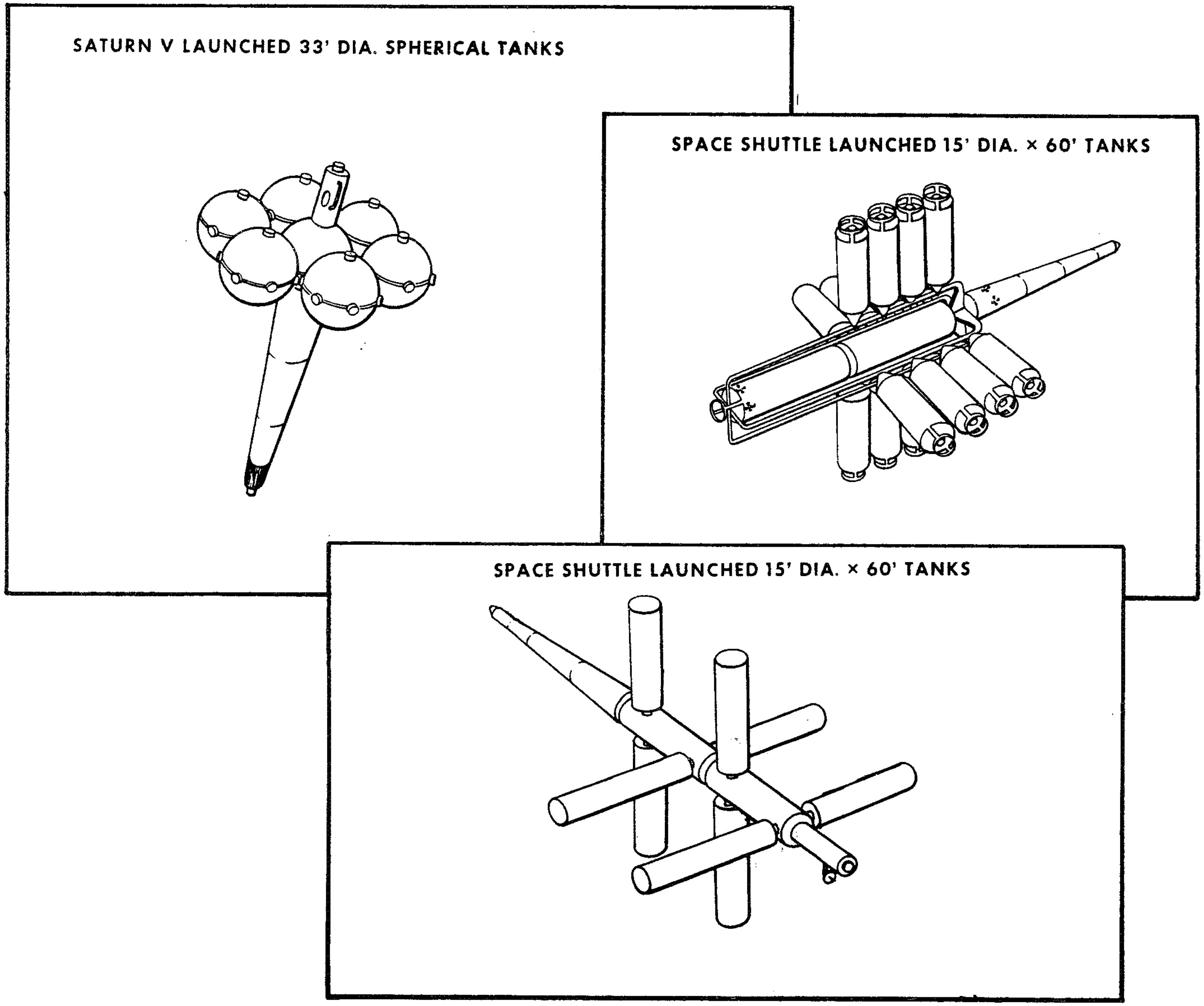

Figure 1. Propellant depot concepts (using rotational acceleration for transfer).

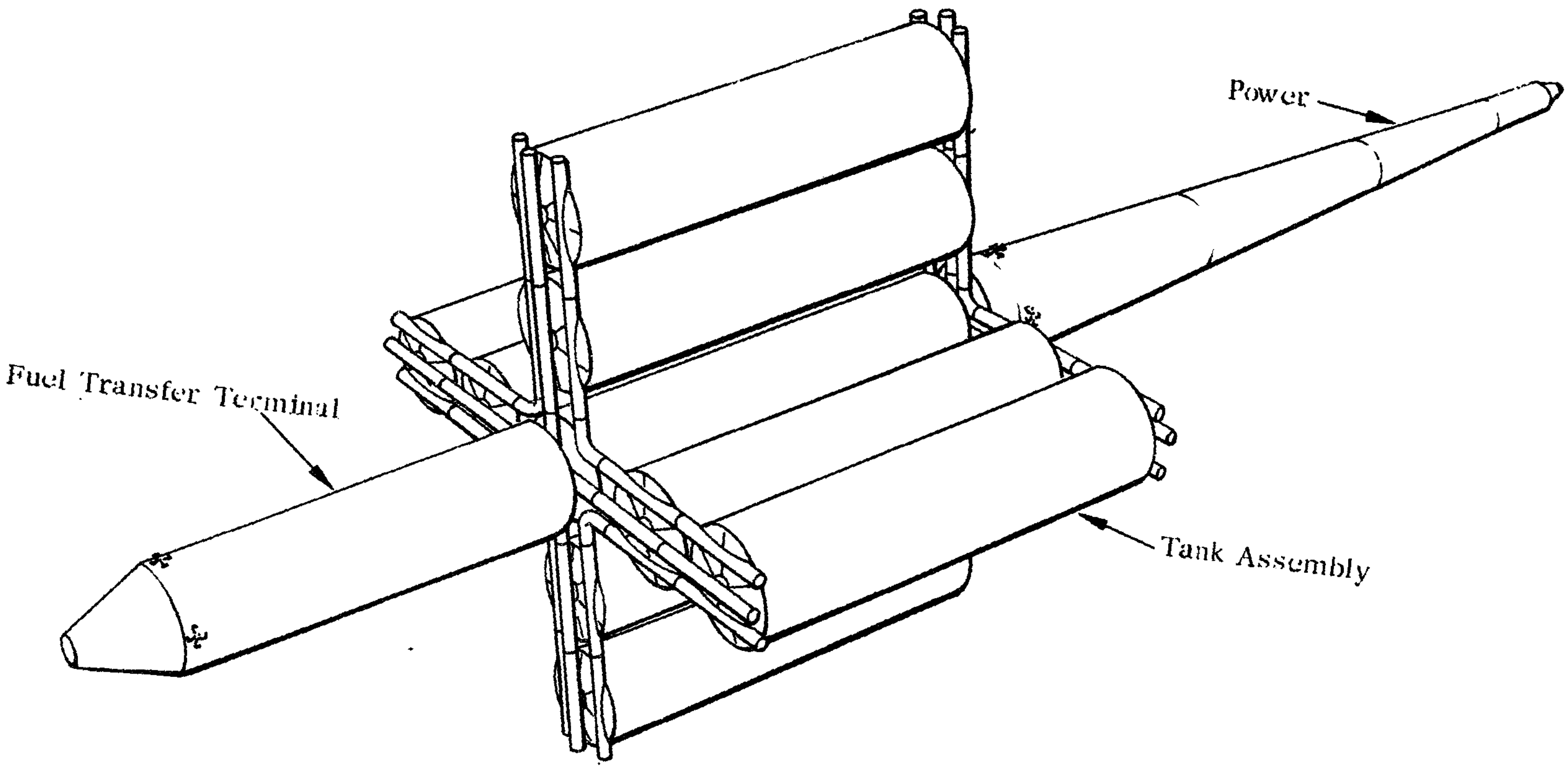

Figure 2. Propellant depot concept (linear acceleration transfer).

fluid transfer or by transfer of the propellant and its tank (container) as an integral (total package) unit. For propellant delivery, the largest volume requirements would be in conjunction with LH_2. The 10 000-cubic-foot volume presently contemplated for the Shuttle bay would be more than adequate. The 25 000-pound payload of the Space Shuttle [2] could possibly be utilized as shown in Table 2.

TABLE 2. LH_2 CARGO — SHUTTLE PAYLOAD CAPACITY UTILIZATION

Item	Volume (ft^3)	Weight (lb)
Liquid Hydrogen (4.37 lb/ft^3)	5000	20 850
Ullage, Baffles, etc.	200	400
Tankage, Insulation, etc.	400	3 000
Transfer Mechanisms	250	750
Unused Volume	4150	0

Recent studies of orbital refueling techniques and systems [3, 4, 5] suggest that fluid transfer of the propellant alone from the Space Shuttle to the orbital storage unit in a neutral-gravity environment would be strongly limited by available technology. Metallic bladders for use in a positive expulsion method of fluid transfer do not presently appear to be available for use with cryogenics such as LO_2 and LH_2. Discussions with persons working in cryogen technology development also tend to suggest that such capability will probably not be available within the initial time frame currently being discussed.

All three of these studies [3, 4, 5] concluded that fluid mechanics (behavior) knowledge with respect to orbital transfer of cryogenic liquids is currently (and in the foreseeable future) considered insufficient for the design of efficient and reliable fluid-transfer systems to be operated in a neutral-gravity field. Therefore, present indications are that the propellants will probably need to be transferred from the Space Shuttle to the storage depot in an integral propellant/tank mode and from the depot to the user systems via an induced-gravity field in conjunction with low-pressure pumping systems.

The use of rotational acceleration may bring technology problems in the areas of seals for nonrotating transfer hubs and attachments, coriolis acceleration effects, stabilization and control requirements, spin and despin thruster system, etc. The linear acceleration transfer mode may encounter both operations and technology problems in the areas of facility orientation, orbit changes, transfer times, etc. Additional investigation into the potential problems enumerated above may be disirable.

The transfer of cryogens in earth orbit will, generally, be affected by operation in the orbital environment. Some of the potential effects are:

a. The general weightlessness of the fluids may cause problems in maintaining the desired liquid/gas interfaces, in general orientation of the fluids, and in acquisition of the fluids by transfer devices; however, it appears that these problems will not be present if fluid transfer is conducted in an artificially induced field of gravity.

b. Although the presence of a hard vacuum will tend to be beneficial with respect to insulation efficiency and in case of spills, this same vacuum may possibly present problems with respect to seals, micrometeroid puncture, materials outgassing, etc.; however, it presently appears that adoption of a tank exchange mode of operation with the propellant storage depot would tend toward minimizing these problems.

In addition to the potential difficulties mentioned above, the decision process on transfer mode should also give consideration to the effect of transfer system efficiency. If it is assumed that each transfer operation is 95-percent efficient, then double transfer of the propellants from the Shuttle to the storage depot to the user vehicle results in the ultimate consumer tanks receiving only about 90 percent of the propellant sent from earth to orbit. The tank-plus-propellant method of operation can potentially negate one of these steps and thus possibly effect a 5-percent gain in utilization of propellant sent into orbit. Figure 3 presents one possible concept for this operational mode. Another possible method of utilizing this mode of operation is shown in Figure 4.

V. TECHNOLOGY

A propellant depot in earth orbit which is resupplied by a Space Shuttle, such as that shown in Figure 5, will provide considerable flexibility in scheduling Lunar Shuttle missions. Operating in conjunction with such a propellant depot, the Lunar Shuttle can refuel and take on the necessary cargo and personnel within hours instead of days. Without the depot, multiple Space Shuttle flights (as many as 12 to 16 per nuclear Lunar Shuttle mission) would be needed to refuel each waiting Lunar Shuttle. The depot could also act as an orbiting resupply station (with both hydrogen and oxygen) available to other vehicles operating in its vicinity, including possibly the Space Station, a Space Tug, and both interplanetary and interstellar probes.

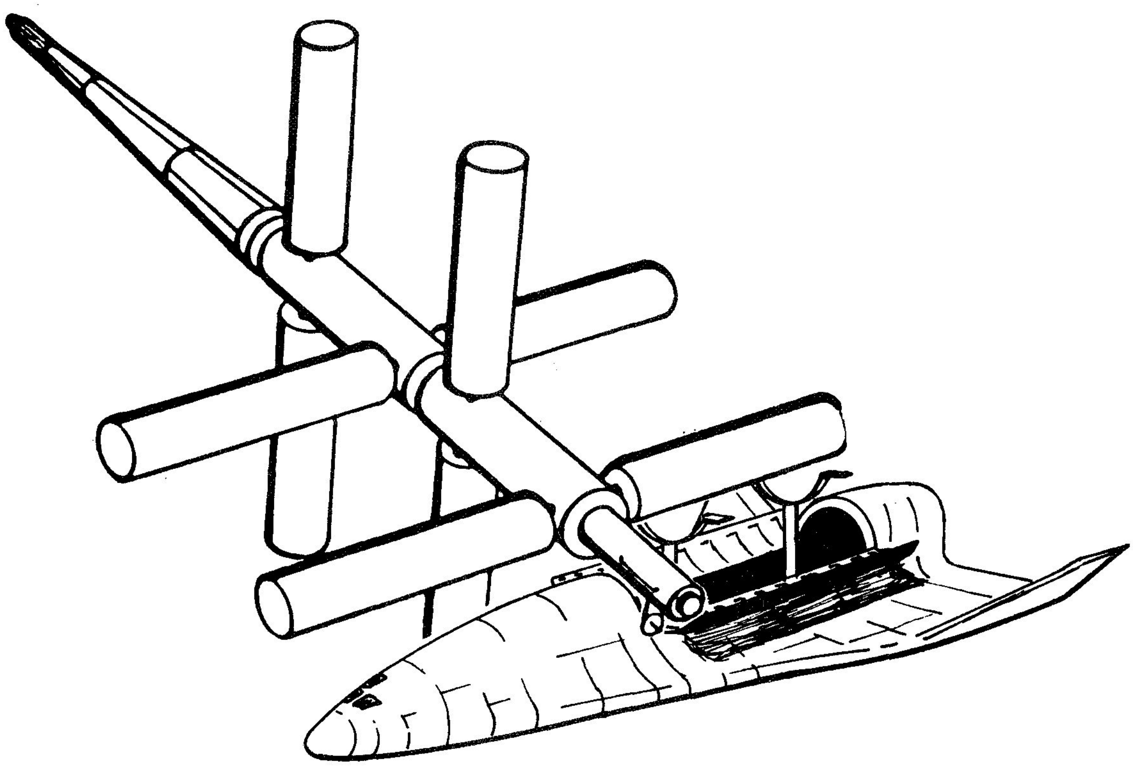

Figure 3. Integral tank delivery of propellant to the orbital storage facility.

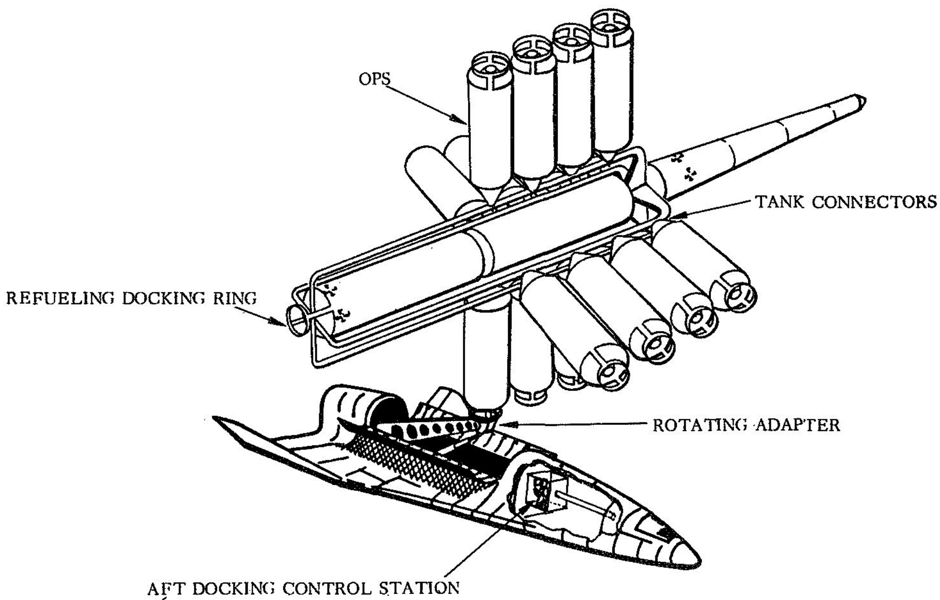

Figure 4. Space Shuttle propellant tank transfer concept.

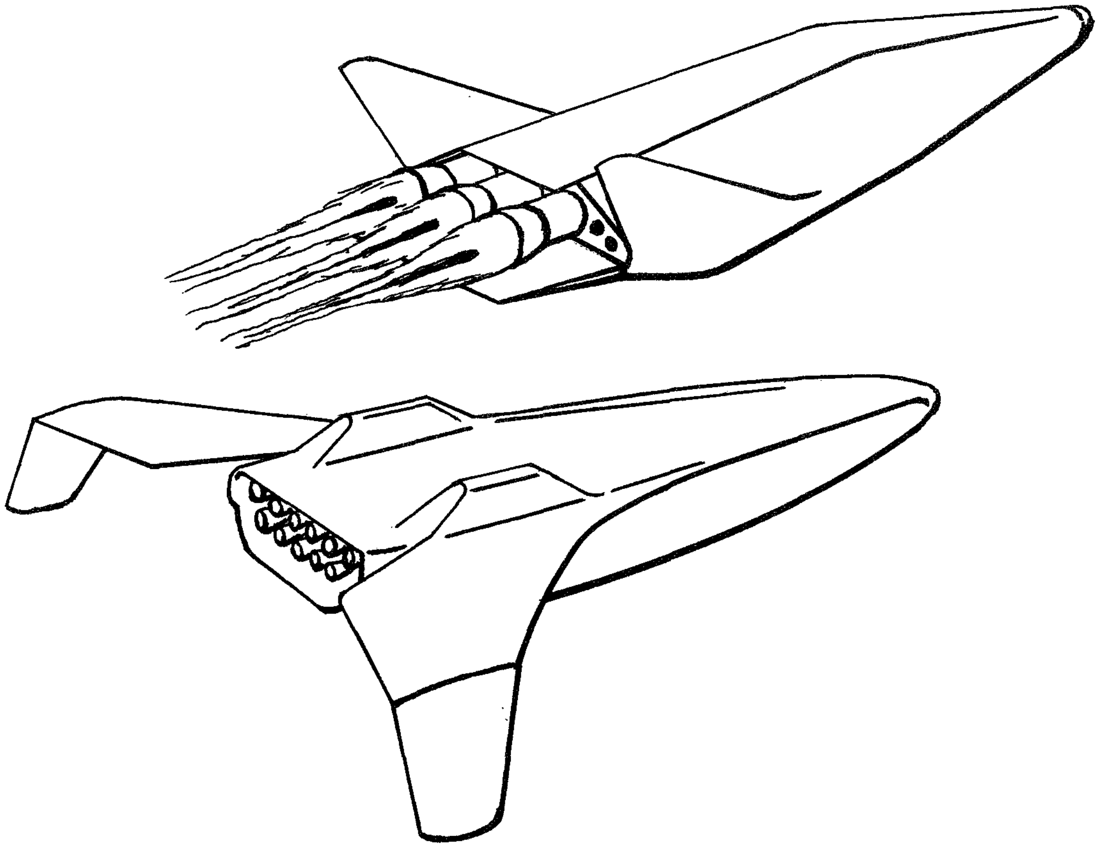

Figure 5. Two-stage Space Shuttle.

In consideration of the many facets of the proposed program, it may also be advisable to consider the introduction of new methods of operation and the use of new technologies such as using slush hydrogen in orbital and lunar operations. The tradeoffs necessary to make the firm decisions are not yet available but further study is deemed advisable.

Slush hydrogen offers several advantages over other propellants as a Lunar Shuttle propellant. Hydrogen has a very high specific impulse and, because of increased density of the slush, the density impulse of slush hydrogen (impulse per given volume) is higher than for liquid or gaseous hydrogen. Because of the absence of the normally low specific impulse gelling agent, it is also higher than the specific impulse for gelled hydrogens available today. Slush hydrogen will absorb more heat than liquid or gaseous hydrogen for a given increase in pressure because of the energy absorbed from heat or fusion of the solid hydrogen in the slush.

A. Launch Pad Operations

If it proves feasible for orbital operations, then slush hydrogen must be generated, stored, and transferred to the Space Shuttle at the launch pad. The National Bureau of Standards [6] initially performed analytical and experimental work in these areas, and later, on a larger scale, Lockheed Missiles and Space Company [7, 8] worked in this area. To date, four methods have been evaluated for producing the slush [9]: helium refrigeration, helium bubbling, continuous vacuum bubbling, and intermittent vacuum pumping (freeze-thaw process). Of these four, the freeze-thaw process has appeared most promising. A 35-percent slush fraction (slush quality) is normally achieved from the freeze-thaw process. A 60-percent solid fraction may be achieved through slush topping and liquid draining with a 2-day aging period to allow the slush solids to break into finer particles and settle to the bottom of storage dewar.

After the slush is generated, it must either be stored or transferred directly to the Space Shuttle. Two methods available for transfer are (1) pressure, and (2) pump. Experiments have been successful in transferring slush by both methods with equipment designed for LH_2. In experiments at Lockheed [8] difficulties were encountered in maintaining high slush quality in transfer lines designed for liquid hydrogen. Severe thermal oscillations at valve stems and bayonet fittings caused considerable slush quality degradation during transfer. Methods of reducing these oscillations are currently being investigated.

Current Space Shuttle concepts are considering total discretionary cargo capacities of up to approximately 25 000 pounds. For the propellant tanker design concepts, the estimated amount of LH_2 deliverable per trip is about 21 000 pounds. The optimum slush qualities must be determined for the various phases of the orbital propellant depot mission from generation at the pad through transfer to the Lunar Shuttle. Launch pad slush hydrogen facilities must be designed to generate and transfer slush of quality and quantity consistent with optimum mission performance.

B. Space Shuttle Internal Slush Facilities

If slush hydrogen is determined to be operationally desirable, then slush storage tankage in the Space Shuttle cargo bay will receive the slush hydrogen from the transfer lines at the launch pad. The slush must be stored in the Shuttle under multiple environmental conditions as follows:

1. Prelaunch — ambient temperature and pressure, little vibration, 1-g gravity.

2. Launch — increasing and later decreasing temperatures, decreasing pressures, vibration, increasing and later decreasing gravity.

3. Orbital rendezvous — orbital temperatures, low pressure, little vibration, near-neutral gravity.

The multiple environmental conditions dictate strenuous requirements for the slush thermal protection system.

Preliminary investigations indicate that a 50-percent slush mixture contained in the Shuttle tankage insulated by a 1-inch-thick internal conventional foam will melt completely within approximately 6 hours after completion of topping operations. Therefore, to minimize slush melting while it is stored on the Shuttle, an optimum thermal protection system (TPS) will be required. One candidate TPS is a composite foam internal insulation and high performance external insulation system. The foam would provide the primary insulative capacity for the relatively short period between fluid topping completion and high performance insulation (HPI) evacuation. The HPI would be the primary insulator for the longer period of time between HPI evacuation and slush transfer to the orbital storage facility. Reusability is the primary design criterion for the TPS.

HPI is effective only when the space between the insulative layers is evacuated. This can be accomplished as follows:

1. Using a double-walled dewar with a considerable weight penalty.

2. Employ a flexible vacuum jacket surrounding the HPI (in the 1 atm prelaunch environment, the HPI and vacuum jacket compresses and most of the HPI effectiveness is lost).

3. Employ a cool helium gas (noncondensible at slush hydrogen temperatures) to purge the space between the HPI layers prior to launch.

Two concepts currently appear competitive for slush storage and transfer from the Shuttle. In one concept, the slush hydrogen and its storage tanks would be transferred as an integral unit from the Space Shuttle to the orbital storage module(s). In the other concept, the slush would be transferred from the Shuttle to the storage unit via transfer lines without removing the tank hardware. The primary advantage in the "total-tank-transfer" procedure is that some of the problems of fluid transfer in the orbital, neutral-gravity environment are eliminated. The primary disadvantages of the total-tank-transfer method (therefore, advantages of the slush-only-transfer method) are problems associated with full, massive hydrogen tanks and with maintaining the insulation without major degradation.

Transferring slush hydrogen from the Space Shuttle to the orbital storage unit and again to the Nuclear Shuttle presents several interesting problems, such as illustrated in Figure 6. Slush hydrogen transfer in orbit may be accomplished by:

1. Positive Displacement — Flexibility of bladders at the slush cryogen temperature (25°R) and in the hydrogen environment presents a reliability problem and the mounting of instrumentation and other internal equipment to avoid interference with the bladders may prove difficult.

2. Pressurization or Pumping — Transfer by pressurant or pumping is similar to transfer of the slush in the launch-pad environment except for the slush-vapor interface control requirement. If no means for interface control is provided, much vapor will likely be transferred to the receiver tankage and a residual slush will remain in the supplier tankage. Methods for interface control currently under investigation are:

a. Linear acceleration

b. Centrifugal acceleration.

c. Dielectrophoresis.

d. Phase-change liquid-gas separators.

All of these control methods present technology problems or operational costs yet to be resolved.

C. Orbital Propellant Depot Spacecraft

Unique design criteria for the orbital propellant depot spacecraft include systems for transfer and long-term storage of slush hydrogen in space. More conventional requirements which are nevertheless quite important include transportation of the depot components to orbit, orbital assembly, attitude control, command and control, and power supply and distribution. Since the

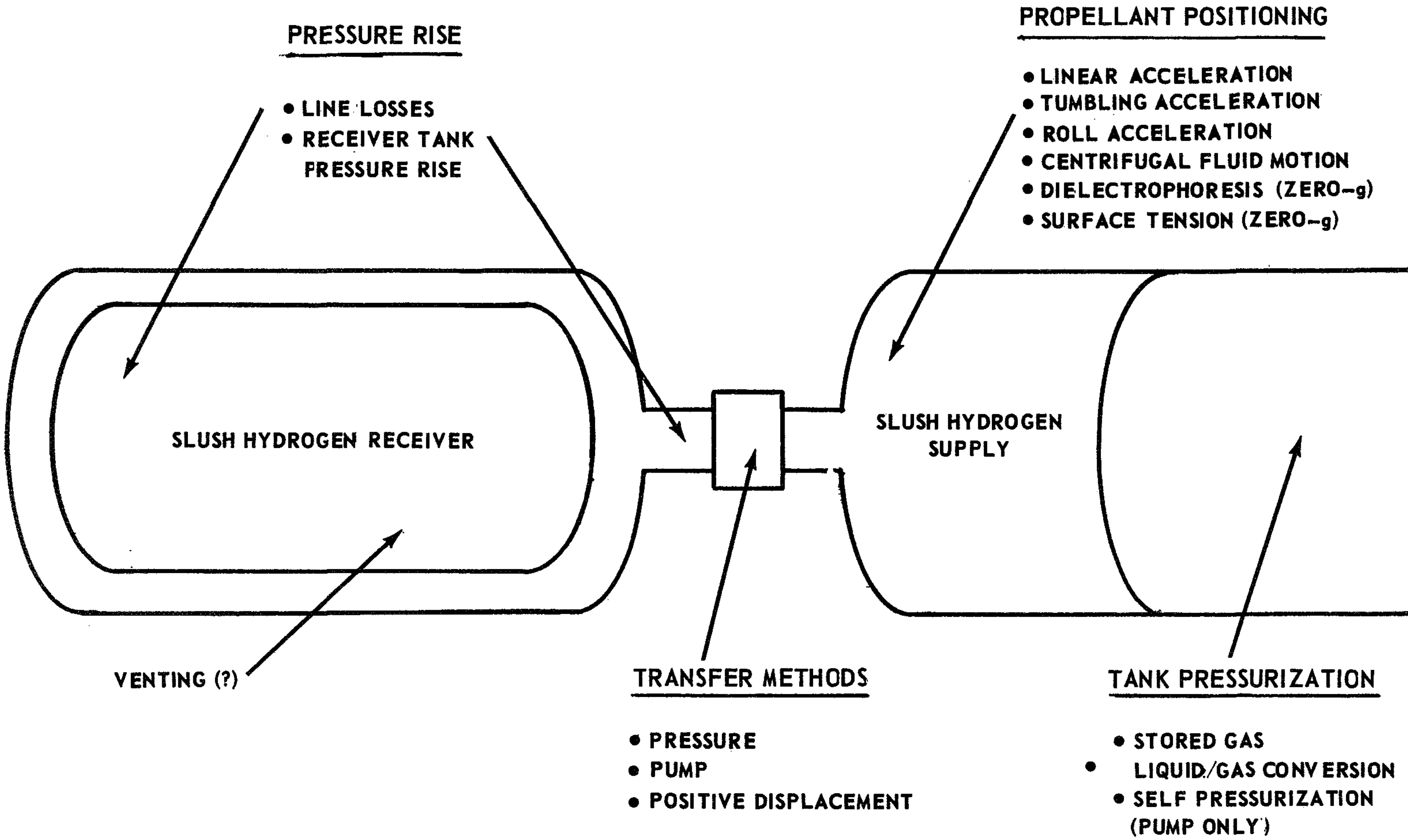

Figure 6. Factors influencing propellant transfer.

Saturn V assembly line may be closed down in the near future, consideration should be given to injecting the tanker into orbit via a Space Shuttle. This would probably require one of the following:

1. A highly collapsible depot configuration which could be inflated and rigidized in space.

2. A depot composed of multiple plates and shells which would be assembled in orbit.

3. A depot composed of multiple smaller tanks transported to orbit individually by the Space Shuttle.

Another large vehicle, perhaps a derivative of the Saturn V such as the Intermediate 21, may possibly be available for use in orbiting the propellant depot.

If docking is to occur between space vehicles, attitude control is an especially important consideration. Attitude control may be accomplished by active or passive means or by a hybrid system. Active attitude-control systems require continuous or intermediate expenditure of energy and are normally used for short-lifetime vehicles or vehicles requiring very precise positioning. Reaction-control and control-moment gyros are potential active attitude-control systems. Passive attitide-control systems usually require little additional expenditure of energy after once being activated. Gravity gradient structures and spinning or rotating bodies provide attitude-control mechanisms.

Sloshing liquids in the depot tanks would tend to complicate the attitude-control problem. Gravity gradient attitude control of the propellant depot does not appear practical because of the changing system moment of inertia caused by the sloshing liquids. Attitude control of the depot through a rotational motion of the depot itself appears promising. Motion of this type may also be capable of providing the slush-vapor interface desirable for slush transfer from the tanker. It may also make possible the uniform heating of the tanker surface, a potentially desirable characteristic for long-term cryogen storage.

The reception of slush by the storage module, long-term orbital slush storage, and transfer of slush to the Lunar Shuttle are design criteria which are unique to the orbital propellant depot. Past studies [8] have indicated that nonvented transfer of liquid cryogen is quite feasible if a mixed thermodynamic model is maintained within the receiver. Nonvented acceptance of slush cryogen by the propellant storage tanks must now be considered. Depot capacity, geometry and operating pressure, and fluid flow and mixing rates are among the factors affecting slush receptance.

Thermal protection of the slush hydrogen onboard the depot is an area of prime importance for the orbital system. Contrary to slush storage on the Shuttle, slush storage aboard the propellant depot requires operation in only one environment. That environment is a hard vacuum, neutral or induced gravity, little or no vibration, and a temperature environment corresponding to earth orbit. The TPS used on this modular depot is, therefore, required to function only in this orbital environment and can be optimized with respect to it. Optimization of the slush thermal protection will include consideration of the following:

1. Surface vacuum insulation such as radiation shields or multilayered insulation.

2. Surface coatings.

3. Vehicle geometry and components arrangement.

4. Vehicle orientation and shadow shields.

Surface insulation will be the first line of defense against heat leakage to the stored cryogen. Radiation foils are highly efficient surface vacuum insulators for small enclosures; however, for large bodies such as the orbital depot, structural limitations will likely preclude effective radiation shield use. A more practical surface vacuum insulation is multilayered HPI. HPI must be optimized for propellant storage tank utilization with respect to weight efficiency, fabrication ease, compressibility, and reliability. Although most HPI composites are lightweight, consideration must be given to total HPI system weights. Fabrication techniques have until recently been a major problem in HPI system designs. Many HPI composites that are highly efficient under ideal conditions are unsatisfactory and unreliable when subjected to slight compressive loads.

HPI systems must be designed to minimize penetration heat leaks from fluid access lines, instrumentation connections, and structural supports. Heat leaks can reduce HPI system efficiency significantly if they are not carefully considered. Heat reflective surface coatings can be used to reduce insulation requirements. Vehicle geometry optimization from the thermal protection standpoint will provide maximum volume for minimum surface area. Components of opposite temperature extremes, such as nuclear reactors and slush storage facilities, should be separated and thermally isolated as much as practical to minimize slush losses. Shadow shields, although usually not employed for thermal protection in near-earth orbits, should be considered for thermal protection along with vehicle orientation with respect to the earth and sun. All of these thermal protection factors must be considered in the optimization of the total-integrated orbital propellant storage system.

The safe-operating pressure of this cryogen storage system will be an important factor in the structural design of the storage system. Stratification of the cryogen may increase ullage pressure buildup by as much as two orders of magnitude over that of unstratified storage. This problem may be alleviated by distributing the thermal-energy leak uniformly throughout the cryogen bulk by mixing or by provision of many high-conductance paths throughout the tanker interior.

If slush solid can be regenerated in orbit from melted slush, thermal protection requirements may be reduced. A tradeoff analysis between weight of slush regeneration equipment (including added power generating equipment), complications, reliability, and expense versus insulation requirements without regeneration should be conducted.

Hydrogen stored in an orbital environment must be protected from the micrometeoroid environment. Options available to prevent storage system failure because of micrometeoroid puncture include micrometeoroid shields (Whipple bumper) [10], multicompartment tanks, and self-sealing tanks [11].

Concepts that apply to transfer of cryogens to the Lunar Shuttle from the propellant depot also apply for transfer from the Space Shuttle to the depot as discussed in earlier paragraphs. The primary differences in the concepts are: (1) a much larger quantity of cryogens, stored for a longer period of time must be transferred, and (2) the transfer system will not be subjected to launch pad and launch environments. The choice must again be made between transferring cryogens only and transferring some tankage and structure along with the propellants.

Instrumentation will be required during all operational phases of the operation of orbital propellant storage system. Requirements for slush quantity and quality monitoring as well as temperature and pressure monitoring must be defined, and a program to develop the required instrumentation must be planned.

Refrigeration technology for such an orbital propellant storage system is yet to be developed. Areas needing significant effort include those of heat-rejection methods, system cycles and efficiencies, and power sources and distribution; however, these should not be considered the only ones.

VI. CONCLUSIONS AND RECOMMENDATIONS

This report indicated that the presently postulated NASA ISP will consume large quantities of LO_2/LH_2 propellants annually during the next

20 years. The yearly usage rate of LH_2 starting near the end of this decade may possibly go as high as 3 500 000 to 4 000 000 pounds. On this basis, detailed analysis of an orbital propellant storage and transfer unit is recommended. This analysis should consider the requirements for such a depot and the potential modes of operation. Specifically, the main points recommended for inclusion in future efforts are:

a. In-depth assessment of the time-phased requirements for various propellants based on the total space program as outlined in the ISP.

b. Evaluation of the results and recommendations of past and current studies with regard to orbital propellant storage requirements for the ISP.

c. Establishment of a baseline orbital propellant storage unit configuration and consideration of alternates thereto.

d. Evaluation of proposed propellant storage and transfer concepts and establishment of a preferred mode of operation.

e. Development of a comprehensive experiment program which includes any precursor ground-based technology developments and any necessary flight demonstrations and experiments necessary to permit establishment of an operational orbital propellant depot by 1980.

f. Identification and delineation of the presently foreseen program costs and schedules.

REFERENCES

1. Integrated Space Program — 1970-1990. MSFC Internal Note IN-PD-SA-69-4. Huntsville, Alabama, December 1969.

2. Whitacre, W. E.: An Analysis of Potential Space Shuttle Cargo Handling Modes of Operation. NASA-Marshall Space Flight Center, February 27, 1970.

3. Burge, G. N.; Blackmon, J. B.; and Madsen, R. A.: Analytical Approaches for the Design of Orbital Refueling Systems. McDonnell-Douglas Astronautics Company, Presented at the AIAA Fifth Propulsion Joint Specialist Conference, June 1969.

4. Boreta, J. E.: Orbital Refueling Techniques. TRW Systems Group, Presented at the AIAA Fifth Propulsion Joint Specialist Conference, June 1969.

5. Wood, C. C.; and Trucks, H. F.: Evaluation of Experiment and Analytical Data for Orbital Refueling Systems. NASA-Marshall Space Flight Center, Presented at the AIAA Fifth Propulsion Joint Specialist Conference, June 1969.

6. Mann, B. B., et al: NBS Report 8881, October 1965.

7. Morgan, L. L., et al: Orbital Refueling and Checkout Study. LMSC T1-51-67-21, App. A;, Vol. 7, Lockheed Missiles and Space Company, Sunnyvale, California, Feburary 1968.

8. Keller, C. W., et al: A Study of Hydrogen Slush and/or Hydrogen Gel Utilization. LMSC K011-68-1K, Lockheed Missiles and Space Company, Sunnyvale, California, October 1968.

9. Vaniman, J. L., et al: Slush and Subcooled Propellants for Lunar and Interplanetary Missions, in "Advances in Cryogenic Engineering." Vol. 14, Plenum Press, New York, 1969, p. 20.

10. Burkley, R. A., et al: Development of Materials and Materials Application Concepts for Joint Use as Cryogenic Insulation and Micro-meteoroid Bumpers. Ger 11676-47, Goodyear Aerospace Corp., Akron, Ohio, June 1968.

11. D'Anna, P. J.; and Heitz, R. M.: Evaluation of Self-Sealing Structures for Space Vehicle Application. NASA CR 485, Northrop Corp., Hawthorne, California, May 1966.

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AN ANALYSIS OF POTENTIAL ORBITAL PROPELLANT STORAGE REQUIREMENTS AND MODES OF OPERATION

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