Sensitivity of Propulsion System Selection to Space Station Freedom Performance Requirements

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Space Station Freedom's propulsion system performs several functions key to spacecraft survival, namely, altitude maintenance (reboost), backup attitude control, collision avoidance, and contingency maneuvers. Two types of concepts have been considered for this role: selecting the appropriate one depends on how much the Freedom program is willing to invest in the system's development. The simple, inexpensive concept, hydrazine, is best for limiting initial costs and freeing up funds for development of near-term payload services; while the advanced system, water electrolysis, is preferred for minimizing Station logistics support and life cycle costs. Resistojets offer similar operational cost benefits, but only by reducing the reboost propellant requirements of either primary system. This selection rationale resulted from prior trades that compared point designs of various standalone and combined system concepts. Unfortunately, the designs were sized to meet performance requirements which have subsequently changed with maturation of the Station's design. The objective of this study is to reassess life cycle costs using an approach that is immune to changes in the Station's configuration. Rather than using point designs, the concepts are evaluated over a range of anticipated performance requirements. In addition, the full benefits of resistojets are accounted for by regarding the total impulse requirements for reboost and high-thrust maneuvers as separate and distinct. The results clearly indicate that the selection rationale, which has predicated previous changes to the baseline, is invalid for some possible combinations of performance requirements.

Nomenclature

$C_{i(x)}$ = initial costs (system x)
C_{LCC} = propulsion life cycle costs
$C_{o(x)}$ = operating costs (system x)
$C_{P(x)}$ = power costs (system x)
$C_{res(x)}$ = propellant resupply costs (system x)
$C_{ret(x)}$ = water return costs (system x)
c_L = specific launch costs; \$ per lbm
c_P = specific power costs; \$ per kW · hr
f_D = ratio of downsupply costs to launch costs
f_R = ratio of reboost to overall total impulse ($= It_{reb}/It_{req}$)
f_T = carrier fluid mass fraction
$Is_{(x)}$ = specific impulse; sec (system x)
It_{acs} = high-thrust total impulse; lbf · sec/yr
It_e = max total impulse from water electrolysis; lbf · sec/yr ($= W_w \cdot Is_e$)
It_{gr} = max total impulse from gas resistojets; lbf · sec/yr ($= W_g \cdot Is_{gr}$)
It_{reb} = reboost total impulse; lbf · sec/yr
It_{req} = overall total impulse ($= It_{acs} + It_{reb}$)
It_{wr} = max total impulse from water resistojets; lbf · sec/yr ($= W_w \cdot Is_{wr}$)
$P_{(x)}$ = specific power consumption; kW · hr/lbm (system x)
t = time or costing period; yrs
W_e = electrolyzed water; lbm/yr
W_g = waste gas availability; lbm/yr
W_{pres} = propellant resupply requirement; lbm/yr
W_w = excess water availability; lbm/yr
W_{wret} = water return requirement; lbm/yr

Propulsion System Subscripts (x)
e = water electrolysis
gr = gas resistojets
h = hydrazine
wr = water resistojets

Introduction

PROPULSION is one of many systems comprising Space Station Freedom. Although necessary for Station survival, it does not play a critical role in supporting on-board users, payloads and experiments. Its importance lies in the heavy reliance it could eventually place on expensive launch and logistic services. Thus, identifying an affordable option, which will not overly burden operational costs, has always been a major goal of the Freedom program.

The following paper presents a system comparison that differs markedly from previous assessments. Rather than relying on point designs, the study examines the sensitivity of life cycle costs over a range of performance requirements. The results are subsequently expressed in the form of a graph that identifies the lowest cost options for different combinations of requirements. This propulsion system selection map provides a valuable systems engineering tool for guiding the down-selection of options as the Station design evolves and becomes more definite.

Propulsion System Functions

The principal function of the Station's propulsion system is to maintain altitude and compensate for the cumulative effects of drag. This maneuver, otherwise known as reboost, is executed at preplanned intervals and does not require the short response times and precise acceleration levels that characterize typical reaction control firings. Because there is no minimum acceleration limit for this maneuver, reboost can be performed with either chemical thrusters, using propellants such as hydrazine and gaseous oxygen/hydrogen (O2/H2), or low thrust devices, such as gas and water resistojets.

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The propulsion system also performs maneuvers that require short response times and predictable performance. One of these roles is to serve as a backup to the primary attitude control system (ACS), which nominally relies on control moment gyros (CMG)s for stability and orientation. This includes the periodic firing of propulsion thrusters to desaturate (i.e., realign and adjust) the principal spin axes of the CMGs. In a similar role, propulsion provides for rapid changes in orbital direction or gross corrections in orientation. This includes collision avoidance maneuvers and compensation for disturbances induced by Shuttle Orbiter dockings. In contrast to reboost, all of these maneuvers require the higher thrust levels that can only be obtained with chemical thrusters.

Propulsion System Options

Many types of propulsion concepts have been evaluated for use on the Station.[1-3] These assessments have generally supported hydrazine and water electrolysis as the most practicable candidates for performing all propulsion functions (i.e., primary system role), and have recommended the use of resistojets to augment the reboost capability of either primary system.

A hydrazine system has usually been preferred whenever the Freedom program concentrated on limiting development and initial hardware costs. Because of hydrazine's prevalent use on satellites and spacecraft, it is feasible that such a system could be built from existing "off-the-shelf" hardware, thereby minimizing development risk to the program. The chief disadvantage with hydrazine is its complete reliance on logistics for propellant resupply. This could result in exorbitant life cycle expenditures considering the propellant's relatively low specific impulse, Is_h, of 220 s.

The other primary system option, water electrolysis, employs thrusters which use gaseous oxygen and hydrogen (O2/H2) produced from electrolyzed water. The key advantages of this system are its relatively high specific impluse, Is_e, of 380 s and ability to use water discarded by other Station systems and payloads.[4-7] These advantages translate into two effects which mutually contribute in reducing demand on Shuttle and logistics services.

Most obvious is reduction in propellant resupply and launch costs. The less apparent effect, reduction in Shuttle return cargo, arises from the strict contamination limits imposed by observational payloads and prohibition on dumping into the immediate external environment. The Shuttle is the preferred option for removing wastes because other alternatives, such as deorbit and aero-incineration, unduly tax on-orbit operations and payload integration activities. Downsupply capability for the Shuttle, however, is a limited resource and favors the consumption of water on-orbit. Therefore, the savings accrued from reducing both resupply and downsupply could make the electrolysis system less expensive to operate over the Station's lifetime and could more than compensate for its higher development costs.

The third set of options, namely, gas and water resistojets, are practical only for augmenting the reboost capability of either a hydrazine or water electrolysis system. Heat transfer inefficiencies and reduced chamber pressures restrict their use to low thrust applications. Although the specific impulses of these devices typically range between 120 s to 160 s, under some conditions, resistojets can significantly improve the life cycle costs of either primary system.

Although gas and water resistojets are similar in terms of design, function, and performance, their individual effects on life cycle costs are quite different. Water resistojets, like the electrolysis system, reduce Shuttle resupply and return requirements. Under some conditions, this feature can be exercised in conjunction with an electrolysis system to optimize water usage and eliminate transportation requirements.

The influence of gas resistojets is different. Venting of the waste gases produced by experiments and other Station systems is undesirable from the standpoint of observational payloads.[7] However, it may still be required to alleviate the high costs associated with compressing, storing, and transporting low-density mixtures to Earth. If venting is permitted then gas resistojets are beneficial only in reducing propellant resupply and have no influence on downsupply.

These differences make it extremely important to distinguish the two types of resistojets when making any cost assessment. It also suggests that using the two together would exploit their principal strengths and provide simultaneous reductions in reboost propellant requirements and water return costs. Therefore, to examine the entire range of possible cost benefits, all combinations of resistojets and primary systems must be considered. This results in the eight standalone and combined system options shown in Table 1.

Problem

A series of studies was conducted in 1985 and 1986[8,9] to determine an appropriate propulsion baseline for the Station. Several concepts, which essentially paralleled the options in Table 1, were compared on the basis of development and life cycle costs. These studies were significant because they resulted in the selection rationale that has predicated all subsequent changes to the baseline, that is, hydrazine having the lowest development cost and water electrolysis having the lowest life cycle cost.

These studies were rigorous in their level of detail, particularly with regards to hardware costs and operational requirements. Detailed designs and layouts of each propulsion concept were developed in order to estimate the number and size of different components. In addition, operations costs were calculated by examining resupply, downsupply, and maintenance requirements for each flight increment during the Station's lifetime.

Unfortunately, this detailed approach limited the overall utility of these studies. The life cycle cost of each point design strongly depends on the total impulse requirements (i.e., performance requirements) assumed for the Station configuration. These, in turn, are dictated by the flight profile, reboost schedule, mass, and design of the reference configuration. Since these studies were performed, the Station's design has matured to where the originally assumed performance requirements are no longer representative of the current configuration. This is important from a selection standpoint because any shift from the original requirements will change the magnitude of life cycle cost for each option. Most importantly, it could, depending on the amount of available waste fluids, alter the cost relationship between the different propulsion concepts, thereby invalidating the selection rationale established in prior studies.

Objectives

The chief limitation of these studies was their failure to acknowledge the indefinite nature of Station performance requirements. Their utility would have been greatly improved if the sensitivity of life cycle cost over an anticipated range of performance requirements had first been determined. Rather than pointing to a single option, this approach would have identified the most viable candidates for different design conditions and would have effectively provided an intermediate step in the selection process. With this information, the Freedom program could downselect to the most viable candidate as the design matured and performance requirements became better understood.

Table 1 Propulsion options

Primary system resistojets	Hydrazine	Water electrolysis (O2/H2)
None (Standalone)	1A	2A
Gas Only	1B	2B
Water Only	1C	2C
Gas and Water	1D	2D

The objective of the study presented in this paper is to compare the life cycle costs of several standalone and combined systems over a range of expected reboost and high-thrust maneuver requirements, and thus provide the intermediate step that was missing from previous assessments. The two main products of this analysis are a series of parametrics, which illustrate how life cycle cost varies for each option, and a propulsion system selection map, which identifies the lowest cost alternatives as function of reboost and high-thrust maneuver requirements.

Before proceeding, two points should be made about the representation of total impulse requirements and the assumed values of waste fluids availability. First, there are several ways of representing total impulse while distinguishing between requirements for reboost and high-thrust maneuvers. One is to keep the two maneuvers separate and define them in terms of their actual values, namely, It_{reb} and It_{acs}. Another way is to use the overall requirement, It_{req}, and a variable that defines what fraction of this pertains to reboost, f_R. Both methods are used throughout this paper. However, the final results (i.e., parametrics) are portrayed in terms of It_{req} and f_R in order to highlight how changing the allocation between reboost and high-thrust maneuvers influences cost.

The other point deals with the values of waste water and gas. The cost relationships used in this study show that the on-orbit fluid balance has as much impact on life cycle costs as total impulse. Since this balance also depends on the Station configuration, a thorough assessment of propulsion alternatives must account for the variance of these values as well. This entails the consideration of four independent variables, which is well beyond the scope of this paper. Therefore, the quantities of waste fluids in all calculations are held at values indicative of typical Station operational conditions,[4,5,7,9,10] namely, 3497 lbm/yr for waste gas and 3920 lbm/yr for excess water. Note that the cost impact of varying these parameters could be assessed by applying the same approach and algorithms described in this paper.

Approach

The approach differs markedly from prior assessments. It relies on a set of life cycle cost algorithms that account for the individual impacts of development, performance requirements, fluids availability and Shuttle transport. The method treats the contributions of these effects in a general manner and neglects transient variations in performance over the Station's lifetime. Although this approach tends to simplify cost estimates, it suffices for examining parametric trends without resorting to sophisticated computational models.

The scope is restricted to the eight concepts defined in Table 1. The first two options, 1A and 2A, represent standalone versions of the primary systems. The last six concepts are included to assess the potential benefits of employing various combined systems and represent all reasonable combinations of hydrazine, water electrolysis, gas resistojets, and water resistojets. Note that this group includes two cases, 1D and 2D, for examining the simultaneous use of gas and water resistojets.

The approach entails constructing a cost algorithm for each of the options in Table 1. These algorithms are then incorporated into a computer code to enable rapid calculations at different values of total impulse.

The formulation of cost algorithms consists of a two step process, that could also be applied in similar analyses for orbital spacecraft other than Space Station Freedom. The first step is to derive a general equation for life cycle cost and express it as a function of key design and operational parameters. This is done by considering the equation as the sum of five separate terms, each representing a distinct expenditure incurred over the propulsion system's lifetime.

Several of these terms strongly depend on the relationship between performance requirements (i.e., total impulse required for reboost and high-thrust maneuvers) and the quantity of available waste fluids (i.e., water and waste gas). Although the latter set of values is fixed in this study, the relationship still changes depending on the total impulse values specified in the algorithm. This effect becomes most notable with the combined electrolysis/water resistojet system, which attempts to optimize the allocation of waste water between its O2/H2 and resistojet thrusters.

This situation necessitates the inclusion of logic in each algorithm to account for different conditions between the assumed fluids balance and specified performance requirements. Once the conditions are defined, the general equation is used to develop cost relationships which correspond with each condition. The conditions are expressed in the form of a decision tree that guides the selection of appropriate cost relationships in a simple computer program. When run, the program determines the appropriate condition from input values of total impulse and applies its corresponding relationship to calculate life cycle cost.

Life Cycle Cost Equations

The life cycle cost of each option shown in Table 1 is expressed as the sum of the following 5 terms:

$$C_{\text{LCC}} = C_i + C_p + C_{\text{res}} + C_{\text{ret}} + C_o \qquad (1)$$

Each of these terms represents a distinct expenditure incurred during the propulsion system's lifetime. Because of its general nature, this equation can be used to express propulsion life cycle costs for any orbital spacecraft that depends on intermittent logistics support.

Initial Costs

The first term, C_i, represents costs incurred before the system begins operating, and includes expenditures for development, test, integration, launch, and final assembly. C_i is primarily a function of the system's technical sophistication and level of development. Realistically, it also depends on performance requirements, which influence the number and size of key components (e.g., accumulators, lines, conditioning equipment, and thrusters). When comparing systems of similar capability, however, this effect is secondary and is ignored in order to simplify the costing relationships.

A fixed value of C_i is defined for each of the primary systems (i.e., hydrazine and electrolysis) and each of the resistojet augments (i.e., gas and water). Costs for the combined concepts are determined by summing the C_i values of their primary and resistojet elements.

Prior cost estimates for hydrazine[8,11,12] have typically varied between \$75 million and \$125 million. These values are predictably low since most of the system could feasibly be built from existing "off-the-shelf" hardware. In fact, a simple configuration comprised of transportable thruster/storage modules would require no enabling development at all. For lack of any firm designated cost, an intermediate value of \$100 million is assumed for this analysis.

The cost of an electrolysis system is anticipated to be greater since this type of propulsion has never been used on a spacecraft. Most of this extra cost is due to the added risk in developing and qualifying the system's long-life gaseous O2/H2 thrusters, accumulators, and high pressure electrolyzers. Technology activities in these areas[13,14] have shown that the development issues associated with these components are resolvable by the time the Station design is finalized. However, most sources project the initial costs to be 25% greater than a comparable hydrazine system.[8,11,12]

Both of the resistojet systems considered in this study are simpler, smaller, and consequently less expensive than either of the primary systems. For this study, a value of \$12 million was assumed for each.[15] Note that the resistojet costs for options 1D and 2D are assumed to be \$24 million.

The remaining terms in Eq. 1 represent costs that recur over the system's lifetime and increase linearly with time.

Three of these, namely, power, resupply, and water return, are sensitive to propellant requirements and the amount of excess fluids produced on-orbit.

Power Costs

All of the systems besides hydrazine require a substantial amount of power to operate. Electrical power, however, is a limited resource that must be selectively allocated to many Station users and payloads. Implementing an energy-intensive propulsion system, such as electrolysis and/or resistojets, would limit the power available to experiments and restrict the Station's overall utility. This penalty is accounted for in the following term:

$$C_p = c_p P_e W_e t \tag{2}$$

Although this equation is expressed in terms of electrolysis system parameters, the same general relationship holds for calculating resistojet power costs.

The value of c_p used in this analysis, \$123.30/kW · hr,[12] is based on a Phase B estimate that considered the costs of building and maintaining a 150 kW power system. P_e represents the power required to utilize 1 lbm of propellant, and it is a function of the system's design and operational characteristics. For electrolysis, its value depends chiefly on electrolyzer design parameters, such as oxygen/hydrogen generation rate and operating pressure. For this study, a solid polymer-type unit operating at 3000 psi is assumed,[16] thus yielding a specific power consumption of 2.68 kW · hr/lbm of water.

Power costs for resistojets differ only in the values for specific power consumption and the amount of fluid consumed. For gas resistojets, the energy provided to heat the propellant also influences specific impulse, which varies linearly with the ratio of power to thrust.[17,18] This is extremely difficult to fix because the composition of waste gas mixtures will fluctuate over time. It is also beyond the scope of this steady-state analysis. Therefore, a reasonable energy requirement, P_{gr}, of 0.24 kW · hr/lbm is assumed, thus yielding an average specific impulse, Is_{gr}, of 160 s.

The same methodology can be applied to water resistojets. However, additional energy for vaporization and superheat is needed upstream of the thrust chamber to prevent condensation and deposition within the nozzle. This extra energy is substantial and comprises nearly 47% of the heat delivered to the flow.[19] For this analysis, a heat transfer efficiency of 0.35 and specific energy of 0.57 kW · hr/lbm is assumed, thus yielding a specific impulse, Is_{wr}, of 180 s.

With hydrazine, only a small amount of energy is required for external tank heating, valve actuation, and control. The requirements, in fact, are roughly 100 times less than that of a comparable electrolysis system. For this reason, this term is ignored in the cost expression for hydrazine.

Propellant Resupply Costs

The term, C_{res}, represents propellant resupply costs. Apart from a few constants, which account for inert weight of the propellant carrier and launch costs, this term is directly proportional to the mass of propellant carried to the Station

$$C_{res} = c_L/f_T(1 + (1 - f_T)f_D)W_{pres}t = LW_{pres}t \tag{3}$$

The effect of carrier structure and tankage is accounted for by f_T, which represents the ratio of propellant mass to fully loaded tanker mass. This variable is useful in distinguishing the tankage required for fluids with different densities and storage states. However, this is not important when comparing water and hydrazine, because both fluids are earth-storable with approximately equivalent densities. Therefore, the mass fraction for both is set at 0.7, a reasonable value for this type of carrier.

Besides propellant mass, the most significant parameters in Eq. (3) are c_L and f_D. The cost of launching 1 lbm of cargo, c_L, is estimated by dividing the cost for a typical Shuttle launch by its total payload lift capability. With an assumed capacity of 33,000 lbm and cost of \$100 million, this equates to \$3,000/lbm.[8] Note that this assumes launch weight to be the chief constraint on Shuttle manifest and ignores any limitations imposed by the cargo bay's volume.

The variable that accounts for return of the empty carrier, f_D, is important, because Shuttle return mass, like power and launch manifest, is a limited resource. Only a small amount of cargo carried to the Station is actually consumed or disposed of in orbit. During steady-state operations, almost all of it is "converted" into spent hardware, wastes, and experiment products. Because of the prohibition on dumping, most of this converted cargo is returned to Earth, thereby placing a downsupply demand on the Orbiter. Note that deorbit and aero-incineration have been studied for on-orbit disposal of waste. However, they have not been widely accepted because they would unduly tax on-orbit operations and reduce crew time available for experiments and payloads.

Downsupply is further constrained by the smaller cargo return capability of the Shuttle. Although this aspect depends on several factors such as landing location and Station altitude, it is approximated as being roughly half of the lift capacity (i.e., 17,000 lbm).[8] The return capability is thus less than the demand.

To correct this situation, extra unused Shuttle space must be allocated at launch. Obviously, any reduction in downsupply weight by consuming water on-orbit should be reflected as a reduction in the propulsion system's costs. With the assumptions that resupply approximately equals downsupply and shuttle return capability equals 17,000 lbm, eliminating the return of 1 lbm of cargo reduces 2 lbm of unused Shuttle launch manifest. This represents a \$6000 savings in launch costs and yields a ratio of downsupply costs to launch costs of 2.0.

Water Return Costs

The term, C_{ret}, in Eq. (1) represents the cumulative cost of returning unused water to Earth. Although this is not a responsibility of the propulsion system, it is included to account for the cost benefits of on-orbit consumption and reduction in downsupply demand. This term is similar to Eq. (3), but is based on launching an empty carrier to orbit and filling it completely before its return to Earth.

$$C_{ret} = c_L/f_T[(1 - f_T) + f_D]W_{wret}t = RW_{wret}t \tag{4}$$

This term primarily depends on the unused quantity of water leftover from propulsion. For a standalone hydrazine case, it would include all the excess water produced by onboard systems. With electrolysis or water resistojets this term may be either reduced or eliminated.

Other Operational Costs

The last term in Eq. (1) accounts for the continuous maintenance, upkeep, and repair of the system. Typical estimates for hydrazine are \$1.5 million per year. Similar costs for electrolysis are approximately 50% higher due to increased maintenance of high pressure gas distribution lines and external electrolysis units. Resistojet maintenance costs are assumed to be \$1.5 million/year for each system because of their reduced complexity.

Life Cycle Cost Comparisons

The expressions in Eqs. (1) to (4) provide a basis for developing costing algorithms for each option in Table 1. As stated earlier, it is extremely important to consider how the relationship between total impulse requirements (It_{acs} and It_{reb}) and total impulse available from waste fluids (It_e, It_{wr} and It_{gr}) varies over the expected range of performance requirements.

Table 2 Cost algorithms—standalone options

Fluid balance conditions		C_i	C_o	C_P	C_{res}	C_{ret}
Hydrazine	All total impulse values	C_{ih}	$C_{oh}t$	—	$\left(\frac{It_{req}}{Is_h}\right)Lt$	W_wRt
O2/H2	$It_{req} \geq It_{gr}$	C_{ie}	$C_{oe}t$	$P_e\left(\frac{It_{req}}{Is_e}\right)C_pt$	$\left(\frac{It_{req}}{Is_e} - W_w\right)Lt$	—
	$It_{req} < It_{gr}$	C_{ie}	$C_{oe}t$	$P_e\left(\frac{It_{req}}{Is_e}\right)C_pt$	—	$\left(W_w - \frac{It_{req}}{Is_e}\right)Lt$

Table 3 Cost algorithms—gas resistojet options

Fluid balance conditions			C_i	C_o	C_p	C_{res}	C_{ret}
Hydrazine		$It_{reb} \geq It_{gr}$	$C_{ih} + C_{igr}$	$(C_{oh} + C_{ogr})t$	$P_{gr}W_gC_pt$	$\left(\frac{It_{req}}{Is_h} - W_g\right)Lt$	W_wRt
		$It_{reb} < It_{gr}$	"	"	$P_{gr}\left(\frac{It_{reb}}{Is_{gr}}\right)C_pt$	$\frac{It_{acs}}{Is_h}Lt$	W_wRt
Water Electrolysis (O2/H2)	$It_{acs} \geq It_e$	$It_{reb} \geq It_{gr}$	$C_{ie} + C_{igr}$	$(C_{oe} + C_{ogr})t$	$\left[P_e\left(\frac{It_{req} - It_{gr}}{Is_e}\right) + P_{gr}W_g\right]C_pt$	$\left(\frac{It_{req} - It_e - It_{gr}}{Is_e}\right)Lt$	—
		$It_{reb} < It_{gr}$	"	"	$\left[P_e\left(\frac{It_{acs}}{Is_e}\right) + P_{gr}\left(\frac{It_{reb}}{Is_{gr}}\right)\right]C_pt$	$\left(\frac{It_{acs} - It_e}{Is_e}\right)Lt$	—
	$It_{acs} < It_e$	$It_{req} \geq It_e + It_{gr}$	"	"	$\left[P_e\left(\frac{It_{req} - It_{gr}}{Is_e}\right) + P_{gr}W_g\right]C_pt$	$\left(\frac{It_{req} - It_e - It_{gr}}{Is_e}\right)Lt$	—
		$It_e + It_{gr} > It_{reb} \geq It_e$	"	"	$\left[P_{gr}\left(\frac{It_{req} - It_e}{Is_{gr}}\right) + P_eW_w\right]C_pt$	—	—
		$It_{req} < It_e$	"	"	$P_e\left(\frac{It_{req}}{Is_e}\right)C_pt$	—	$\left(W_w - \frac{It_{req}}{Is_e}\right)Rt$

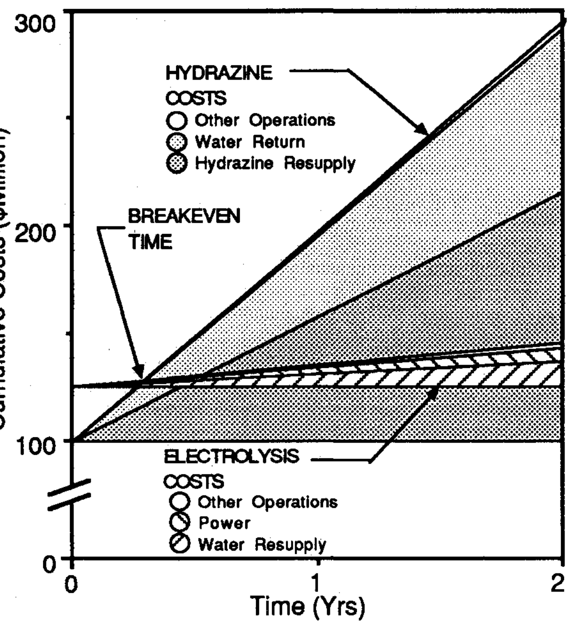

Fig. 1 Standalone system comparison.

Therefore, each algorithm includes a decision tree to account for the different conditions or ways in which propellant is allocated for reboost and high-thrust maneuvers. Each condition represents a branch in the decision tree that leads to a corresponding equation for life cycle costs. These equations are derived from Eq. (1) and reflect the manner in which propellant and waste fluids are allocated for a given condition. The following section presents the equations used in each algorithm and shows how they are used to generate parametric plots of life cycle costs.

Standalone Systems

The costing algorithms and equations for the standalone concepts (options 1A and 2A) are shown in Table 2. The algorithm for hydrazine (1A) is the simplest and accounts for only one condition in the propellant balance. Because this option is unable to utilize waste fluids, hydrazine must be used for all maneuvers, regardless of the partitioning between low and high-thrust requirements. In addition, return costs remain constant due to the system's inability to consume waste water on-orbit.

In contrast, the costing algorithm for water electrolysis (2A) accounts for two conditions which denote whether there is enough waste water to meet propulsion requirements. The first equation is used whenever the specified value of total impulse exceeds the total impulse available from electrolyzed waste water (i.e., $It_{req} \geqslant It_e$). The equation accounts for the extra amount needed through resupply (C_{res}), and does not include any water return. The other equation is used if the total impulse available from the water effluent exceeds propulsion requirements (i.e., $It_{req} < It_e$). In this case, no resupply is required, but, as shown by C_{ret}, the system is burdened by having to transport the unused excess back to Earth.

The concurrent features of reducing resupply and consuming on-orbit water supports the conclusion of water electrolysis being superior to hydrazine, at least in terms of recurring costs. This is illustrated in Fig. 1 which shows a comparison of cumulative costs between options 1A and 2A over a two-year period with a fixed total impulse of 1.85×10^6 lbf · sec/yr[8,9] and water availability of 3,920 lbm/yr.[4,5,10] Note that these represent the values assumed when the electrolysis system was originally baselined in the Freedom program. With these conditions, the development cost of the electrolysis system is paid back, relative to hydrazine, within a half year after completion of assembly. Beyond this point, the cost advantages become even more pronounced. For instance after the 10-

year nominal costing period assumed in this study, the costs are \$1078 million for hydrazine and \$228 million for electrolysis—a difference of \$850 million.

Although the savings appear dramatic, they only pertain to the standalone systems and only one set of design conditions. The following subsections show that including resistojets not only improves the magnitude of life cycle costs but also dramatically alters the relative costs between hydrazine and water electrolysis.

Augmentation with Gas Resistojets

Including gas resistojets for augmentation of reboost complicates the costing algorithms considerably. As shown in Table 3, this is due to the increased number of conditions needed to define the relative fluid balance.

With hydrazine (1B), two conditions are possible. If the specified value for reboost, $It_{\rm reb}(=f_R \cdot It_{\rm req})$, is less than the total impulse available from waste gas, $It_{\rm gr}$, then all reboost requirements are satisfied by using gas resistojets. In this case, the only propellant resupplied is for high-thrust requirements, $It_{\rm acs}$. On the other hand, if the total amount of waste gas is insufficient for meeting reboost requirements, then extra hydrazine, in addition to the amount required for high-thrust maneuvers, must be resupplied. This illustrates the unique aspect of the combined systems, namely, that resupply and life cycle costs are driven by the partitioning between reboost and high-thrust requirements.

This effect is illustrated in Fig. 2 which compares the life cycle costs of options 1A and 1B over a range of total impulse ($0 \leq It_{\rm req} \leq 3.0 \times 10^6$ lbf · s/yr) and reboost fraction ($0 \leq f_R \leq 1.0$). As expected, the life cycle cost of the standalone system increases linearly with total impulse and is independent of the relationship between reboost and high-thrust requirements. This is not true for option 1B which exhibits a notable sensitivity to the value of f_R. The cost curves for 1B are bounded by two extremes. The top curve, which runs parallel to the standalone case, represents the situation where high-thrust maneuvers comprise all propulsion requirements. In this case, the investment in resistojet hardware is superfluous and can be viewed as a constant cost delta added to the standalone system. The lower curve, which also parallels the standalone case, represents the situation where all excess gas is used for reboost. Any increase in total impulse requirement is accommodated by a proportional increase in resupply. The curves between these two bounds represent situations where the amount of available gases exceeds the specified reboost requirement. Along these curves, life cycle cost is nearly always lower than the standalone system.

The costing algorithm for the combined electrolysis/gas resistojet system (2B) is shown in Table 3, and is structured around two categories of conditions. The algorithm is more complex than before because five conditions are required to define the allocation of two waste fluids. In addition, the conditions prioritize the use of waste water over waste gas in an effort to minimize high water return costs.

The first category represents conditions in which total impulse for high-thrust maneuvers exceeds the impulse available from electrolyzing all on-board waste water ($It_{\rm acs} \geq It_e$). For

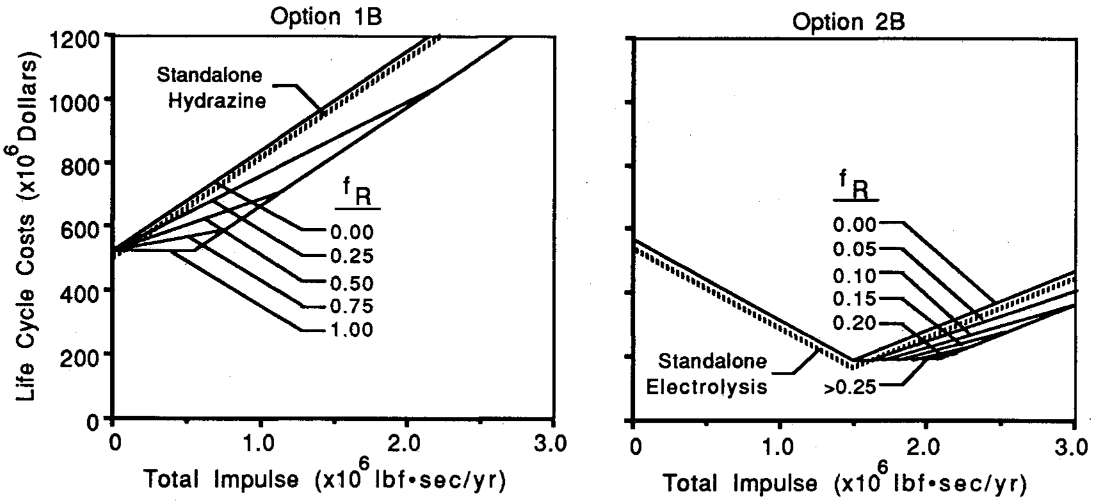

Fig. 2 Gas resistojet options.

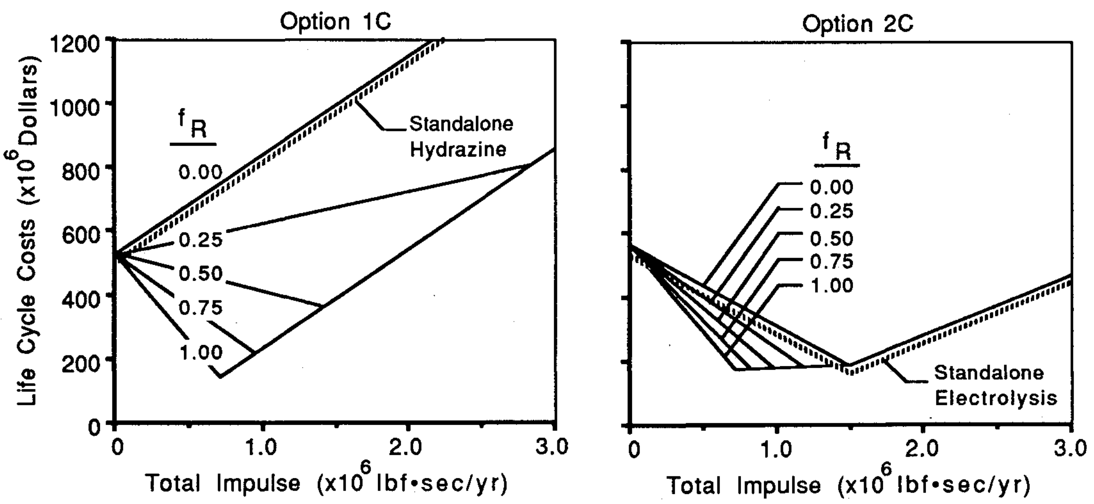

Fig. 3 Water resistojet options.

Table 4 Cost algorithms—water resistojet options

	Fluid balance conditions	C_i	C_o	C_p	C_{res}	C_{ret}
Hydrazine	$It_{reb} \ge It_{wr}$	$C_{ih} + C_{iwr}$	$(C_{oh} + C_{owr})t$	$P_{wr}\left(\frac{It_{wr}}{Is_{wr}}\right) C_p t$	$\left(\frac{It_{req} - It_{wr}}{Is_h}\right) Lt$	—
Hydrazine	$It_{reb} < It_{wr}$	"	"	$P_{wr}\left(\frac{It_{reb}}{Is_{wr}}\right) C_p t$	$\frac{It_{acs}}{Is_h} Lt$	$\left(W_w - \frac{It_{reb}}{Is_{wr}}\right) Rt$
Water electrolysis (O2/H2)	$It_{acs} \ge It_e$	$C_{ie} + C_{iwr}$	$(C_{oe} + C_{owr})t$	$P_e\left(\frac{It_{req}}{Is_e}\right) C_p t$	$\left(\frac{It_{req} - It_e}{Is_e}\right) Lt$	—
Water electrolysis (O2/H2), $It_{acs} < It_e$	$It_{reb} \ge It_e - It_{acs}$	"	"	"	"	—
Water electrolysis (O2/H2), $It_{acs} < It_e$	$It_e - It_{acs} > It_{reb} \ge \frac{Is_{wr}}{Is_e}(It_e - It_{acs})$	"	"	$\left[P_{wr}\left(\frac{It_e - It_{req}}{Is_e - Is_{wr}}\right) + P_e\left(\frac{It_{req} - Is_{wr}W_w}{Is_e - Is_{wr}}\right)\right] C_p t$	—	—
Water electrolysis (O2/H2), $It_{acs} < It_e$	$\frac{Is_{wr}}{Is_e}(It_e - It_{acs}) > It_{reb}$	"	"	$\left[P_{wr}\left(\frac{It_{reb}}{Is_{wr}}\right) + P_e\left(\frac{It_{acs}}{Is_e}\right)\right] C_p t$	—	$\left(\frac{It_e - It_{acs}}{Is_e} - \frac{It_{reb}}{Is_{wr}}\right) Rt$

these cases, the amount of water resupplied depends on how much of the reboost maneuver can be accomplished using gas resistojets. If there is not enough waste gas to perform the entire maneuver, then extra water, above the amount needed for high-thrust maneuvers, is required. However, if there is enough gas, then resupply is solely dictated by the propellant needed to satisfy high-thrust requirements.

The other category consists of three conditions and represents situations where the impulse available from electrolyzed water exceeds high-thrust requirements ($It_{acs} < It_e$). If reboost requirements are such that using all available waste water and gas is insufficient to meet total propulsion requirements, then additional water must be resupplied. On the other hand, if reboost requirements are accommodated with the remaining water and a portion (or all) of the waste gas, then no resupply or return is required. The third case arises when the amount of available water exceeds both reboost and high-thrust requirements. In this case, resistojets make no contribution to reboost and the remaining water is transported back to Earth.

The cost parametrics for option 2B are also shown in Fig. 3. The condition in which all performance requirements are satisfied by the electrolysis system is represented by the curve immediately above the standalone option. Up to a total impulse value representing the maximum available from electrolyzed waste water, approximately 1.48×10^6 lbf · s/yr, cost is independent of the distribution between reboost and high-thrust requirements. This is due to the prioritization of water usage over waste gas which eliminates the use of resistojets. Above this value, the resistojets are used progressively to offset resupply requirements for reboost. Note that this crossover point corresponds to the situation where the impulse available from water equals total impulse requirements for reboost and high-thrust maneuvers.

An important conclusion is that gas resistojets have a greater impact on life cycle costs for hydrazine than for electrolysis. In fact, gas resistojets serve no benefit at all for the electrolysis system unless total impulse requirements are above the amount available from electrolyzing all on-board waste water.

Augmentation with Water Resistojets

The benefits of including water resistojets with either a hydrazine or water electrolysis system are clearly more dramatic. As shown in Table 4, the cost algorithm for the combined hydrazine/water resistojet system (1C) is very similar to its gas counterpart (1B). However, Fig. 3 shows that the magnitude of cost improvements is much greater. In fact, these improvements are marked enough to make option 1C the lowest cost alternative under certain combinations of total impulse requirements. This is primarily due to the combined reduction of hydrazine resupply and water return.

The cost improvements are not as significant for the combined water electrolysis/water resistojet system (2C). Unlike the option with gas resistojets (2B), this system's costing algorithm restricts use of resistojets to the lower end of reboost requirements (i.e., $< 1.48 \times 10^6$ lbf · s). Above this value all maneuvers are performed with the electrolysis system in order to maximize propulsive efficiency and minimize resupply.

Water resistojets are effective with electrolysis only for instances in which the amount of water available on the Station exceeds performance requirements. The resistojets provide an inefficient way of disposing as much excess as possible while reducing (or eliminating) water return requirements. This situation is noted by two conditions in Table 4 and illustrated in Fig. 3. If the total impulse obtained from electrolysis is greater than the actual reboost requirement, then the remaining water is optimally partitioned to eliminate return. However, if the total impulse obtained from the sole use of resistojets exceeds reboost requirements, then water return is necessary. Although downsupply cannot be eliminated with this condition, it is much less than if the electrolysis system performed the entire maneuver.

Combined Augmentation with Both Gas and Water Resistojets

The life cycle costs for the multiple resistojet options (1D and 2D) are based on the most complex algorithms used in this study. Because both options consider the use of two waste fluids and three propulsion elements, more equations are necessary to account for added complexity in the propellant/fluid balance. For brevity's sake, these algorithms are not presented here. However, they generally represent a combination of the conditions for the single resistojet options and are strongly driven by the prioritization of water usage.

As shown in Fig. 4, augmenting hydrazine with two types of resistojets (1D) extends the cost advantages associated with resistojets over a greater range. Except for the offset caused by the \$12 million difference in initial costs, the variation of life cycle cost at low values of It_{req} duplicates the trends for option 1C in Fig. 3. For this case, however, the benefits continue beyond the point representing complete consumption of on-orbit water. Rather than engaging the hydrazine element for reboost, the gas resistojets are used to preclude further resupply and maintain low life cycle cost. Only when all excess water and waste gas is consumed does the cost for option 1D parallel that of the standalone case.

The electrolysis/multi-resistojet option (2D) is always more expensive than either of its single resistojet counterparts. This

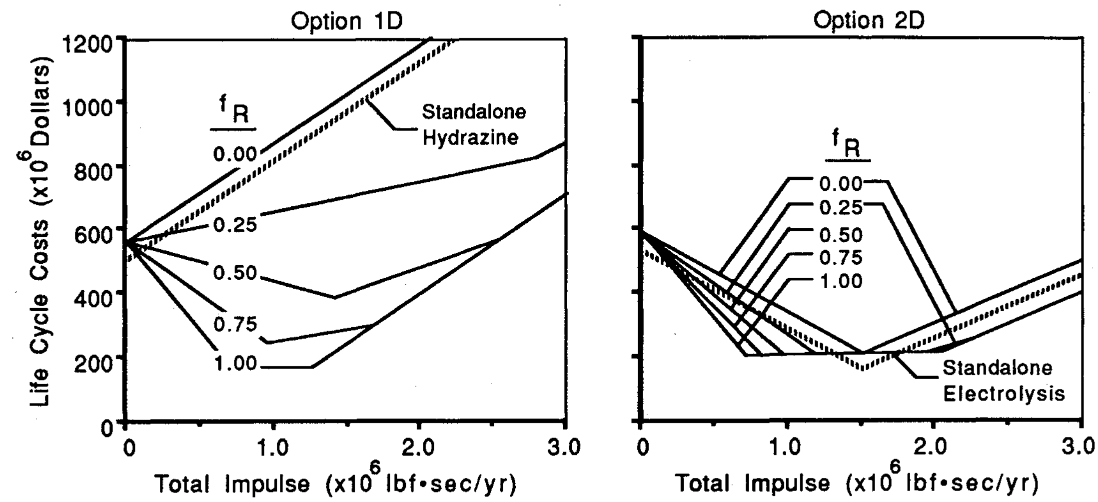

Fig. 4 Gas/water resistojet options.

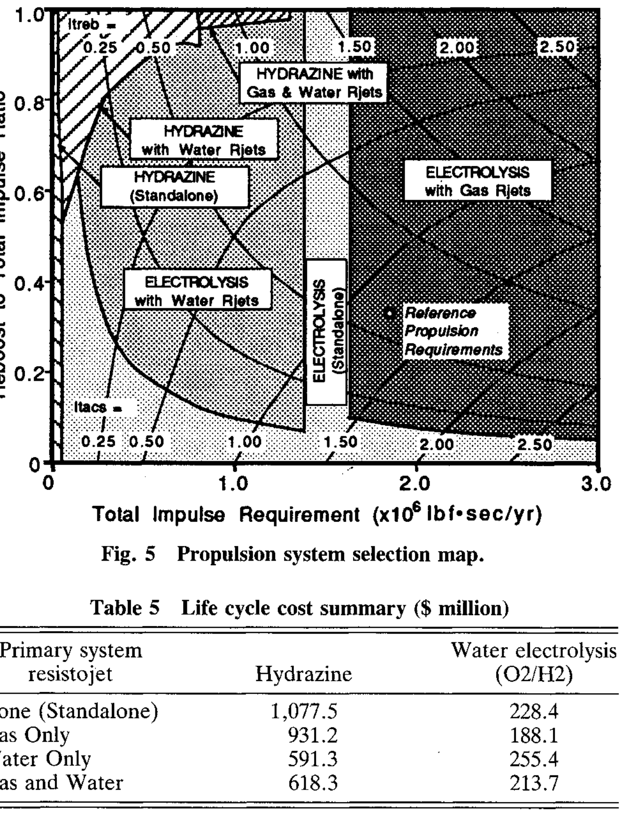

Fig. 5 Propulsion system selection map.

Table 5 Life cycle cost summary ($ million)

Primary system resistojet	Hydrazine	Water electrolysis (O2/H2)
None (Standalone)	1,077.5	228.4
Gas Only	931.2	188.1
Water Only	591.3	255.4
Gas and Water	618.3	213.7

is explained by noting the different regions over which each type of resistojet operates. At the value of It_{req} that represents optimum consumption of water ($It_{req} = It_e$), both of the single resistojet options (2B and 2C) rely solely on water electrolysis and have the same life cycle costs. This point demarcates the regions in which each type of resistojet is preferred. As shown in Fig. 4, the same cost relationships hold for option 2D when both resistojets are implemented simultaneously. Only the $12 million cost differential, due to the added investment in two resistojet systems, prevents this case from being a mere superposition of its single resistojet counterparts. The cost differential also prevents option 2D from ever being the most cost effective electrolysis option. For instance, when $It_{req} < It_e$, only a combination of electrolysis and water resistojets is used and the investment in gas resistojets is superfluous. Alternatively, when $It_{req} \geq It_e$, the water resistojets never operate and their implementation is likewise superfluous. Consequently, the only situation that favors selecting option 2D is if the uncertainty in propulsion requirements ranges between values that are less than and greater than It_e.

Summary and Conclusions

The parametrics represented in Figs. 2 to 4 are indispensable for understanding the sensitivity of life cycle cost to performance requirements. They are also useful in making direct comparisons at specific design conditions. This is done in Table 5 which shows the life cycle costs of all eight options with the total impulse and waste fluid values defined previously. Note that f_R is held at 0.324, the value assumed in the original analysis.[4,5] This point design comparison confirms the superiority of the combined electrolysis/gas resistojet system at the assumed conditions.

This type of comparison, however, is extremely limited for identifying which options to consider in the early phases of spacecraft definition. A more useful summary shows which systems are best suited over a range of anticipated requirements. This is done by again using the cost data from Figs. 2–4. From these parametrics, the lowest cost options are identified at different combinations of reboost and high-thrust requirements. The corresponding ranges of values are portrayed in the propulsion system selection map of Fig. 5. This chart shows which of the eight options achieve the lowest life cycle cost over the assumed range of performance requirements. It also provides a valuable roadmap for determining which options deserve further consideration and which warrant elimination, even with indefinite performance requirements. Its utility is further enhanced by overlaying constant values of It_{reb} and It_{acs} to examine discrete changes in reboost and high-thrust requirements.

The selection map shows that the electrolysis system, in either its standalone or combined form, is generally superior over most of the anticipated range. However, this is somewhat misleading because only a minor change in the Station's configuration or mode of operation could alter performance requirements and shift the reference to a different region on the map. For example, use of an alternative momentum management system, such as magnetic torquers, would significantly reduce propulsion attitude control requirements. If this decrease amounted to 97% of the original value while reboost requirements remained constant, then a hydrazine/water resistojet system would become the preferred option.

In conclusion, this paper has demonstrated the need for a comprehensive ranking of viable standalone and combined system options and identification of the lowest cost options over the entire range of propulsion requirements. This is necessary to ensure that the Freedom program selects a propulsion system that is properly suited for the final configuration. Although it was not considered in this study, the effect of varying the waste fluid aggregate should also be examined.

This will allow a downselection of viable alternatives as Freedom configuration and operational characteristics become more definite.

Acknowledgments

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References

[1]Wilkinson, C. L., and Brennan, S. M., "Space Station Propulsion Requirements Study," NAS3-23353, June 1985.

[2]Wilkinson, C. L., and Brennan, S. M., "Space Station Propulsion Options," AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, July 1985.

[3]Brennan, S. M., and Donovan, R. M., "Space Station Benefits from ECLS—Propulsion System Synergism," AIAA/SAE/ASME/ASEE 22nd Joint Propulsion Conference, June 1986.

[4]Schmidt, G. R., "The Impact of Integrated Water Management on the Space Station Propulsion System," AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, June 1987.

[5]Schmidt, G. R., "Impact of Water Integration on the Space Station Freedom Propellant Availability," AIAA *Journal of Spacecraft and Rockets*, Vol. 26, No. 4, 1989, 259–265.

[6]NASA, "Fluid Management System Architectural Control Document," Space Station Program Office, SSP-30264 Rev. E, March 1988.

[7]Bicknell, B., Wilson, S., and Dennis, M., "Space Station Integrated Propulsion and Fluid Systems Study," Marshall Space Flight Center, NAS8-36438, April 1988.

[8]Jacobsen, W., "Propulsion System Selection," Presentation to Marshall Space Flight Center Propulsion Design Review, Nov. 1985.

[9]Schmidt, G., "Selection of Combined Water Electrolysis and Resistojet Propulsion for Space Station Freedom," 39th Congress of the IAF, October 1988.

[10]Kahl, R., and Hastings, L., "Waste Fluids Action Item Report," Presentation to Space Station Control Board, April 1986.

[11]Knowles, P., "Propulsion Critical Issues," Presentation to NASA Space Station Propulsion Workshop, October 1985.

[12]Brennan, S., "Water Electrolysis Technical Analysis," NASA MSFC Propulsion Design Review, November 1985.

[13]Finden, L., Briley, G., and Iacabucci, R., "25-lbf GO_2/G Space Station Thruster," AIAA/SAE/ASME/ASEE 24th Joint Propulsion Conference, Boston, MA, July 1988.

[14]Jones, L., and Bagdigian, D., "Space Station Propulsion: Advanced Development Testing of the Water Electrolysis Concept at MSFC," AIAA/SAE/ASME/ASEE 25th Joint Propulsion Conference, Monterey, CA, July 1989.

[15]Jones, R. E., "Space Station Propulsion: The Advanced Development Program at Lewis," NASA TM 86999, July 1985.

[16]Sargent, D., and Schmidt, G., "Integrated Electrolyzer Studies: Part 1—Feasibility of a Common Electrolyzer," PSC Study No. 3-06, NASW-4300, August 1988.

[17]Zafran, S., "Resistojet Operation with Various Propellants," AIAA Paper 85-1158, Monterey, CA, July 1985.

[18]Brennan, S. M., "Utilization of Effluents for Optimized Flight Profiles and STS Logistics Capabilities," AAS Conference, Boulder, CO, Oct. 1986.

[19]Rocket Research Company, "Theoretical Performance for a Multi-Propellant Resistojet System," Redmond, WA, 1985.