Integratable Propulsion Systems for the Space Station

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Oxygen/hydrogen propulsion system options for space station orbit maintenance and attitude control are developed and evaluated relative to monopropellant and storable bipropellant propulsion systems. Space station propulsion requirements are analyzed in reference to such considerations as station size, altitude, power, crew size, and orbital transfer and orbital maneuvering vehicle servicing requirements. The evolutionary growth of oxygen/hydrogen bipropellant propulsion as an integral part of several interrelated space station functions—e.g., life support, power, and thermal management—is considered. Propellant resupply evolves from resupply based on transport of liquid oxygen and liquid hydrogen to water. The advantages of the operation of the space station based on an oxygen/hydrogen economy are presented and discussed.

Introduction

A PERMANENT, manned space station has long been recognized as an important step in the exploration and exploitation of space. Such a station would serve many functions, including that of an operational platform for studying the physics of the Earth and the universe, a platform for surveying Earth resources, a laboratory for investigating space medicine and material science, a factory for producing materials under zero-*g* conditions, and a transportation hub for servicing satellites, orbital transfer vehicles (OTV), and planetary spacecraft. At this time, the physical and operational characteristics of the space station are undefined. A major effort is currently underway within NASA and industry to define the requirements and characteristics of a space station with an initial operational capability (IOC) in the early 1990's.

Technology development for the space station will parallel the program definition studies. Technology for the initial station must be ready in FY'87-88 to support a 1991 IOC. The station is expected to grow in size and capability with time to capitaize on technology developments that become available after the IOC to improve operational economics and flexibility. The space station will be designed to facilitate this evolution. In selecting technology for the space station, the evolutionary nature of system requirements must be considered and systems which can support the anticipated growth and capitalize on changes in the statiod architecture should be emphasized.

O_2/H_2 propulsion technology is an example of a technology that offers high performance to accommodate increases in space station orbit maintenance and reaction control requirements and the flexibility to take advantage of fluid resupply and storage system commonality with station power, life support, and OTV servicing systems. Such commonality can result in reduced development costs for common components and can provide opportunities to integrate subsystem fluid supply and thermal control systems. Such integration can lead to reduced costs and improved operational flexibility by cutting down on the number of independent fluid supply and conditioning systems required, by reducing the number of different fluids resupplied, and by utilizing waste products and reject heat effectively.

The inital space station power system will likely consist of a photovoltaic array and an energy storage system to supply power during the 35 min of each orbit when the station is in the Earth's shadow. Regenerative oxygen/hydrogen fuel cell technology is an attractive option for the energy storage system. Such a system calls for small inventories of oxygen and hydrogen, has negligible resupply requirements, and therefore is not an unattractive candidate for fluid supply system integration. The regenerative fuel cell technology is, however, very similar to the water electrolysis technology required for the water resupplied O_2/H_2 propulsion system that will be discussed in this paper.

Logistics requirements for two environmental control and life support systems (ECLSS) for an eight member crew are shown in Fig. 1.[1] The baseline ECLSS recycles water used for hygiene, but is otherwise an open system. The partially closed ECLSS is an advanced system with significantly reduced resupply needs. Quantities of materials that must be supplied to the system, as well as waste products that must be returned to Earth, are shown. It should be observed that the logistics requirements are large—10-20 times the propulsion requirement for the baseline ECLSS—and that large quantities of water must be supplied to and returned from the baseline ECLSS. The water loop is closed in the advanced system, but this ECLSS requires, along with other technology development, water electrolysis technology to produce H_2 to reduce the CO_2 produced by the crew to recycle the oxygen.

Space station propellant resupply and storage requirements for a space-based orbital maneuvering vehicle (OMV) or OTV are large by any comparison. An OMV (eight flights) may require 40,000 lbm of hydrazine or 28,000 lbm of NTO/MMH per year[2]; a space-based O_2/H_2 OTV (six flights) may require 270,000 lbm of O_2/H_2 per year.[3] The space-based OTV should be operational in the time frame of the growth station and the boiloff from cryogenic propellant tankage to support this OTV will be more than sufficient to support station propulsion requirements.

It is clear from the preceding discussion that O_2/H_2 chemical and H_2 resistojet propulsion systems have much in

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common with space station power, life support, and OTV servicing systems. The space station is planned to be an evolving system and its propulsion systems should be designed to both facilitate and capitalize on this evolution. The purpose of this paper is to examine, in a preliminary fashion, alternative implementations of O_2/H_2 propulsion for the initial station that achieve this objective.

Propulsion

The space station propulsion system must routinely provide impulse to reboost the space station after orbital altitude decay and to correct for disturbances associated with Shuttle, OMV, and OTV docking.[4] On a contingency basis, the propulsion system must also provide backup to the primary attitude control system (CMG/magnetic torquer), impulse to effect small altitude changes, and impulse to avoid collision with other spacecraft or space debris.

Drag makeup, the dominant impulse requirement, is dependent on the frontal area of the station normal to the velocity vector and to the atmospheric density, which varies widely as a function of orbital altitude and solar activity. The station frontal area is dominated by the photovoltaic array, the area of which scales with station power. The atmospheric density varies by an order of magnitude, at a given altitude, in response to changes in solar activity during the 11-yr solar cycles.[5] Propulsion systems must be sized to safely accommodate contingencies and the worst-case (1992 2σ atmospheric density) drag makeup requirement.

The altitude selected for the space station has a major influence on both the quantity of propellant required to maintain the orbit of the space station and the cost of transporting this propellant from Earth to the station. Higher altitudes require less propellant, but the reduced Shuttle payload capability to these altitudes results in a higher cost-per-unit mass of propellant transported. Recent work at Marshall and Johnson Space Flight Centers has been directed at a 75-kW initial space station that operates at an altitude of approximately 500 km. The annual impulse requirement for orbit maintenance for this station, based on the 1992 2σ atmosphere, is 1.4×10^6 lbf-s (Refs. 6 and 7).

The frequency at which the space station is resupplied and the worst-case atmospheric density directly influence the size of the propulsion system required. If the station is resupplied every 90 days and the propulsion system is designed to maintain the nominal altitude under 2σ atmospheric conditions, in the event of one missed resupply, the propulsion system must be sized for approximately one-half the annual orbit maintenance impulse previously mentioned.

Thrust levels from 0.06 to 0.12 lbf are sufficient to balance the 2σ drag force at 500 km for the space station configurations under consideration.[4] Near continuous thruster operation is required at these thrust levels. Minimum thrust levels from 1.5 to 100 lbf are required for reaction control functions (e.g., Shuttle berthing disturbances) and for orbit maintenance if it is desired to limit thruster operation to a small percentage of the mission duration.

Oxygen/Hydrogen Propulsion Options

Two oxygen/hydrogen propulsion systems are considered for the initial space station. These systems differ only in the manner in which the propellants are transported to the station and stored onboard. The first system is based on liquid oxygen/liquid hydrogen resupply and storage; the second is based on water resupply and storage and onboard production of gaseous oxygen and hydrogen. Both systems are sized to provide an annual impulse of 0.9×10^6 lbf-s. Propellant resupply will normally be accomplished on a 90-day cycle; onboard tankage is sized to provide one-half the annual impulse requirement. The thruster system is the same in all cases and consists of two 30-lbf thrusters operating at a mixture ratio of 5.0 and delivering a specific impulse of 450 s. A larger number of thrusters will be required in a system designed to meet both reaction control system (RCS) and orbit maintenance requirements, but this configuration will serve to provide a comparison between the two systems.

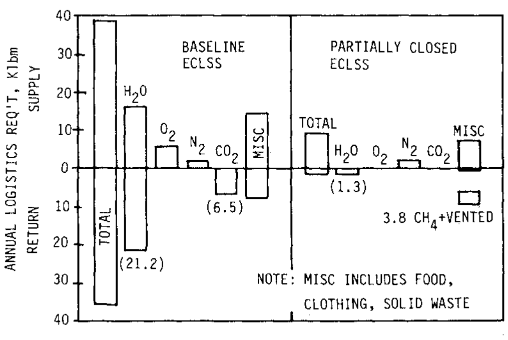

Fig. 1 Environmental control and life support system logistics requirements for eight crew members.

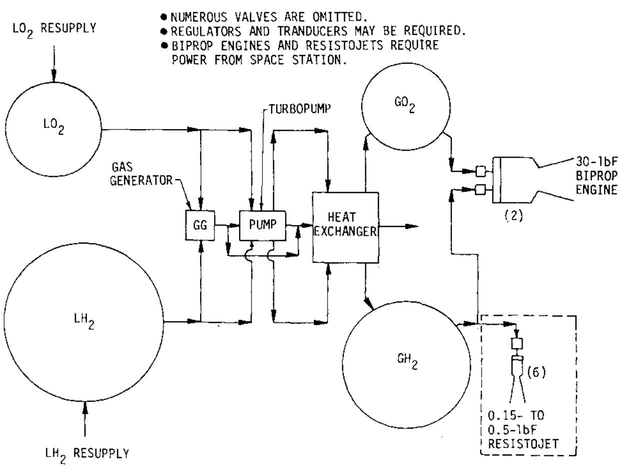

Fig. 2 Early space station oxygen/hydrogen propulsion system based on liquid oxygen/liquid hydrogen resupply.

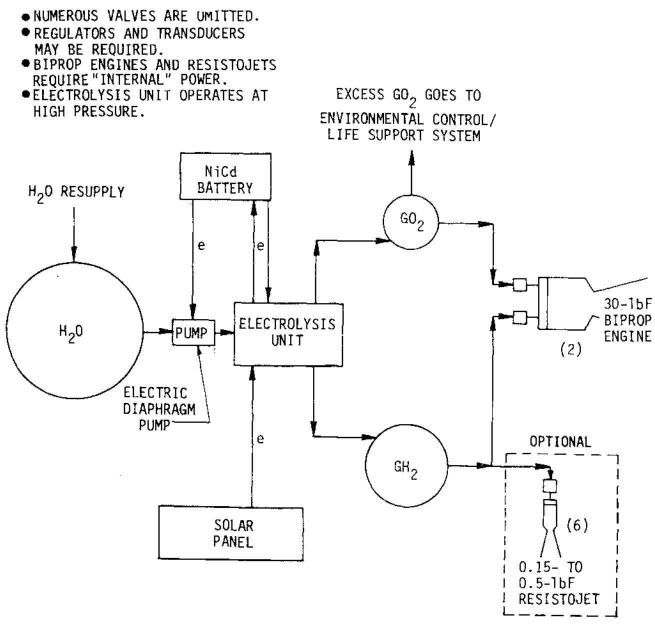

Fig. 3 Early space station oxygen/hydrogen propulsion system based on water resupply: electric diaphragm pump.

The H_2 resistojet is an attractive option for the orbit maintenance function. Such thrusters operate at a specific impulse of approximately 600 s and require approximately 3 kW of power for 0.15 lbf of thrust. Higher performance is possible and is the goal of ongoing technology programs. This thrust level is sufficient to balance the 2σ drag force at a 500 km altitude for continuous operation, but higher thrust levels and powers are required if a shorter period of thruster operation is desired. H_2 resistojets could be used in conjunction with O_2/H_2 chemical thrusters to provide both low-thrust orbit maintenance and high-thrust RCS functions. H_2 resistojet thrusters are shown in each of the schematics presented in this paper but were not evaluated quantitatively. Future studies should consider the advantages of a combined O_2/H_2 chemical and H_2 resistojet system.

Weight is an important factor in the analyses that follow, although it is not considered to be a dominant space station issue at this time. This perception may change as the design matures. Those systems which have paid careful attention to weight may offer required advantages to the early space station in the future.

Table 1 Liquid hydrogen resupply estimated weight summary

Component	Component weight, lbm
30-lbf engine (each of 2)	7.0
0.15- to 0.50-lbf resistojet (each of 6)	a
LO_2 propellant tank (100 psia)	22.5
LH_2 propellant tank (100 psia)	67.3
Gas generator	1.0
Turbopump assembly	3.0
Heat exchanger	11.3
GO_2 accumulator	26.3
GH_2 accumulator	65.0
Valves, regulators, transducers	47.5
Electric harness, lines, supports	16.3
10% contingency	26.7
Total dry weight	293.9
Propellants	1185.0
Total system weight	1478.9
	(1480)

[a] Not included in this study. However, the weight of each resistojet is estimated to be 1.5 lbm including its valve.

Liquid Oxygen/Liquid Hydrogen Resupply Propulsion System

The space station propulsion system based on LO_2/LH_2 resupply is shown in Fig. 2 in a greatly simplified representation. Its major componments are: LO_2 propellant tank; LH_2 propellant tank; fuel rich gas generator; turbopump assembly; heat exchanger; GO_2 accumulator; GH_2 accumulator; two GO_2/GH_2 engines; six GH_2 resistojets; and various valves, regulators, and transducers.

It was assumed that 2000 lbm of propellant will be consumed per year, with one drag make-up burn made every 90 days. Although the space station will be resupplied every 90 days, it was assumed that propellant storage capacity will be required for 1000 lbm of propellant, i.e., two drag make-up burns, to provide an adequate safety margin. In addition, 185 lbm of propellant will be required to drive the tubopump assembly (TPA) and the heat exchanger.

The LO_2 is stored in a 35-in.-diam carbon-epoxy sphere containing a 0.040-in. aluminum inner wall as a barrier between the LO_2 and the overwrap. The sphere is pressurized to 100 psia and weights 22.5 lbm. The LH_2 is stored in a similar 60-in.-diam sphere weighing 67.3 lbm. The sphere weights were estimated using a 4.0 safety factor and include a 25% weight allowance for flanges, supports, etc. Note that the carbon-epoxy spheres weigh less than half of their aluminum counterparts, even at this low pressure.

The gas generator weights 1.0 lbm and operates at a mixture ratio of 0.8, a chamber pressure of 80 psia, and a temperature (T_o) of 1500°R. The hot gas from the gas generator spins a small turbine that drives both the LO_2 and LH_2 pumps. Both propellants are pumped from 100 to 500 psia, requiring a total of only 1.1 hp. This pumping action requires 2% of the total nominal engine flow. The TPA weights 3.0 lbm.

The liquids at 500 psia are passed through a heat exchanger that raises their temperatures to 530°R. The energy from the turbine exhaust gas is not sufficient to vaporize the liquids and raise the temperature of the gases. Additional hot gas from the gas generator is needed to bypass the TPA and enter the heat exchanger directly, requiring an additional 16.5% of the total nominal engine flowrate. The heat exchanger weighs 11.3 lbm.

Table 2 Water resupply estimated weight summary

	Component weight, lbm					
	Electric diaphragm pump			Helium bottle		
Component	90 days	45 days	Daily	90 days	45 days	Daily
30-lbf engines (each of 2)	7.0	7.0	7.0	7.0	7.0	7.0
0.15- to 0.5-lbf resistojet (each of 6)	a	a	a	a	a	a
GO_2 propellant tank	244.5	135.2	6.6	244.5	135.2	6.6
GH_2 propelant tank	656.0	355.9	15.6	656.0	355.9	15.6
H_2O tank	16.0	20.9	25.4	29.1	39.9	50.4
Electric diaphragm pump	1.0	1.0	1.0			
Electrolysis unit	20.0	20.0	20.0	20.0	20.0	20.0
Solar panel	17.9	17.9	17.9	17.9	17.9	17.9
Ni-Cd battery	21.3	21.3	21.3	21.3	21.3	21.3
He bottle				17.0	24.3	31.5
Valves, regulators, transducers	39.5	39.5	39.5	41.8	41.8	41.8
Electric harness, lines, supports	66.6	40.3	10.1	68.6	43.2	13.8
10% contingency	109.0	65.9	16.4	112.3	70.7	22.6
Total dry weight	1198.8	724.9	180.8	1235.5	777.2	248.5
Water	1250.0	1375.0	1500.0	1250.0	1375.0	1500.0
Total system weight	2448.8	2099.9	1680.8	2485.5	2152.2	1748.5
	(2450)	(2100)	(1680)	(2485)	(2150)	(1750)

[a] Not included in this study; however, the weight of each resistojet is estimated to be 1.5 lbm including its valve.

Table 3 Water resupply estimated tank diameters

GO_2/GH_2 engine duty cycle	H_2O tank, in.	GO_2 propellant tank, in.	GH_2 propellant tank, in.	He bottle, in.
Burn every day	43.0	18.0	26.2	25.1
Burn every 45 days	39.0	64.0	93.2	22.8
Burn every 90 days	34.1	80.7	117.4	19.9

Table 4 Weight comparison of water resupply propulsion systems, lbm

GO_2/GH_2 engine duty cycle	Dry weight	H_2O,	O_2/H_2,	Total, weight	Dry weight	H_2O	O_2/H_2	Total weight
Burn every day	180	1500	-	1680	250	1500	-	1750
Burn every 45 days	725	1125	250	2100	775	1125	250	2150
Burn every 90 days	1200	750	500	2450	1235	750	500	2485

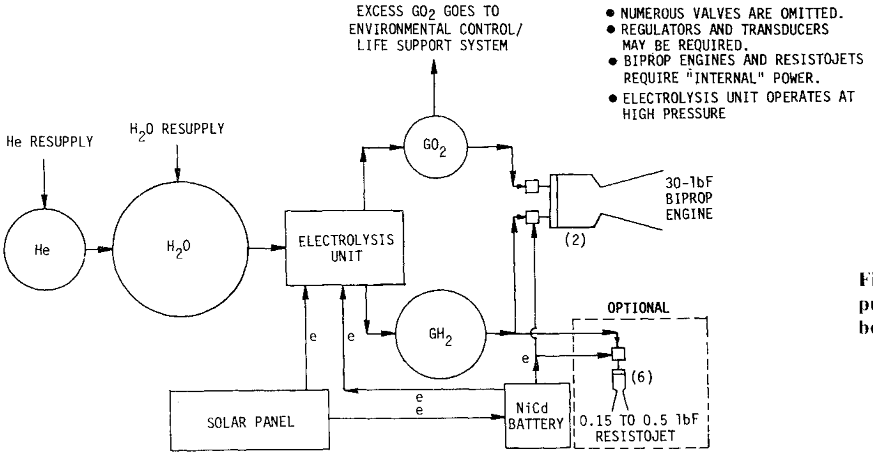

Fig. 4 Early space station oxygen/hydrogen propulsion system based on water resupply: helium bottle.

The GO_2 and GH_2 from the heat exchanger then charge their respective accumulators to 500 psia from which the gases are regulated to 100 psia at the inlets to the engine valve. The GO_2 and GH_2 accumulators weigh 23.6 and 65.0 lbm, respectively. They are of the same carbon/epoxy-aluminum barrier construction. The accumulators allow 15,000 lbf·s of total impulse to be delivered before recharging becomes necessary. This allows most RCS functions to be accomplished without TPA startup, thereby contributing to higher reliability and longer orbital life for the propulsion system. The 30-lbf thrust engines weigh 3.5 lbm each, including their bipropellant valves, and deliver a specific impulse of 450 s. In addition, this propulsion system contains 23 separate valves, 2 regulators, and 6 transducers. Their combined weight is 47.5 lbm.

The total early space station propulsion system based on LO_2/LH_2 resupply weighs 293.9 lbm (see Table 1); the propellant required weighs 1185 lbm, i.e., 1000 lbm for propulsion and 185 lbm to drive the TPA and heat exchanger. The electric power required to operate the propulsion system valves is supplied by the space station power bus.

Propulsion System Based on Water Resupply

Space station propulsion systems based on water resupply are shown in Figs. 3 and 4, in greatly simplified representations. They are comprised of these major components: H_2O tank, electric diaphragm pump, helium pressurant bottle, Ni-Cd battery, electrolysis unit, solar panel, GO_2 propellant tank, GH_2 propellant tank, two GO_2/GH_2 engines, six GH_2 resistojets, and various valves, regulators, and transducers.

The size of the H_2O tank depends upon the number of days between burns. If the engines fire once every 90 days, 500 lbm of GO_2/GH_2 must be available initially in the propellant tanks and 750 lbm of H_2O must be stored in the H_2O tank at ambient pressure to be electrolyzed into 500 lbm of GO_2/GH_2 at a mixture ratio of 5.0, thereby providing a total propellant potential of 1000 lbm and 250 lbm of O_2. Note this "excess" O_2 can be made available to the space station environmental control/life support system.

If a burn is required every 45 days, 250 lbm of GO_2/GH_2 must be available initially for the first burn, while 1125 lbm of H_2O is required to yield 750 lbm of GO_2/GH_2, thereby providing a total propellant mass of 1000 lbm and 375 lbm of O_2. If a daily burn is required, 1500 lbm of H_2O is required to yield 1000 lbm of GO_2/GH_2 and 500 lbm of O_2. In each of these engine duty cycles, a total of 1000 lbm of GO_2/GH_2 is available after resupply.

The data presented in Fig. 5 show that the total tankage weight is much lower when the H_2O based system is fired daily, thereby removing the requirement for comparatively large, heavy-walled propellant tanks. The weights for the several tanks are presented in Table 2; their respective diameters are presented in Table 3.

The diaphragm pump power requirements are based on pumping 750 lbm of H_2O from 14.7 to 500 psia in 75 days. This requires only 0.27 W of power—a very small motor/pump combination. The smallest feasible component weighs 1.0 lbm.

An electrolysis unit capable of converting 750 lbm of H_2O to GO_2/GH_2 at 500 psia in 75 days weighs 20 lbm and has a power requirement of 850 W.[8,9] Since Ni-Cd batteries weigh 0.025 lbm/W, the required Ni-Cd battery weighs 21.3 lbm. Ga-As solar panels weigh 0.013 lbm/W; hence, the required solar panel weighs 17.9 lbm.

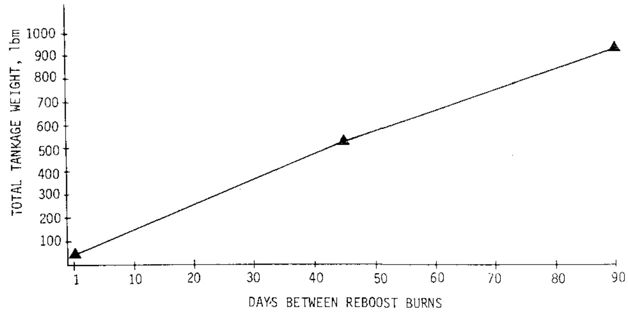

Fig. 5 Total tankage weight vs days between reboost burns for early space station propulsion systems based on water resupply.

The GO_2/GH_2 engines and GH_2 resistojets are identical to those of the LO_2/LH_2 resupplied system. The valves, regulators, and transducers weigh 39.5 lbm.

The effect of replacing the electric diaphragm pump, Fig. 3, with a helium bottle pressurized at 2500 psia, Fig. 4, was studied. Again the weights for the bottles are presented in Table 2 and their respective diameters are presented in Table 3. The valves, regulators, and transducers weigh 41.8 lbm in the helium bottle configuration. The other component weights are unchanged.

A simplified comparison of the electric diaphragm pump and helium bottle water resupply propulsion systems is provided in Table 4. The weight benefit that results from the daily burn duty cycle is clearly evident for both systems; i.e., the pump system weight decreases 770 lbm (31%) from 2450 to 1680 lbm, and the bottle system weight decreases 725 lbm (29%) from 2485 to 1750 lbm.

The weight advantage of the pump system over the bottle system is modest, averaging only 51.7 lbm (2.5%) over the range of duty cycles shown. Therefore, the selection of one of these H_2O resupply propulsion systems for space station application should be based on other considerations—e.g., the need to resupply He, the effect of He on the operation of the water electrolysis unit, and the performance and reliability of the electric diaphragm pump.

Propulsion System Comparison

The LO_2/LH_2 system wet mass of 1480 lbm is 12% less than the mass of the lightest H_2O system (1680 lbm) at a mixture ratio of 5.0. At this mixture ratio the H_2 system does not fully utilize the O_2 available from the water. The oxygen in excess of the propulsion requirement could be made available to the ECLSS, the fuel cell stored energy system, or some other space station function. It should also be noted that cryogenic propellant thermal control requirements were not addressed in this preliminary study and could significantly impact the results of this comparison in favor of the H_2O resupplied propulsion system. The selection of an H_2O resupply propulsion system for the space station propulsion application will be based on broader system considerations, e.g., the comparative cost and ease of H_2O resupply vs LO_2/LH_2 resupply, the benefit of surplus GO_2 to the ECLSS, the performance and reliability of the electrolysis unit. LO_2/LH_2 resupply, requiring less technology development, could serve as the first step in an evolutionary process that leads to a self-contained H_2 resupplied propulsion system and finally to an O_2/H_2 system integrated with the ECLSS or OTV servicing systems.

Summary and Conclusions

Oyxgen/hydrogen chemical propulsion and H_2 resistojet propulsion are not only high-performance options, but are options that potentially can capitalize on commonality with other space station systems. High performance translates into reduced propellant resupply requirements. An O_2/H_2 chemical system requires 30% less propellant than an NTO/MMH system and 50% less propellant than a hydrazine system. An H_2 resistojet requires 45% less propellant than an NTO/MMH system and 65% less propellant than a hydrazine system. Over the life of the space station, the savings in transportation costs for these propellants can be substantial. Possibly more important is the potential that these systems offer for integration with the ECLSS and OTV propellant servicing systems. It may be possible to process waste water from early ECLSS systems to provide all the oxygen and hydrogen needed for Space Station propulsion requirements. Water electrolysis technology is common to the ECLSS, power, and propulsion systems and may be developed synergisticaly. Large amounts of oxygen and hydrogen will be available on the growth station (or a tethered module) to support the space-based OTV. Boiloff from these systems is likely to be more than sufficient to meet space station propulsion needs.

This study has identified and evaluated two O_2/H_2 chemical propulsion options for the space station. The results of this preliminary analysis show promise, but detailed studies directed at specific space station configurations and operational characteristics are required before an accurate technology assessment can be made.

Acknowledgment

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References

[1]"Environmental Control Life Support (ECLS)," Hamilton Standard Presentation, Document 83 D010A, Space Station Concept Development Group Workshop, Sept. 1983.

[2]"Teleoperator Maneuvering System Study, Mission Requirements and System Definition," Vought Corp. Rept 2-32500/1R-52821, July 1981.

[3]"Centaur F Technical Description," General Dynamics Corp. Rept. CFTD-3, Rev. 3, Aug. 1982.

[4]Klemetson, R. W. and Garrison, P. W., "Space Station Propulsion Technology Study," Jet Propulsion Laboratory, Pasadena, Calif. JPL D-972, D-972, Dec. 1983.

[5]"Models of the Earth's Atmosphere (120 to 1000 km)," NASA SP 8021, March 1983, Revision.

[6]Donovan, R. M., Sovey, J. S., and Hannum, N. B., "Space Station Propulsion Analysis Study," AIAA Paper 84-1327, 1984.

[7]Smith, W. W., Wilkenson, C. L., and Valgora, M. E., "Factors that Influence Space Station Propulsion Requirements," JANNAF Propulsion Conference, New Orleans, La., Feb. 1984.

[8]Nuttal, L. J., "Present State-of-the-Art of SPE Fuel Cells and Water Electrolyzers for Space Station Electrical Energy Storage Systems," Space Station Technology Workshop, Williamsburg, Va., March 1983.

[9]McElroy, J., "Present State-of-the-Art and Required Technology Development Associated with SPE Water Electrolysis Subsystem for Space Station Regenerative Life Support Systems," Space Station Technology Workshop, Williamsburg, Va., March 1983.