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Strategy for the Reduction of Total Integrated Fluid Logistics to the Space Station Freedom

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Abstract

The use of an integrated environmental control and life support system (ECLSS) and secondary propulsion system (SRS) on the Space Station Freedom (SSF) has many potential advantages. Through the metabolism of food, the crew on-board the station will produce carbon dioxide as a waste gas and an excess of water in the form of urine and condensate. The processing of these waste fluids by the ECLSS could produce quantities of oxygen that would eliminate the need for cryogenic oxygen resupply and hydrogen, carbon dioxide, and/or methane that could be used with the addition of a resistojet system to provide a constant low thrust for station. This additional thrust would represent significant savings in required hydrazine resupply.

This paper will describe how savings in total fluid logistics can be achieved by using an integrated systems approach. It will include an overview of the technologies being considered to reduce cryogenic oxygen and propellant resupply requirements and will describe the impact of dehydration of the crew's food supply, the availability of Shuttle fuel cell water, and the impact of the implementation of reduction technology to the staged Space Station evolution. Primary comparisons will be in the areas of total upmass, power requirements, and the level of complexity of alternative modifications to baseline systems.

Introduction

From the time the station is permanently manned, the provisions for crew and station operations as well as for experiments will demand significant logistics support. At Permanently Manned Capability (PMC), allocations for crew systems, users, internal and external spares, propellant, cryogenics and fluids will require an estimated five Shuttle flights per year to resupply station. As additional elements are added after the PMC phase the quantity of required resupply by the baseline systems will increasingly dominate the available upmass capability. Therefore, methods that could provide a reduction in resupply requirement through the addition of advanced technology would be beneficial.

At PMC, propellant and cryogenics resupply represent 27% of the total annual logistics allocation (37% of non-user logistics). Along with food provisions for the crew, propellant and cryogenics are the most critical for station and crew survival. The station and crew can survive for an extended period without additional non-dietary crew provisions, spares, or experiment resupply. However, the survival of the station is dependent on maintaining a minimum orbital altitude and the survivability of the crew is dependent on the station for providing a controlled environment. A reduction in the reliance of these areas on resupply logistics not only represents savings in upmass, it also provides an extended capability for the station and crew to survive during periods when resupply to station would be unavailable. In addition, required dietary provisions, the other critical resource, can be reduced by dehydrating the food. This would increase the shelf life and reduce the packaging overhead. Since the water used to re-hydrate the food once it is on orbit will come from station, this process would be closely coupled to the availability of water on station. Therefore, food resupply requirements are considered in the total fluid logistics requirements.

Technology Reduction Options

From the inception of the SSF program, the station has been designed as an evolving spacecraft that will be assembled over a period of several years. The first element launch (FEL) is presently scheduled for the early 1996 time frame. Sixteen assembly flights later, in the year 2000, the Space Station will be capable of supporting a permanent crew of four. However, PMC will not be the final milestone in the Space Station Freedom's evolution. Through design provisions for software "hooks" and hardware "scars," additional elements and advanced technologies will be incorporated into the station configuration. The technologies under consideration that reduce the station's dependence on cryogenic oxygen and propellant resupplies include the addition of the Sabatier carbonation reactor, the Static Feed Electrolyzer, and the resistojet supplemental propulsion system.

Oxygen consumed by humans through respiration metabolizes the hydrogen and carbon contained in foods to release water and carbon dioxide. Make-up of the oxygen lost in the form of carbon dioxide is required. At PMC, this make-up requirement will be accomplished through the resupply of cryogenic oxygen. To reduce this ground-based support for oxygen supply, the addition to station of a regenerable carbon dioxide system has been considered. The leading carbon dioxide regeneration technology is the Sabatier carbonation reactor. The Sabatier reacts hydrogen, provided through the electrolysis of water, and the carbon dioxide collected from the crew to produce methane and water. Comparative testing of the Sabatier as well as other competitive reduction technologies was completed at the Marshall Space Flight Center in 1991. If integrated on SSF in the future, the device would be placed downstream of the carbon dioxide atmospheric removal device, the 4-Bed Molecular Sieve, in both the U.S. Hab and Lab modules.

The Static Feed Electrolyzer (SFE) uses an alkaline electrolyte to break water into its primary constituents of hydrogen and oxygen. The saturated product hydrogen and oxygen gases are then stored and dried and used either to meet crew oxygen requirements, to provide make-up hydrogen for the Sabatier, or to provide a product gas for use in a secondary propulsion system. The Static Feed Electrolyzer is currently under development by Marshall Space Flight Center and by Life Systems, Inc. Initial flight experiments are planned in 1993-94 time period. If placed on station, the device would be located downstream of the water collection and storage subsystem.

Resistojets, as the name implies, derive thrust from the action of gas being expanded as it comes in contact with a resistively heated surface. These gases are dumped overboard at a high temperature and velocity. Initial plans, developed for use on early space station concepts, planned use of the system as the primary means to provide the required impulse for control moment gyro (CMG) desaturation and orbit maintenance. The current design of the Space Station Freedom includes scars on the S-1 and P-1 Pre-Integrated-Truss (PIT) segments for the addition of resistojet devices for supplemental propulsion. In addition, scars also been included for the Waste Gas Collection subsystem on the M-1 PIT segment. The Waste Gas Collection subsystem will provide for the storage and drying of the resistojet gases until they are to be used.

In this study, six options using various levels of technology are considered. They include 1) non-propulsive venting of all excess generated water and carbon dioxide, 2) the addition of a SFE to recover oxygen from excess water while non-propulsively venting the generated hydrogen and carbon dioxide, 3) the addition of a Sabatier and a SFE to recover oxygen from both crew produced carbon dioxide and excess water while non-propulsively venting any excess generated gases, 4) the addition of only a resistojet to produce supplemental impulse from excess carbon dioxide while venting excess water, 5) the addition of a SFE and a resistojet to produce supplemental impulse from excess carbon dioxide and hydrogen produced by the SFE while supplying oxygen from electrolysis to the crew and 6) the addition of a SFE, Sabatier, and a resistojet to provide oxygen to the crew from the electrolysis of excess water and the reduction of carbon dioxide while providing supplemental impulse through the resistojet from hydrogen and methane. These options are illustrated in the figures below.

Option 1: Baseline Configuration - No logistics reduction technology

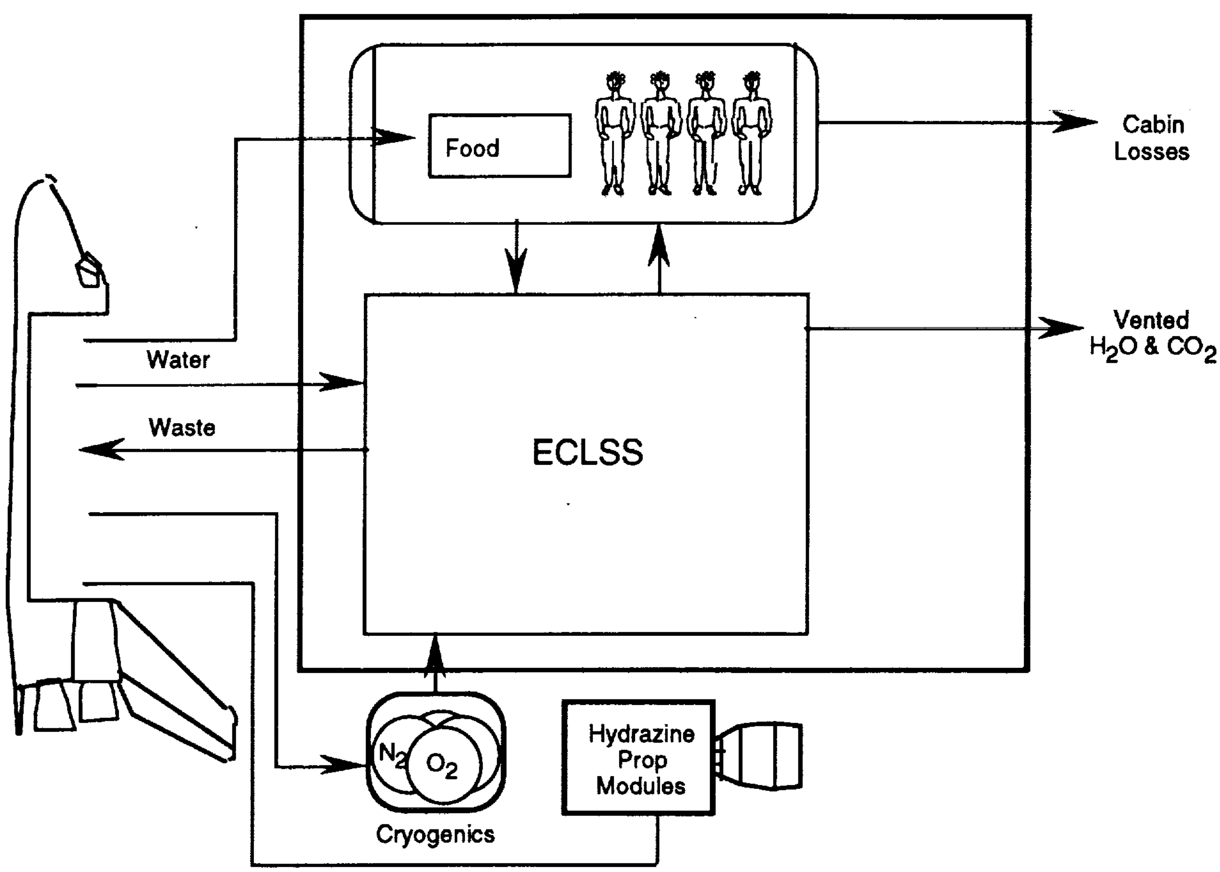

Figure 1

Option 2: Addition of Static Feed Electrolyzer Only

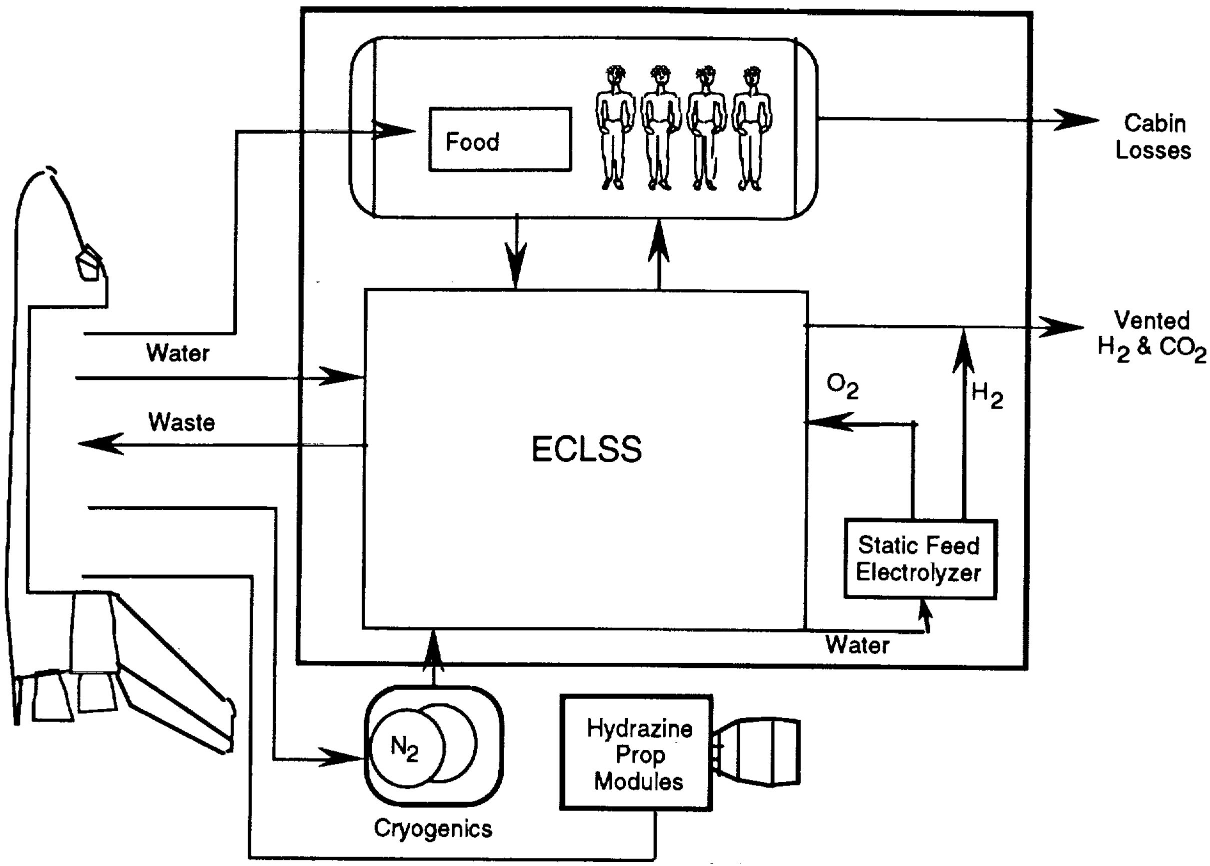

Figure 2

Option 3: Addition of SFE and Sabatier

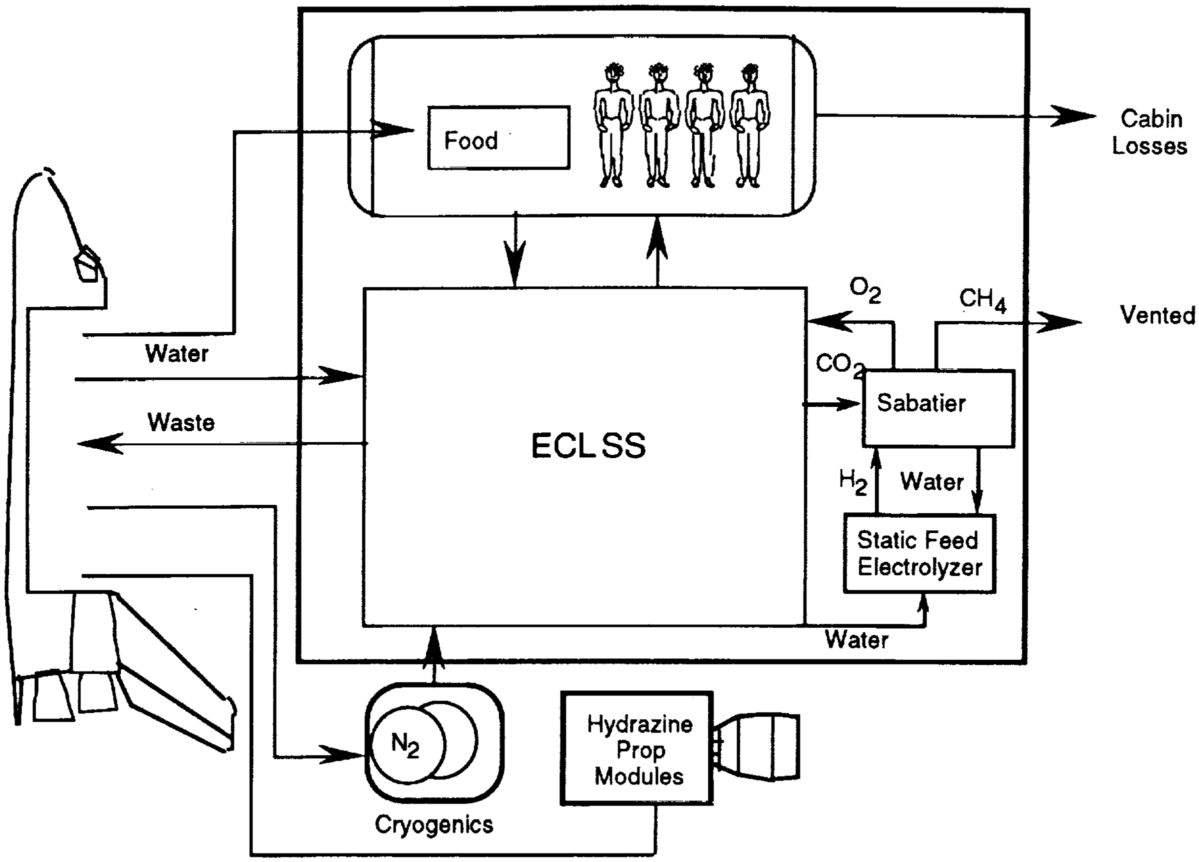

Figure 3

Option 4: Addition of Resistojet Only

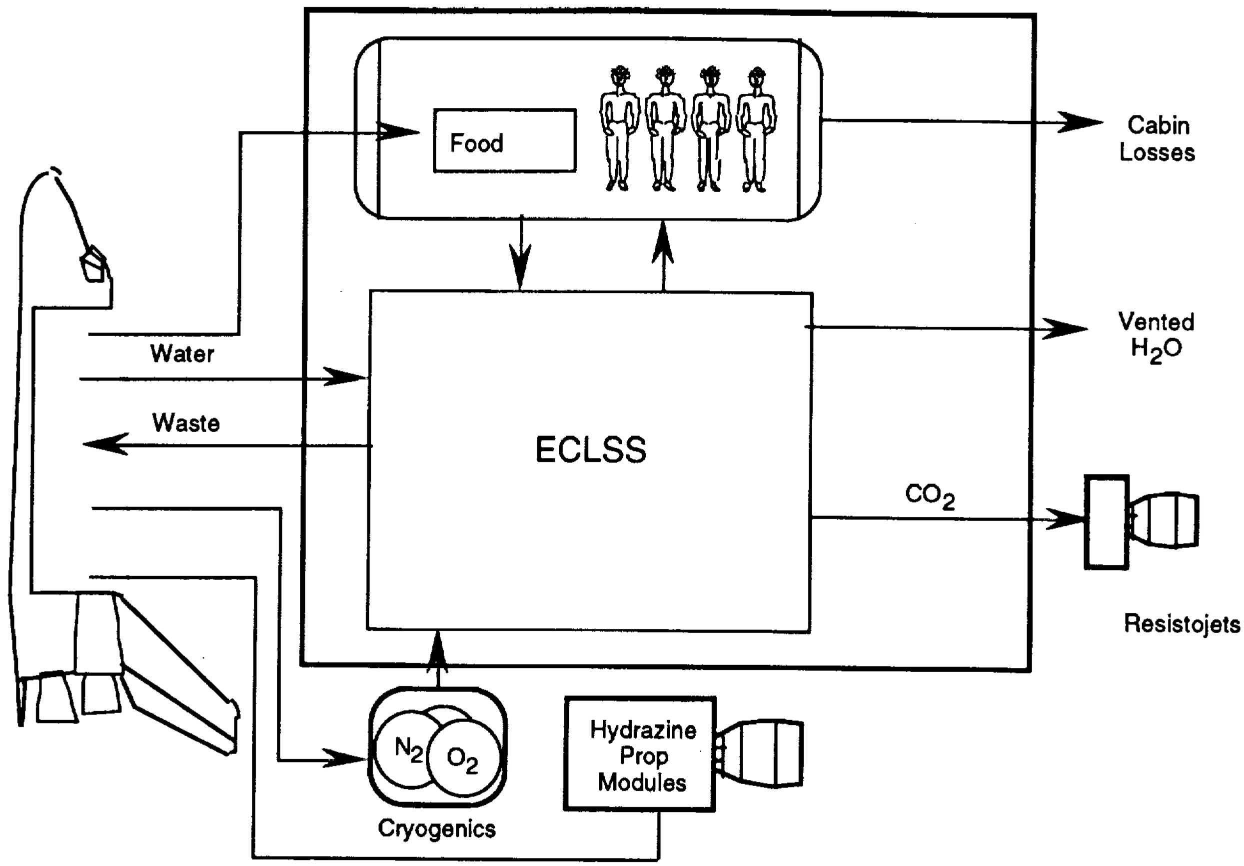

Figure 4

Option 5: Addition of the SFE and Resistojet

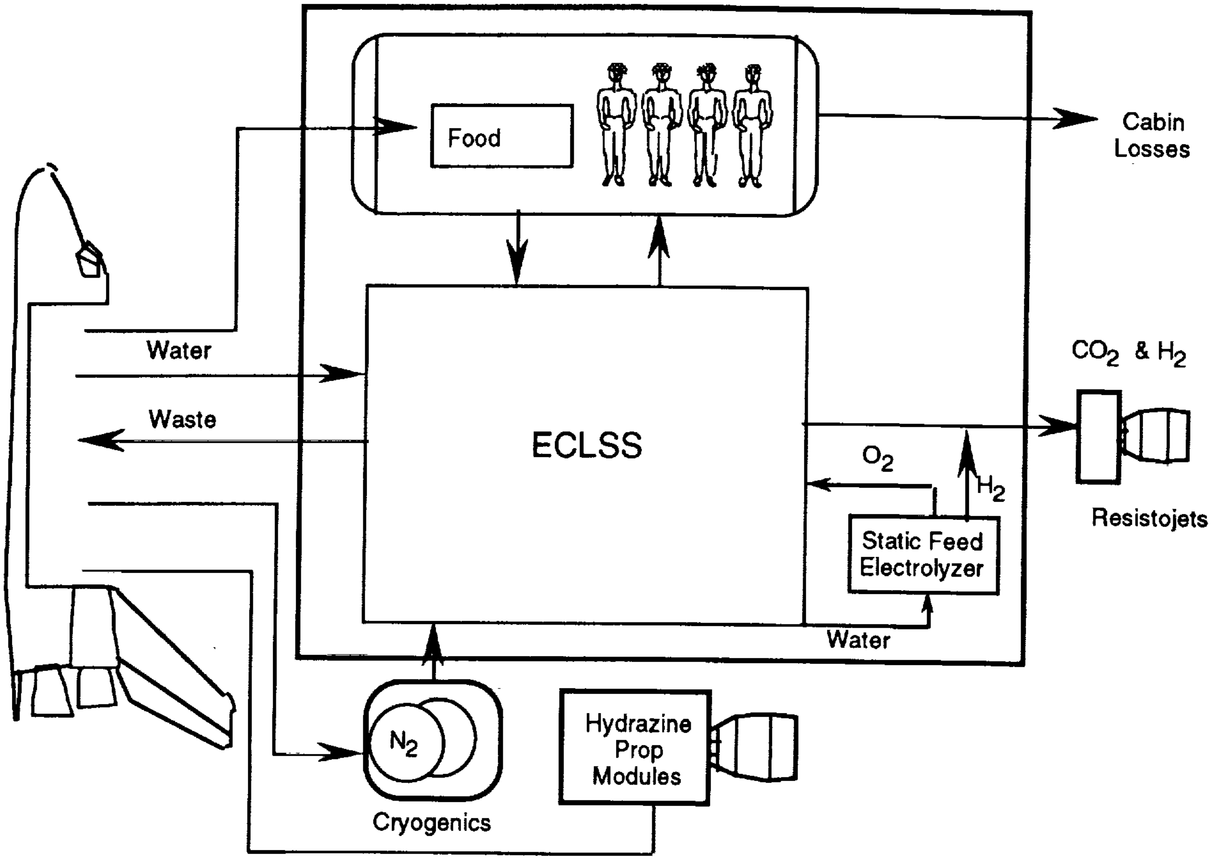

Figure 5

Option 6: Addition of the SFE, Sabatier, and Resistojet

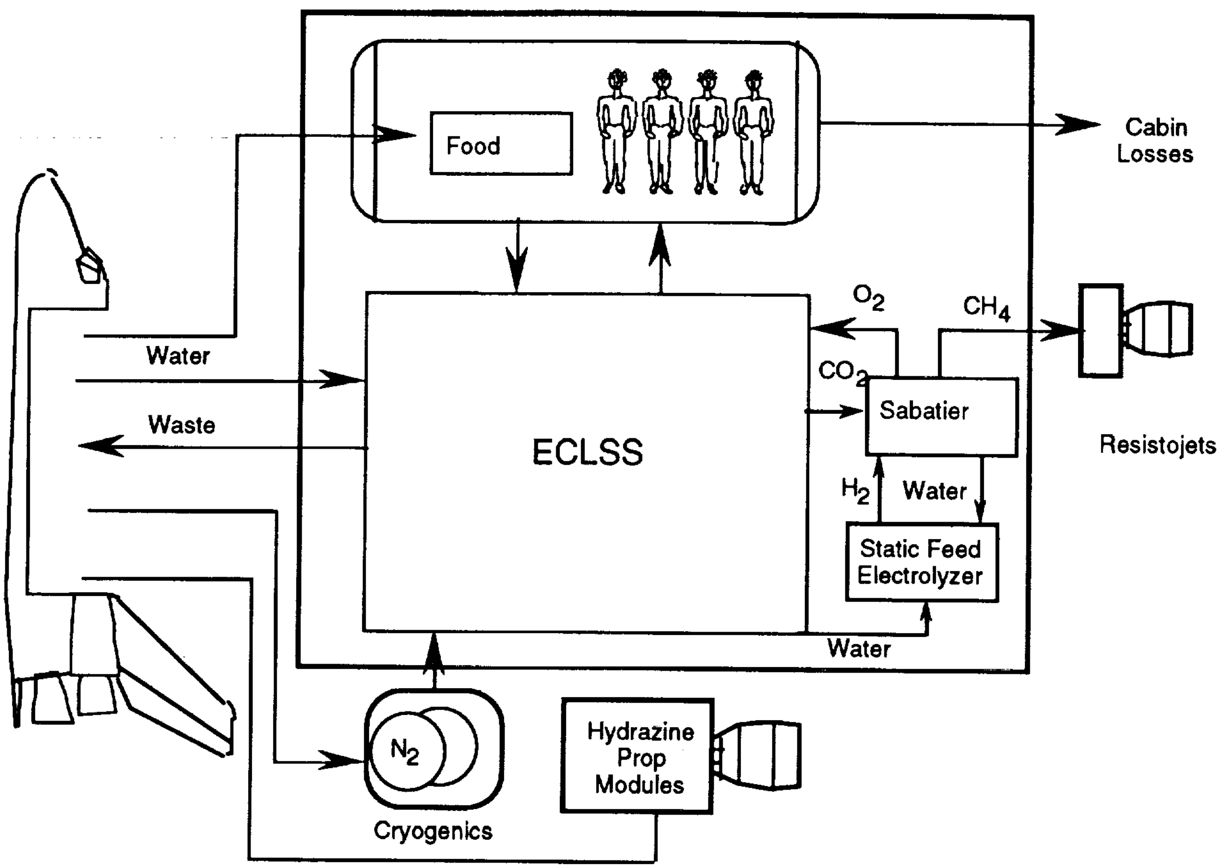

Figure 6

In each case, the ability to utilize up to 1200 lbm/flight of Orbiter-provided fuel cell water and the effect of dehydrating the crew's food supply is also considered. Orbiter fuel cell water could be electrolyzed to provide oxygen for the crew, hydrogen for the Sabatier process, or waste gas for the resistojets. As stated previously, dehydration of the crew's food is considered because of the possibility to reduce the packaged upmass and because of the increased shelf life achieved when food is stored in a dehydrated form. In some options, excess oxygen exists. For the purposes of this study, it was assumed that all excess oxygen is vented non-propulsively to space.

Environmental Control and Life Support Reduction Analysis

The need for resupply of cryogenic oxygen to station is driven by the crew metabolic loses, pressure shell leakage, and airlock gas losses. In addition, a limited amount of oxygen is consumed by the experiment payloads. Program estimates for the PMC station call for an annual delivery of over 3,900 lbm of oxygen. In order to understand the logistics impact due to the addition of regenerative ECLSS technology to station, it is necessary that the mass and fluid balance of the station be quantified.

Table 1
Nominal Crew Member Metabolic Balance (lbm/year)

Input			Output		
Food		lbm/person/day	Waste Solid		lbm/person/day
	Oxygen	0.44		Urine	0.13
	Hydrogen	0.08		Feces	0.07
	Carbon	0.6		Sweat	0.04
	Other	0.24			
Drink			Waste Liquid		
	Water	3.56		Urine	3.31
	Food Prep	1.67		Sweat/Respiration	5.02
	Food H20	2.54		Feces	0.2
Gas			Waste Gas		
	Oxygen	1.84		Carbon Dioxide	2.2
Total		10.97	Total		10.97

In Table 1, the nominal uptake and waste output per crew member are shown. The information from this table is based on a metabolic rate of 11,200 Btu/person/day (2825 Calories/person/day) and a respiratory quotient of 0.87. From Table 1, it can be seen that 1.84 lbm of oxygen is consumed and 2.20 lbm of carbon dioxide is produced per person per day. This represents a loss of 2650 lbm of oxygen and 3168 lbm production of carbon dioxide per year for a four person crew.

Table 2 summarizes all oxygen losses to the PMC station over a 90 day period, including metabolic losses.

.Table 2
Nominal Oxygen Allocation (lbm/90 days)

Usage Event	
Cabin Atmosphere Make-up	lbm/90 days
Element Leakage	104
Metabolic Load	662
CO2 Removal Loss	10
Experiment Ingestion	33
Element Repressurizations	52
EVA Support	
EMU Support	94
SPCU Support	6
HBC Support	6
Miscellaneous	
WRM Support	9
Total	976

The availability of hydrogen on station for use by the Sabatier and resistojet greatly effects the performance of these devices. Lowering the availability of hydrogen reduces the amount of carbon dioxide that can be reduced by the Sabatier and the ability to provide impulse in the resistojet for supplemental reboost. Since the primary source of hydrogen on station will be from the electrolysis of excess water, it is necessary to determine a water balance for the station. This is shown in Figure 7

PMC Space Station Water Balance Diagram

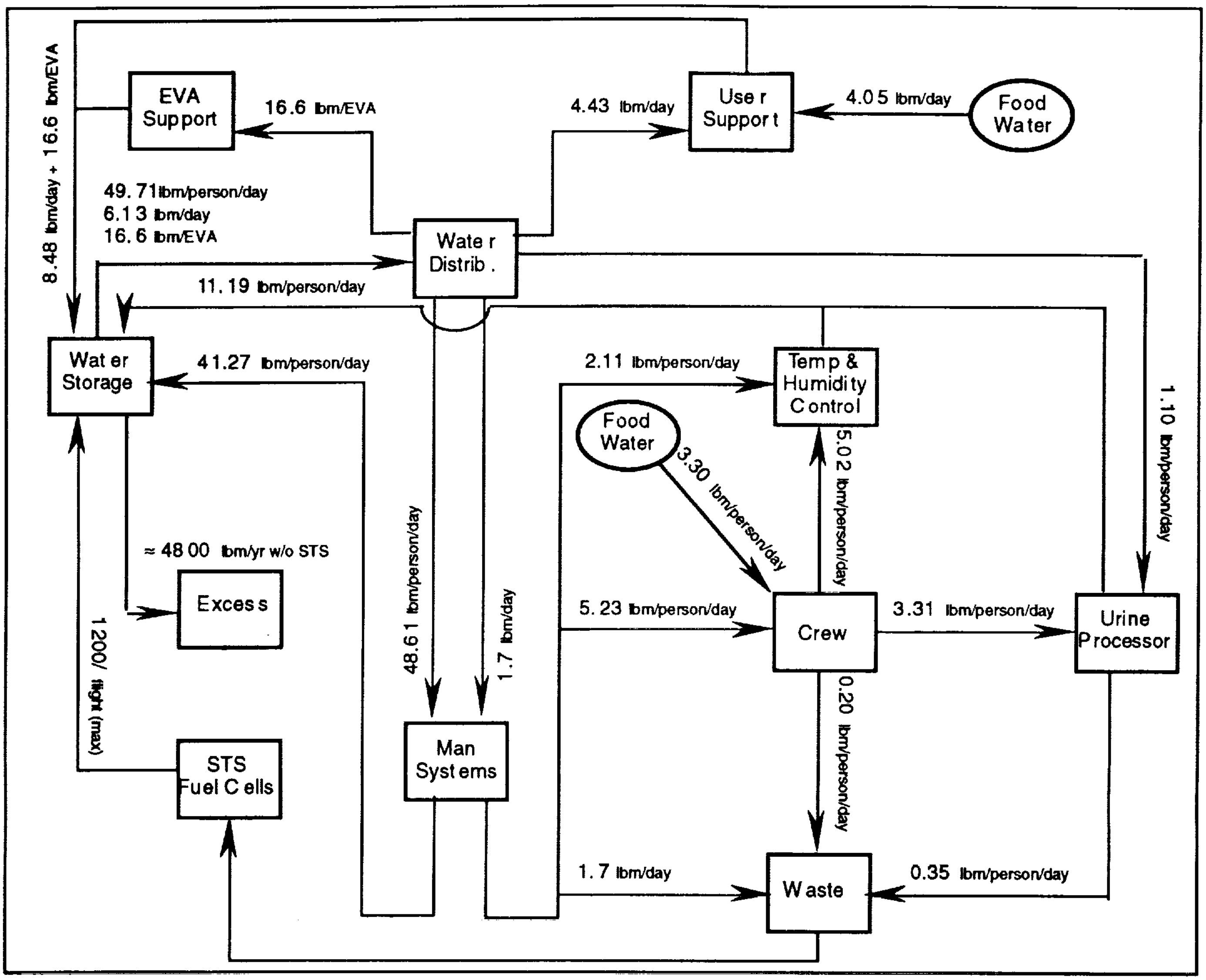

Figure 7

Without the use of Orbiter fuel cell water, approximately 1200 lbm/person/year of excess water exists delivered to station in the form of food. Adding fuel cell water to this increases the amount up 10,800 lbm/year for a four man crew. From this information a similar mass and fluid balance for each option can be developed. Figure 8 illustrates the required cryogenic oxygen resupply based on the technology options for a four person crew.

Oxygen Resupply Requirement

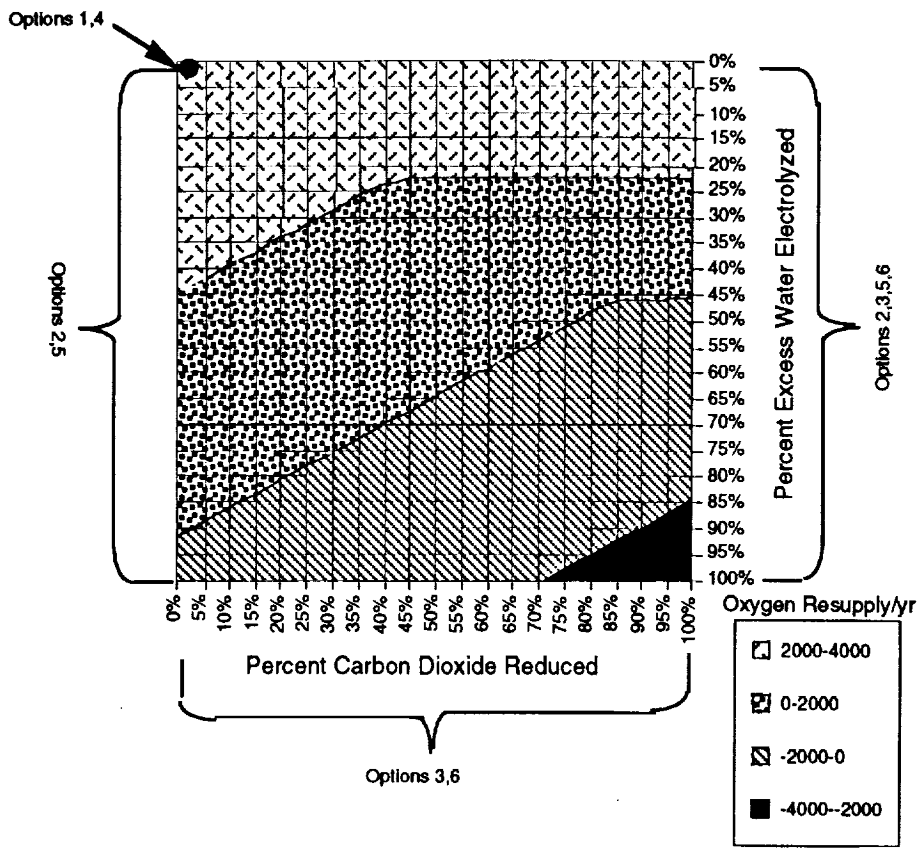

Figure 8

The left hand side of the graph illustrates that in Options 1 and 4 no Sabatier or Electrolyzer exists, therefore, no reduction in cryogenic resupply will be seen in these. In Options 2 and 5 a SFE is present. In these instances, the electrolyzer could process anywhere from none to all of the excess water. In Options 3 and 6, both a SFE and a Sabatier are present. In these cases, the configuration may electrolyze any portion of the excess water and reduce any portion of the carbon dioxide present. However, a minimum requirement for electrolysis must be met to supply the Sabatier with hydrogen. The figure shows that in cases 2,3,5, and 6 it is possible to eliminate the oxygen resupply requirement.

Figures 9 and 10 graphically show the impact to the oxygen requirement based on the availability of Shuttle fuel cell water and the level of food dehydration.

Levels of CO_2 and H_2O processed to Provide for all SSF O_2 Requirements Based on Amount of Excess Water on SSF

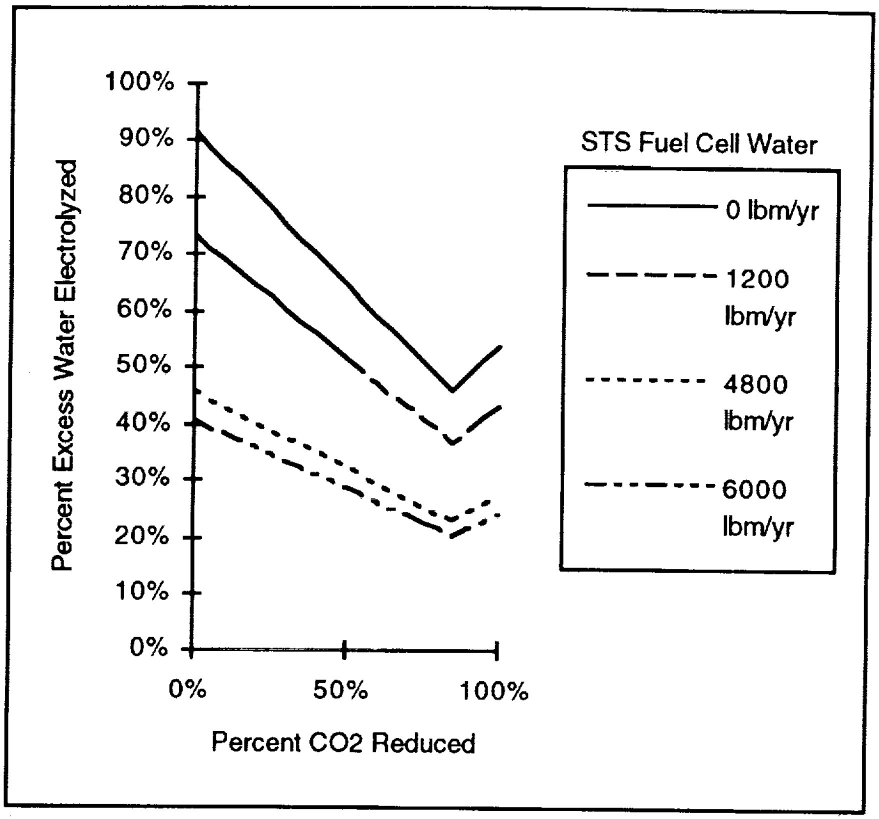

Figure 9

A lower percentage of the total water must be electrolyzed to eliminate oxygen resupply as more water is provided to station by the Orbiter. Likewise, as the amount necessary to rehydrate the crew's food increases, a larger percentage of the total excess is required to eliminate the cryogenic oxygen requirement. In some instances, with certain levels of dehydration the amount of water available after rehydration may be insufficient to provide for total oxygen replacement.

Levels of CO_2 and H_20 processed
to
Provide for all SSF O_2 Requirements
Based on The Amount of Food Dehydration

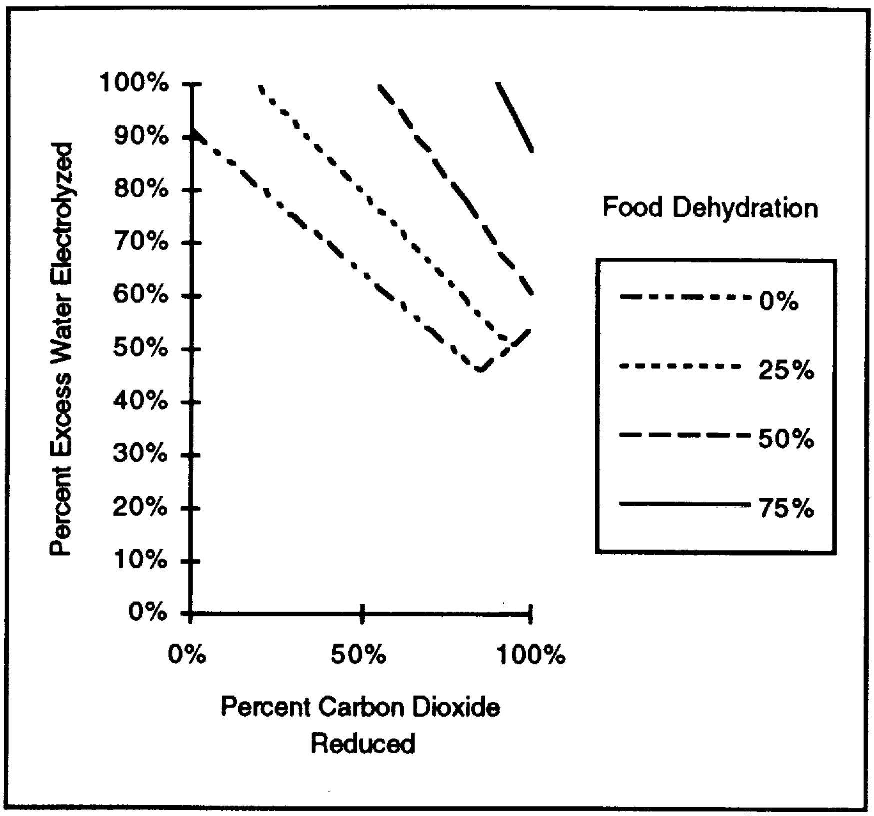

Figure 10

To understand the net effect of excess water on station to the technology options being considered Figures 11 and 12 show the break down of the sources of oxygen makeup for Options 2,3,5, and 6. Since Options 1 and 4 employ no reduction technology, all oxygen must be resupplied in those options.

**Source of Oxygen Resupply
As a Function of
Excess SSF Water Available
-Options 2 and 5-**

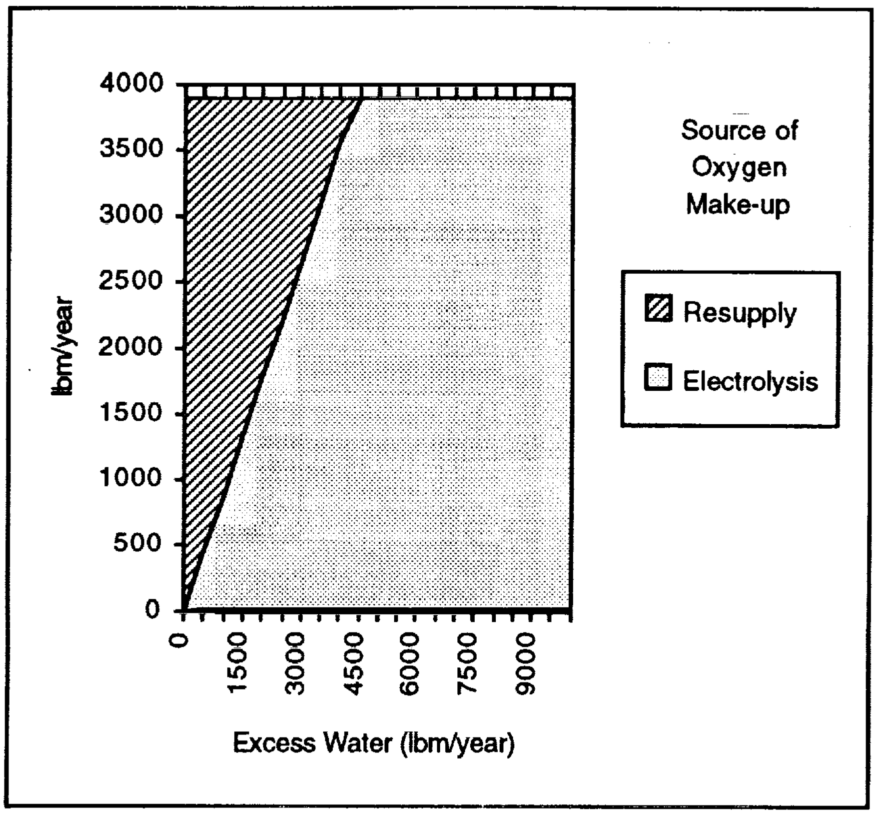

Figure 11

Source of Oxygen Resupply
As a Function of
Excess SSF Water Available
-Options 3 and 6-

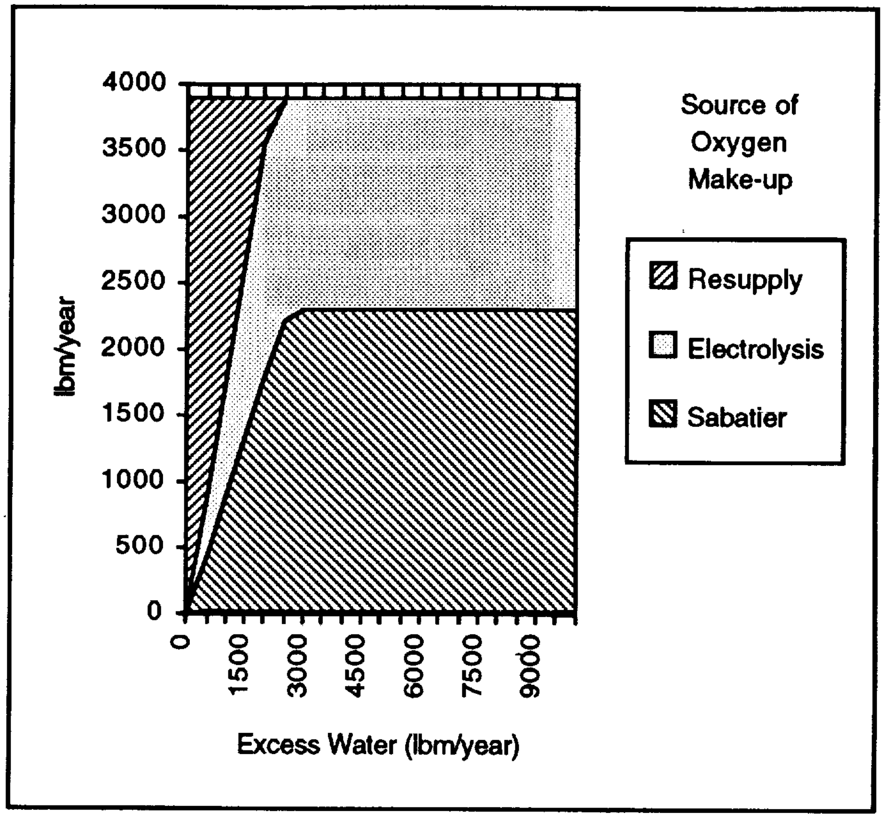

Figure 12

Both figures show the total annual oxygen requirement for the PMC configuration of approximately 3900 lbm/year. In Options 2 and 5, since electrolysis of water is the primary source of oxygen make-up, nearly 4400 lbm of excess water is required to eliminate the need for resupply. In Options 3 and 6, the Sabatier provides 2500 lbm of oxygen in the form of water leaving the SFE to provide another 1400 lbm of oxygen through the electrolysis of excess water. However, another 1000 lbm of water must be electrolyzed to provide the necessary hydrogen to drive the Sabatier process.

Propulsion Reduction Analysis

In order to determine which of the six technology options being studied will be the most beneficial with regards to resupply, not only must cryogenic oxygen resupply and water usage be considered, but also propellant use. The primary propulsion system (PPS) for station will be a hydrazine based reaction control thruster system. This system will provide for reboost and rendezvous maneuvers, CMG desaturation, and attitude control torque support. The total impulse required for station is primarily a function of the spacecraft mass and ballistic coefficient, the atmospheric drag effects, and the desired operational altitude range. At PMC, the station will have a mass of approximately 590,000 lbm. with a ballistic coefficient of 11.45. Figures 13 and 14 show the effect of spacecraft mass and ballistic coefficient on annual propellant requirements based on a nominal atmosphere.

Variation in
Annual Propellant Requirement vs. Spacecraft Mass

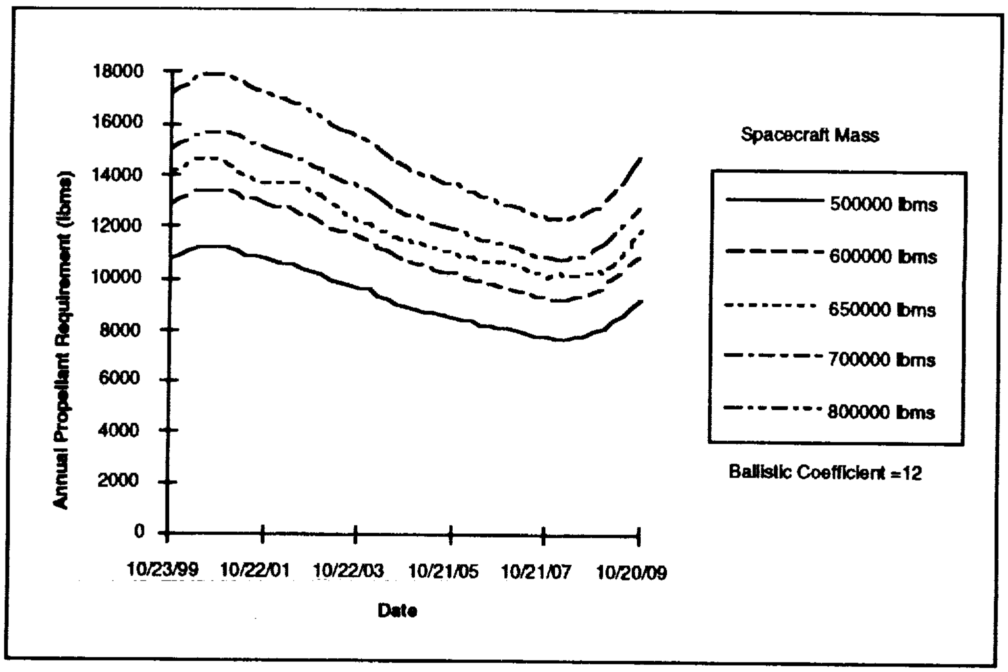

Figure 13

Variation in
Annual Propellant Requirement vs. Spacecraft Ballistic Number

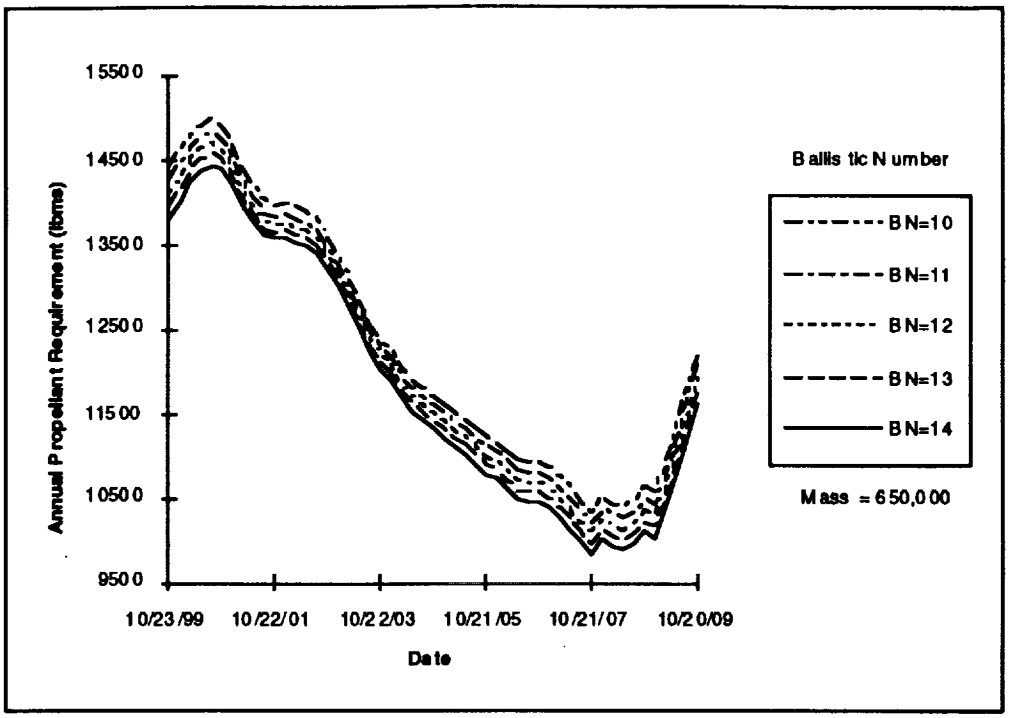

Figure 14

Atmospheric drag effects are related to the level of solar flux shown in Figure 15. As solar flux increases, the Earth's atmosphere expands. This expansion causes an increase in drag to orbital bodies. Therefore, during periods of high solar flux, more propellant is required for station altitude maintenance. The minimum altitude for station is set by the rendezvous altitude with the Space Shuttle and by atmospheric drag/vehicle safety concerns to be 180 days to 150 nautical miles above the Earth. The upper limit is set by the duration between maximum propellant resupply interval of 180 days and crew radiation exposure limitations.

Solar Cycle Trend

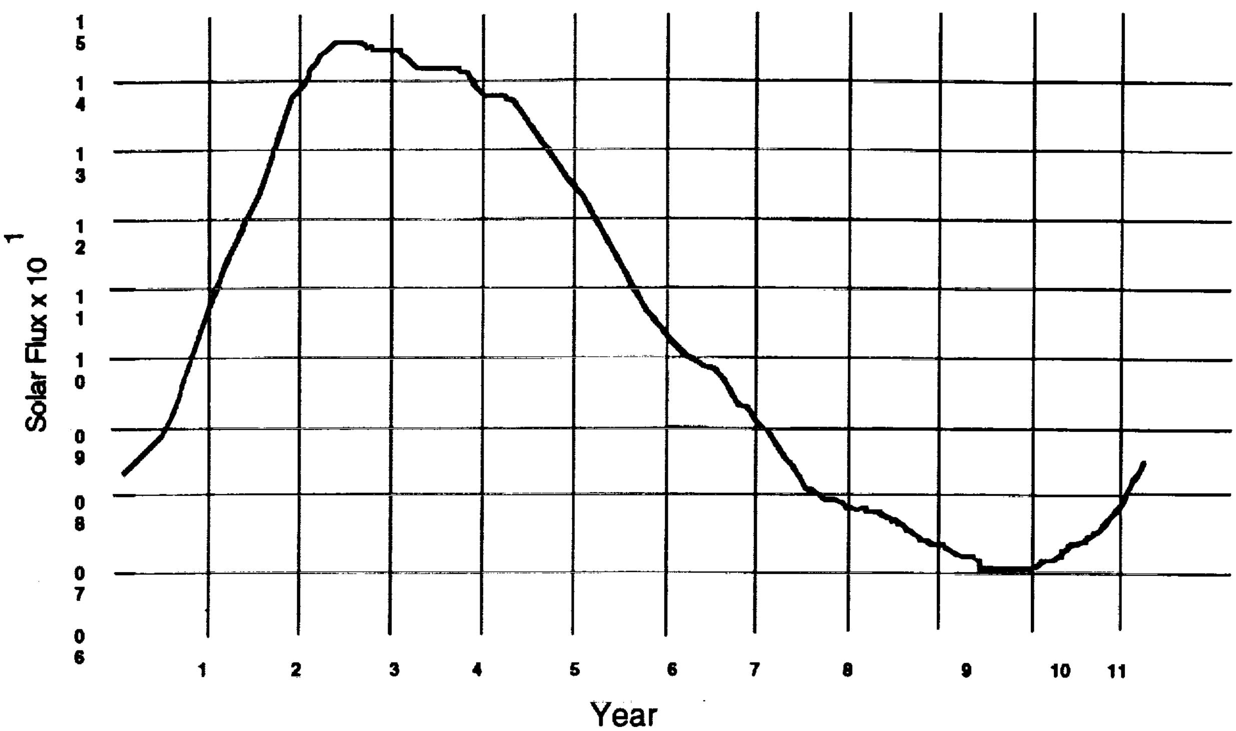

Figure 15

The STation Reboost Analysis Program (STRAP) tool was used to calculate the required propellant for station. STRAP provides SSF altitude profiles based on various altitude strategies. It determines the lower and upper altitudes and estimates the required propellant for each reboost. The inputs to the STRAP program used to simulate the Primary Propulstion System includes the following parameters: spacecraft orbit time interval, spacecraft mass and ballistic number, atmospheric parameters, and propellant ISP. When the Supplementary Reboost System was incorporated into the model, the amount of waste gas available and ISP of waste gas were also included. The effect of augmenting the PPS with the SRS can be demonstrated by comparing the change in the altitude strategy which is shown in Figure 16.

Orbital Decay with and without Resistojet Augmentation

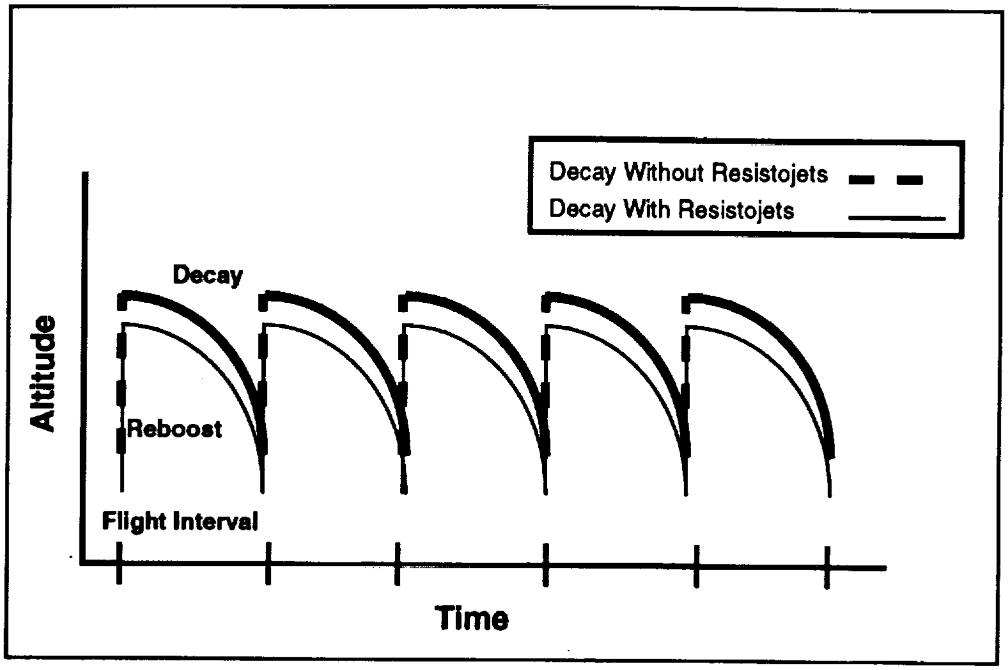

Figure 16

The figure shows that both the upper and lower operating altitude will be reduced through the augmentation of the PPS. This is due to the fact that the resistojet reduces the station's orbital decay rate. Therefore, it will take much longer to decay to 180 days to 150 nautical miles. This allows the station to operate at a much lower altitude.

For this part of the study, a flight rate of five reboosts per year was assumed. While higher or lower annual flight rates may occur, they will have a minimal effect on the average annual propellant required as can be seen in Figure 17.

Effect of Number of Annual Reboosts

on

Propellant Requirements

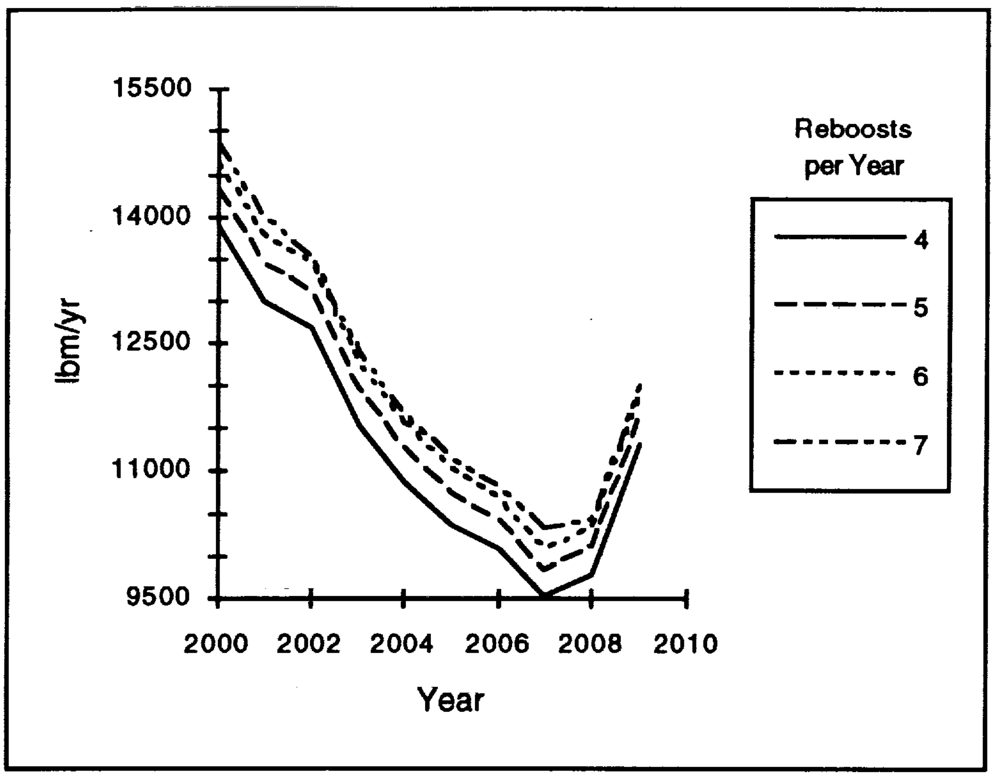

Figure 17

PMC PPS-only Altitude Strategy

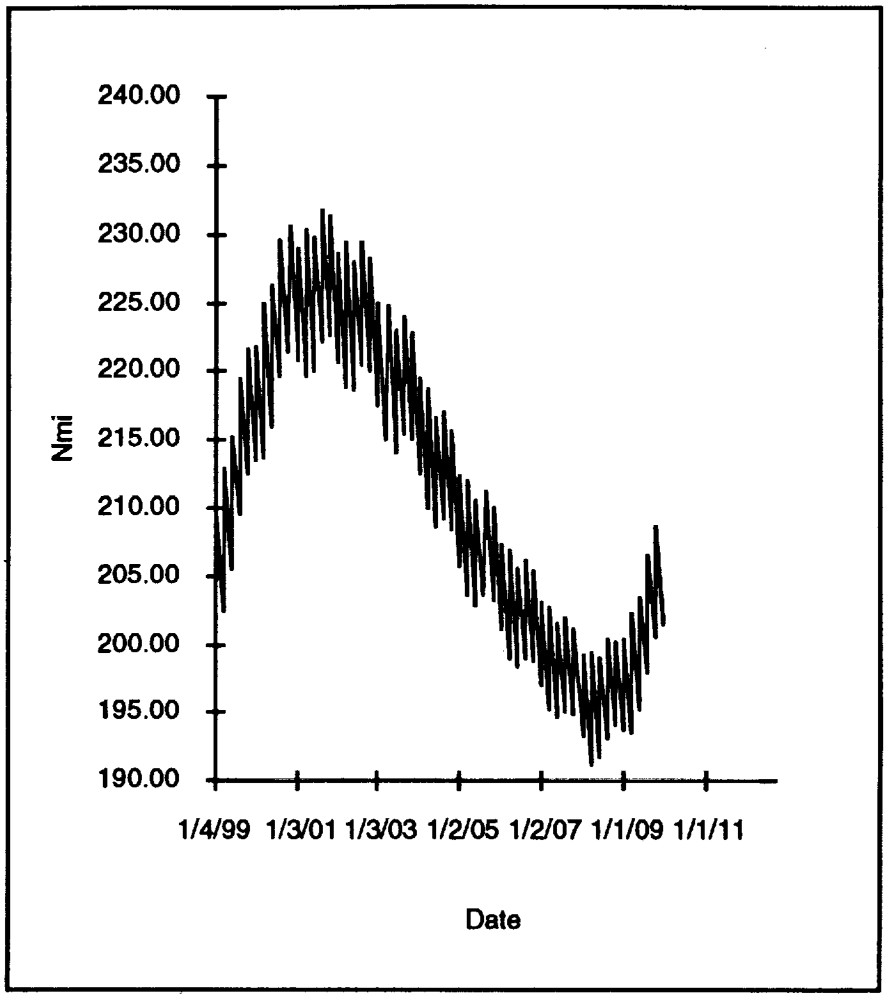

Figure 18

An initial baseline, corresponding to the no-propellant reduction configurations of options 1,2, and 3 was modeled by assuming an orbital lifetime strategy of 180 days to 150 nmi. Figure 18 and 19 show the altitude range and propellant required for the PMC station operating with the PPS-only configurations over an eleven year solar cycle. To reduce this requirement, the PPS can be augmented with resistojets using the waste gases produced by the crew and the ECLSS processors.

PMC PPS-Only Propellant Requirement

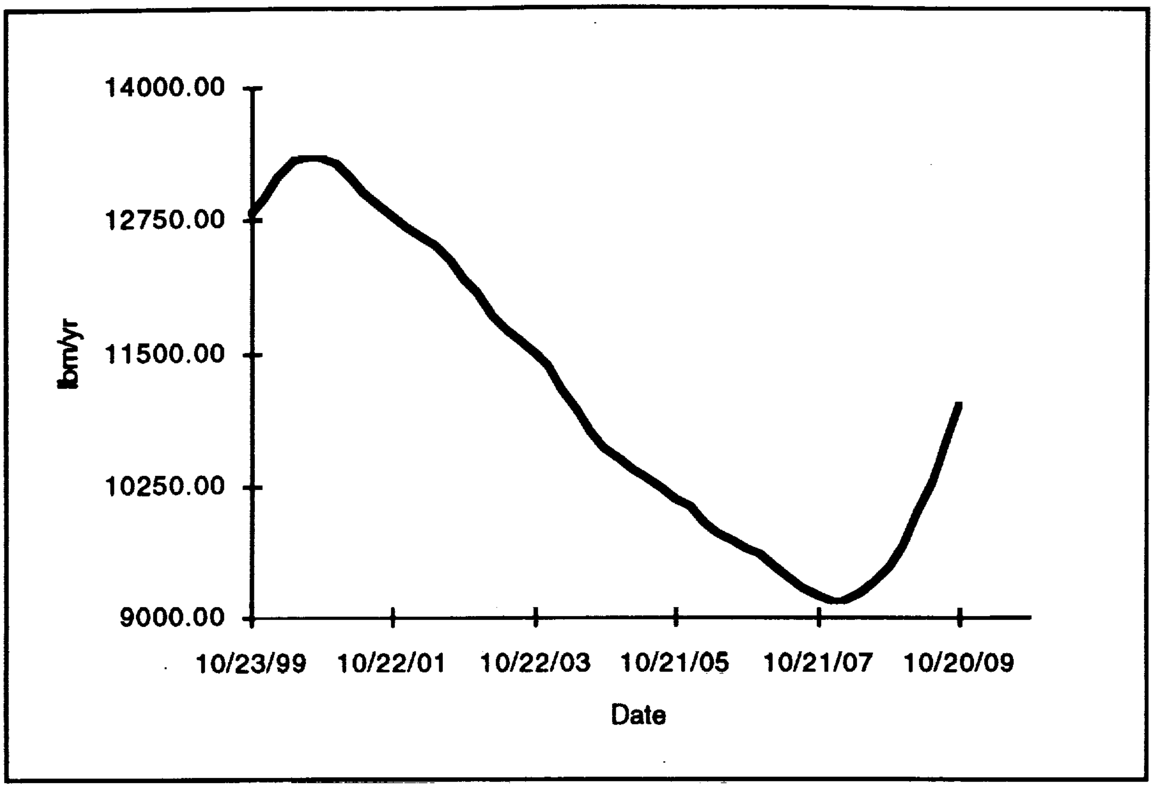

Figure 19

Rather than model every possible combination of Sabatier and Electrolyzer output to the Resistojet over an eleven year solar cycle, several simplifications were used. From Figure 19 it can be seen that the variation in propellant requirements due to solar cycle varies nearly linearly between the 2001-2008 timeframe. Since PMC will not occur until mid to late 2000, annual propellant requirements can be estimated based on the average usage during the maximum and minimum years (2001, 2008) of the solar cycle. A second simplification used was to develop an estimation of the annual hydrazine savings based on the amount of thrust provided by the SRS. The basic equation for thrust is shown in equation (1)

$$T = \dot{m}\, ISP \tag{1}$$

The thrust provided by the SRS on an annual basis can be written

$$T_{SRS} = \int_0^t \dot{m}\, ISP = m_{Waste\ Gas}\, ISP_{Waste\ Gas} \qquad (2)$$

where t is time, $m_{Waste\ Gas}$ is the amount of waste gas available per year, and $ISP_{Waste\ Gas}$ is the effective ISP of the waste gas. The amount of hydrazine saved is that portion that would be required to provide the same amount of thrust the SRS is providing or

$$M_{Hydrazine} = \frac{T_{SRS}}{ISP_{Hydrazine}} = \frac{M_{Waste\ Gas} \bullet ISP_{Waste\ Gas}}{ISP_{Hydrazine}} \qquad (3)$$

In order to validate these simplifications, several sample cases were run. Table 3 summarizes the results of these cases.

Table 3

Comparison of Estimated and Calculated Propellant Savings

Case	Spacecraft Mass (lbms)	Spacecraft Ballistic Number	Waste Gas Amount (lbms/yr)	Waste Gas Effective ISP	Hydrazine-Only (Avg 2001,2008) (lbms)	Augmented (Avg 2001,2008) (lbms)	Estimated Savings (lbms)	STRAP Analysis (lbms)
1	650,000	10	3600	100	12322	10785	1565	1537
2	650,000	12	3600	100	12055	10486	1565	1569
3	650,000	14	3600	100	11837	10289	1565	1548
4	500,000	12	3600	100	9373	7822	1565	1551
5	800,000	12	3600	100	14997	13425	1565	1572
6	590,315	11.45	1440	125	11914	11145	783	769
7		11.45	2880	125	11914	10353	1565	1561
8		11.45	7200	125	11914	8015	3913	3899
9	787,648	14.39	1440	125	14440	13650	783	790
10		14.39	2880	125	14440	12887	1565	1553
11		14.39	7200	125	14440	10517	3913	3923

Cases 1,2, and 3 were used to determine what effect the variation of the spacecraft ballistic number had on the difference between estimated and calculated propellant savings. Likewise cases 2,4, and 5 were used to determine the impact of spacecraft mass. Cases 6-11 tested the consequence of variation in the total thrust provided by the resistojet. The difference between the estimated savings and the STRAP analysis in all comparisons was never greater than 2%. This error occurs principally due to the fact that the effect of solar flux is not completely linear over the time period considered.

Total Integrated Fluid Logistics

Utilizing the estimation method for propellant savings, the integrated fluid logistics for each of the technology options can now be totaled. Based on the PMC configuration, the total fluid logistics for propellant, cryogenic oxygen, and food assuming no food dehydration or use of STS fuel cell water for each of the technology options are shown in the following figures.

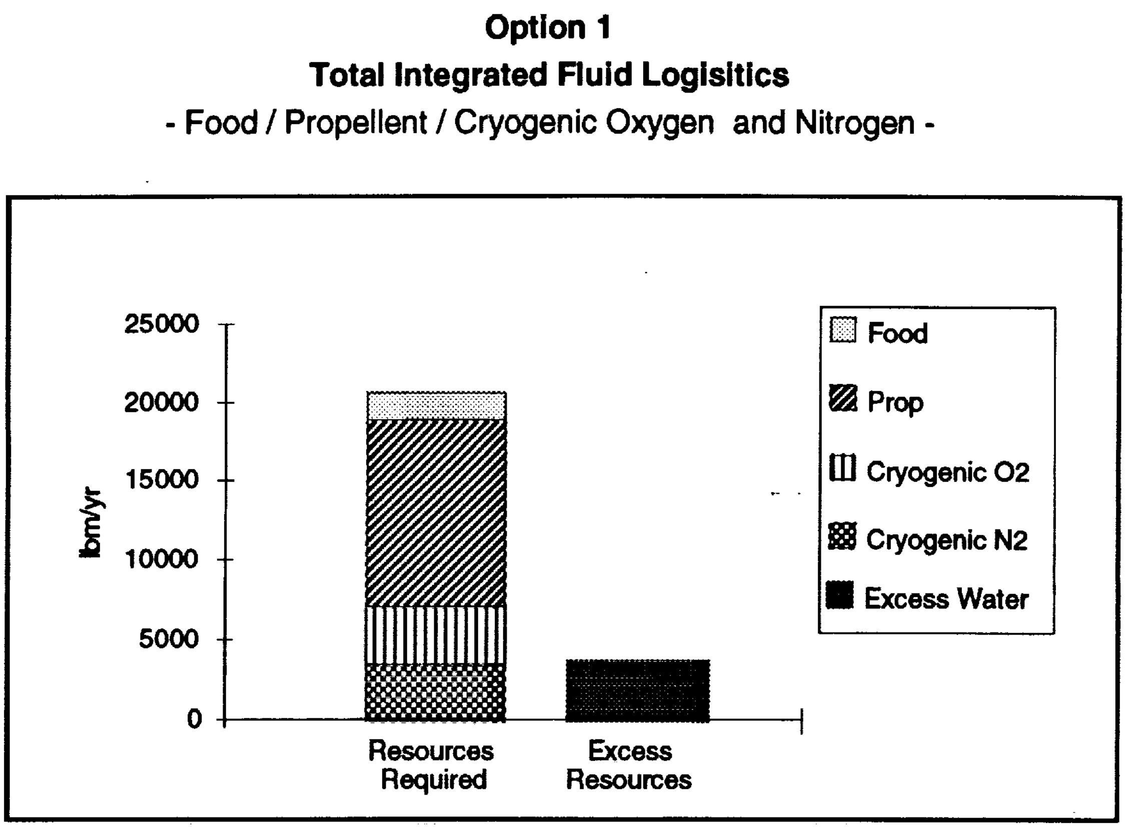

Figure 20

Option 2
Total Integrated Fluid Logisitics
- Food / Propellent / Cryogenic Oxygen and Nitrogen -

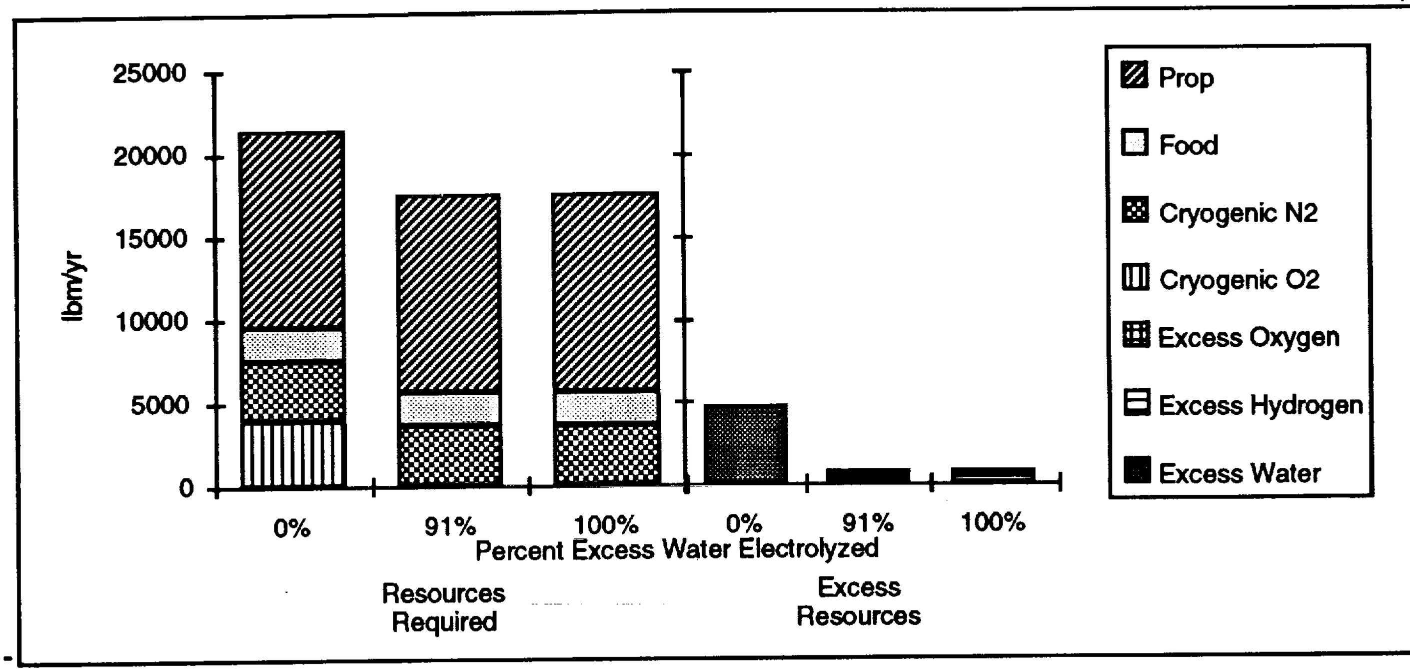

Figure 21

Option 3
Total Integrated Fluid Logisitics
- Cryogenic Oxygen -

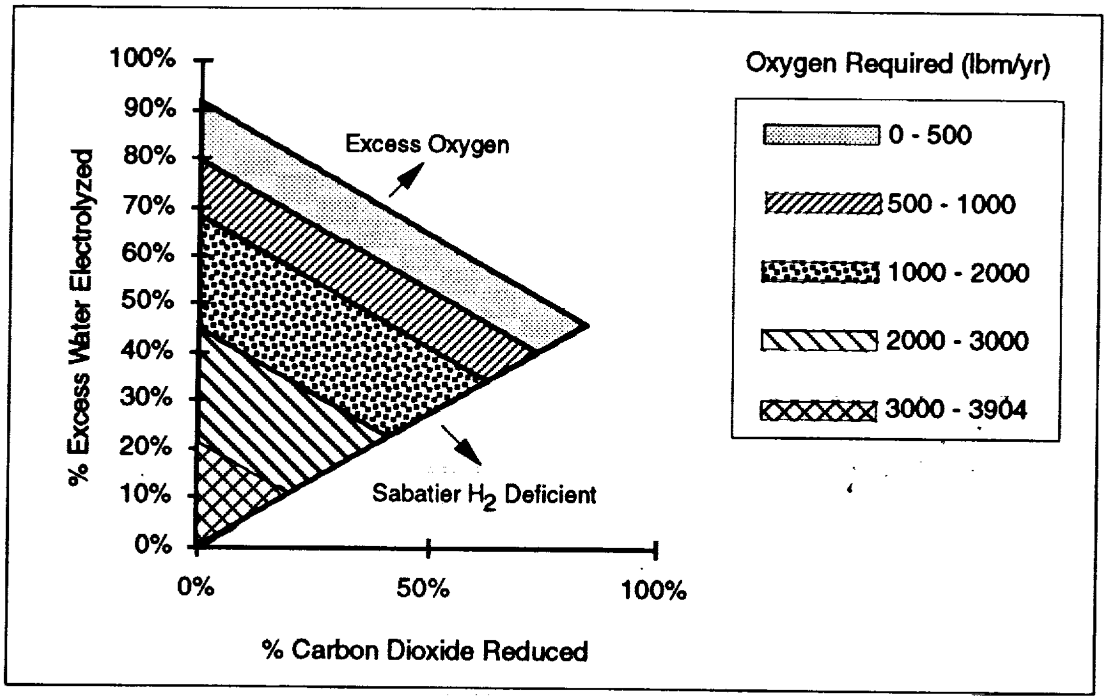

Figure 22 - A

Option 3

Total Integrated Fluid Logisitics

- Food / Propellant / Cryogenic Nitrogen -

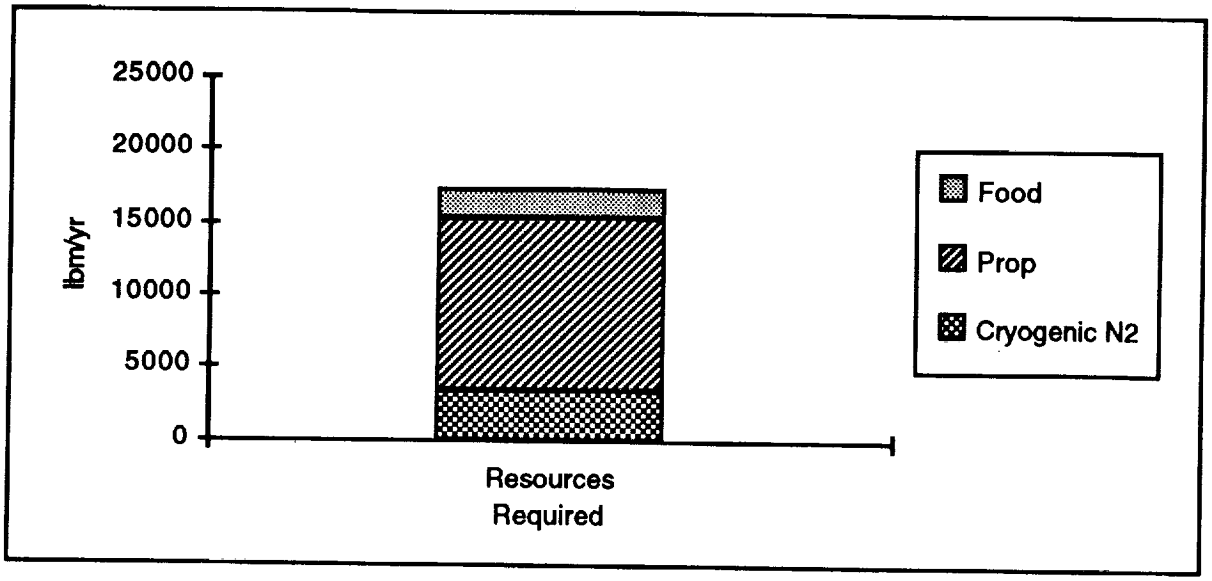

Figure 22 - B

Option 3
Total Integrated Fluid Logisitics
- Excess Water -

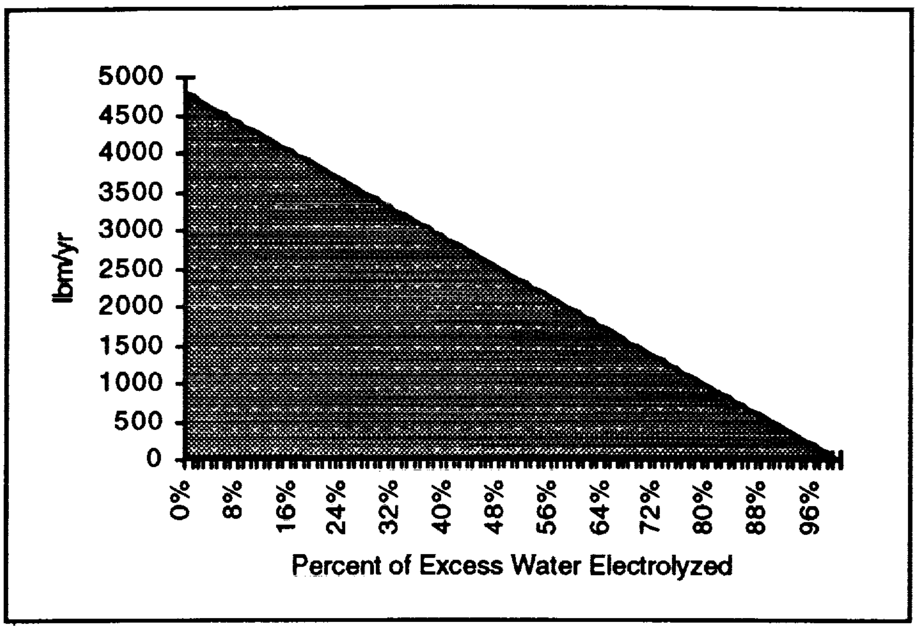

Figure 22 - C

Option 3
Total Integrated Fluid Logisitics
- Excess Oxygen -

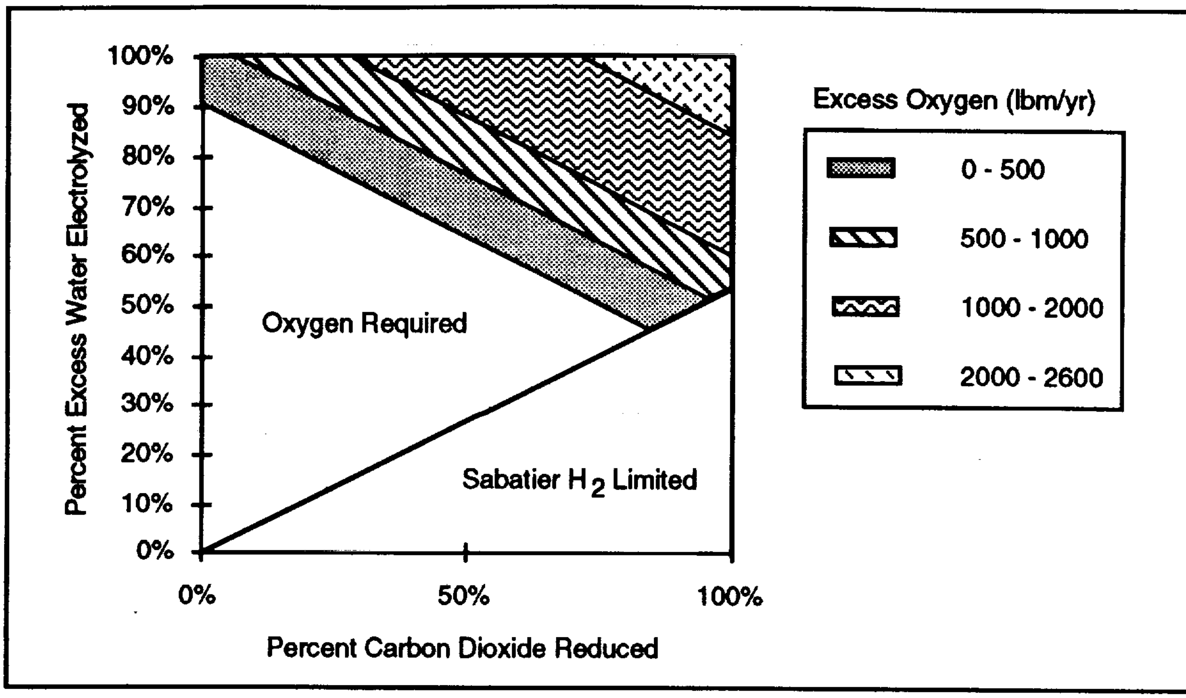

Figure 22 - D

Option 3

Total Integrated Fluid Logisitics

- Excess Hydrogen -

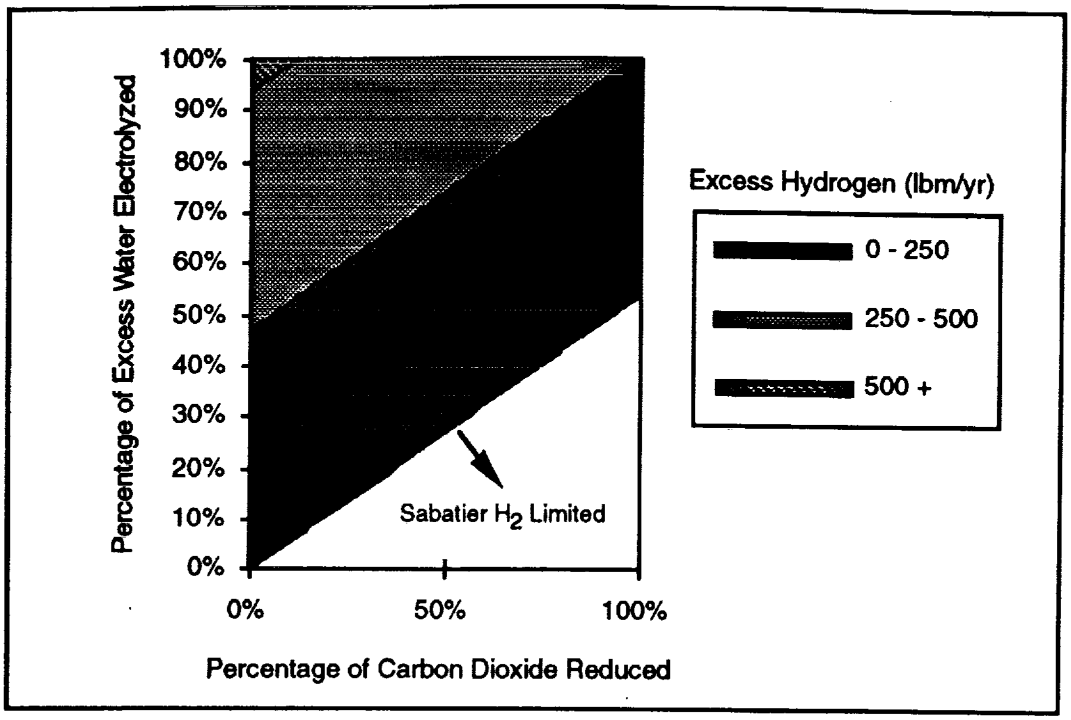

Figure 22 - E

Option 4

Total Integrated Fluid Logisitics

- Food / Propellant / Cryogenic Oxygen / Cryogenic Nitrogen -

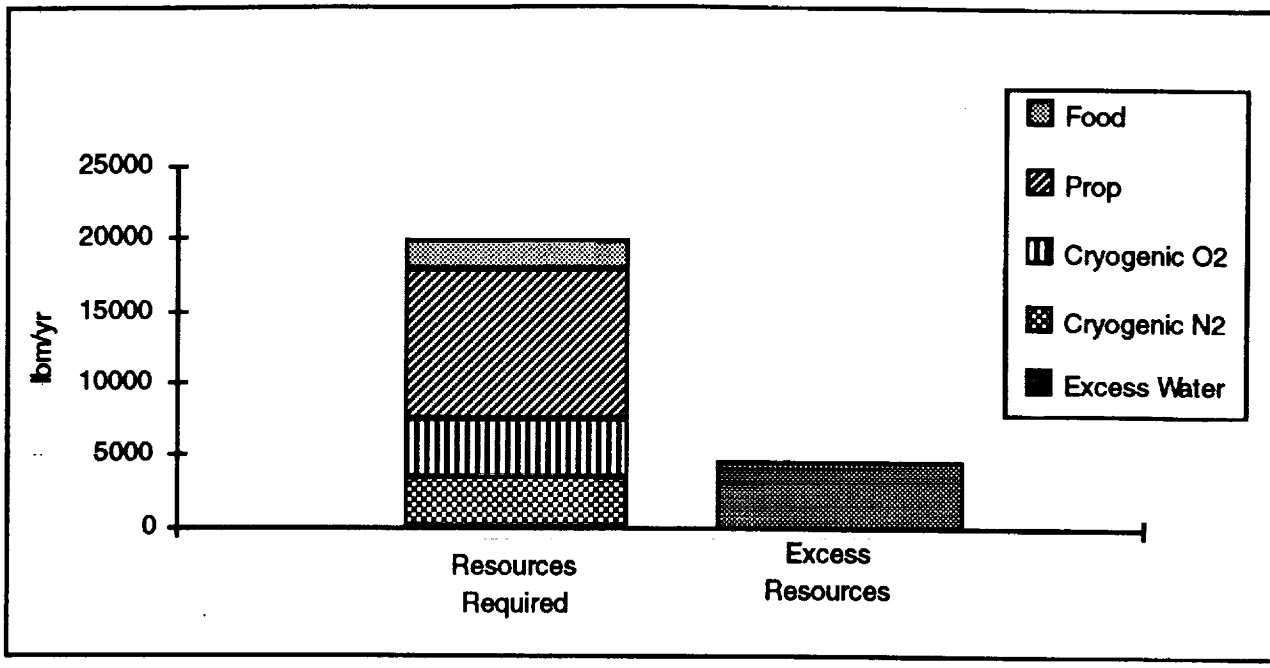

Figure 23

Option 5
Total Integrated Fluid Logisitics
- Food / Propellant / Cryogenic Oxygen / Cryogenic Nitrogen -

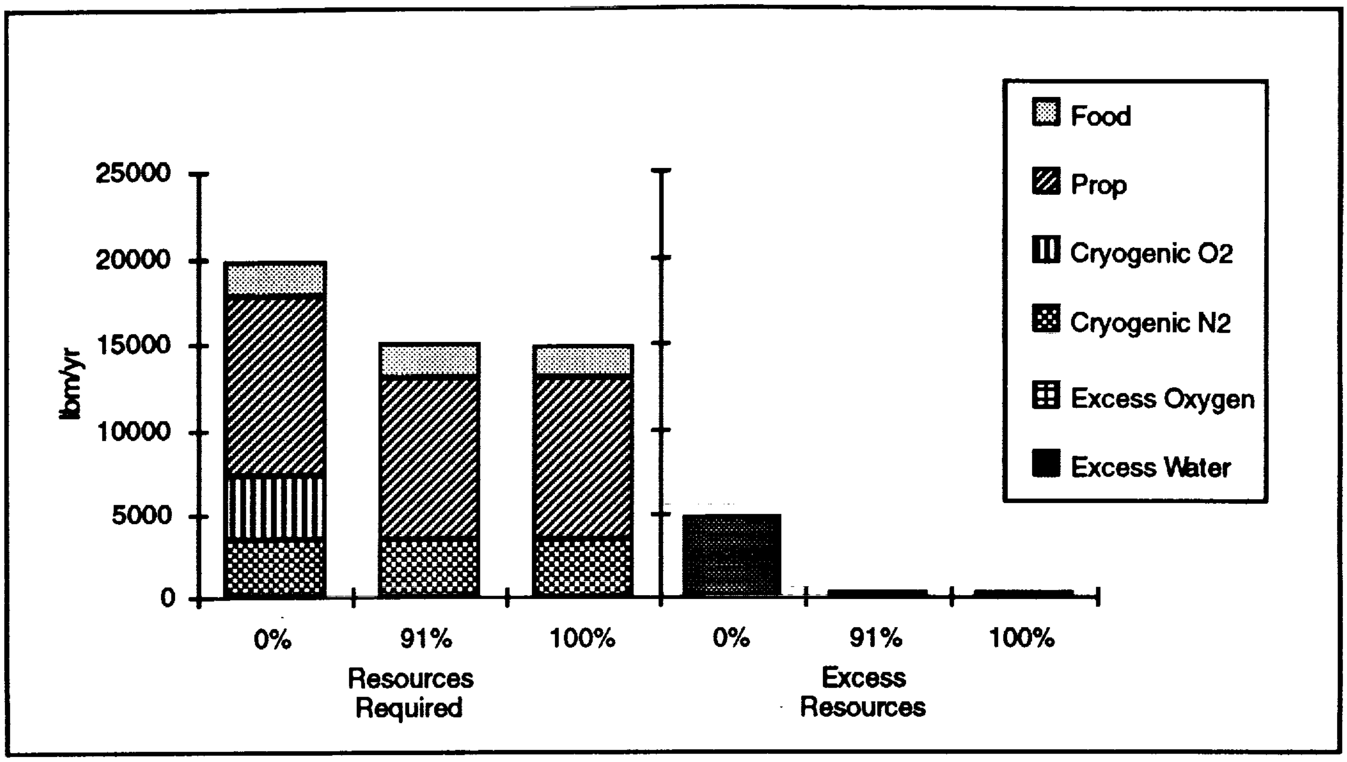

Figure 24

Option 6
Total Integrated Fluid Logisitics
- Cryogenic Oxygen -

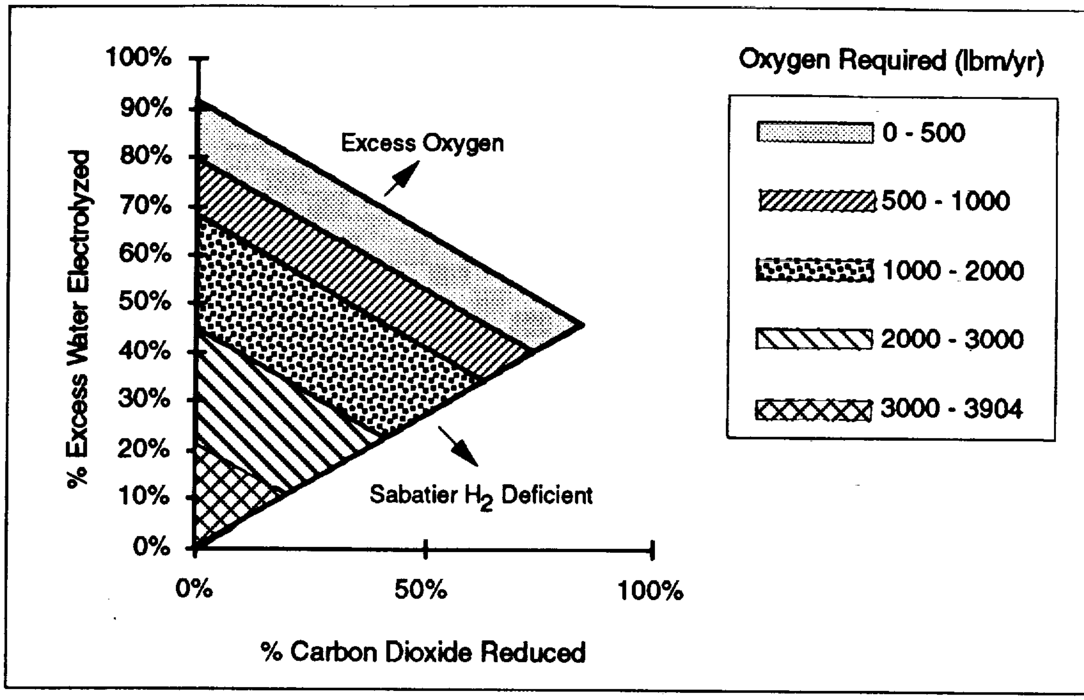

Figure 25 - A

Option 6
Total Integrated Fluid Logisitics
- Propellant -

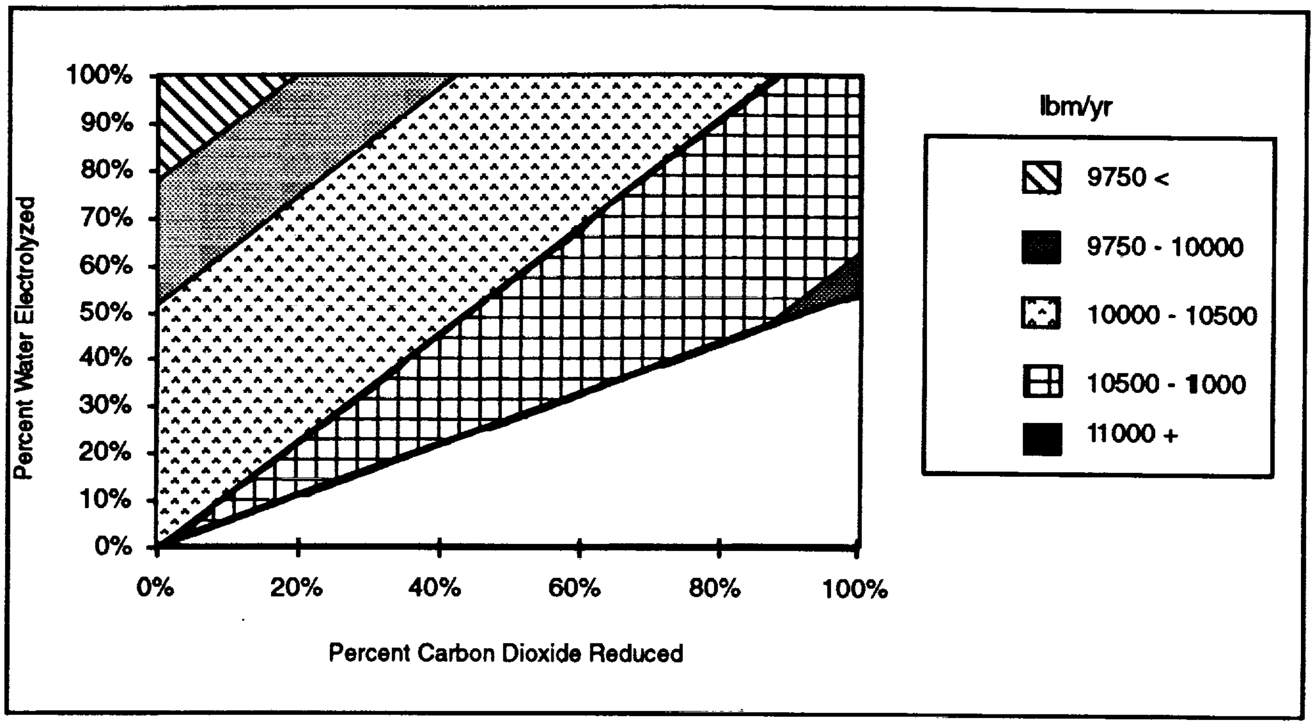

Figure 25 - B

Option 6

Total Integrated Fluid Logisitics

- Food / Cryogenic Nitrogen -

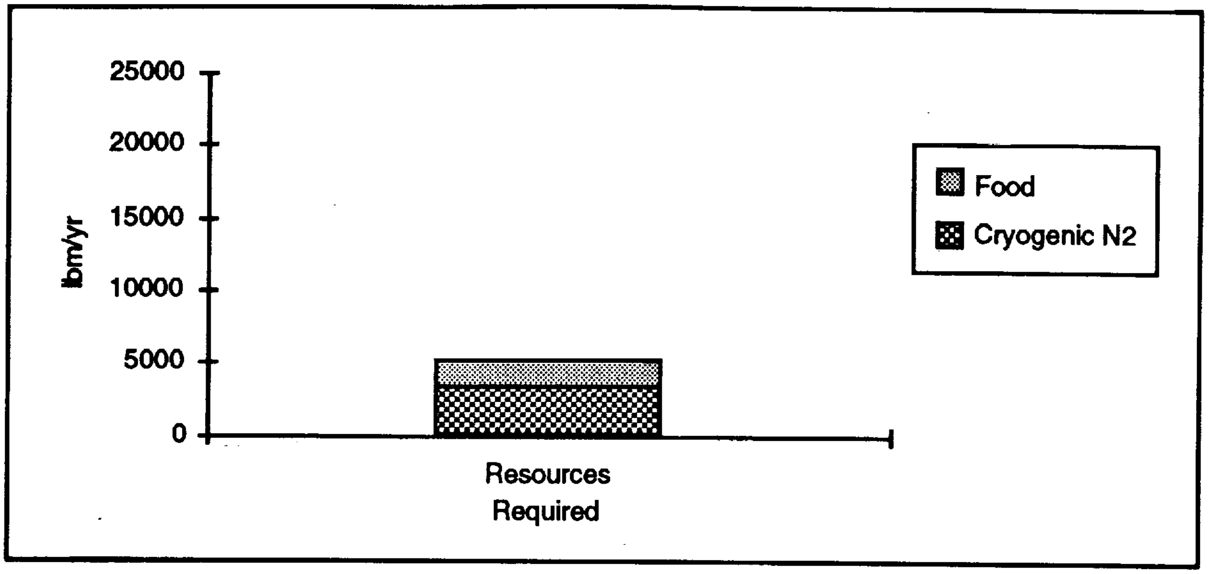

Figure 25 - C

Option 6
Total Integrated Fluid Logisitics
- Excess Water -

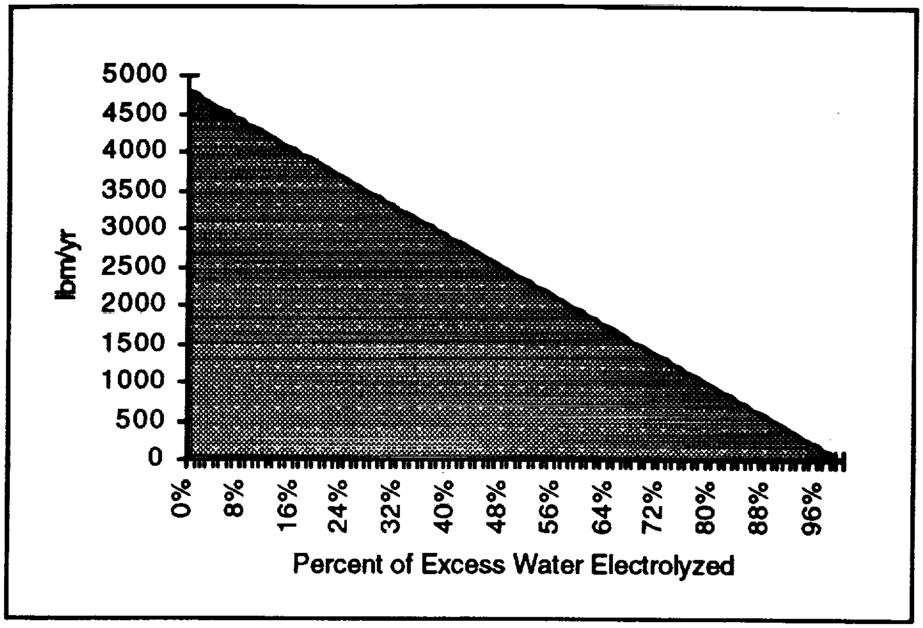

Figure 25- D

Option 6

Total Integrated Fluid Logisitics

- Excess Oxygen -

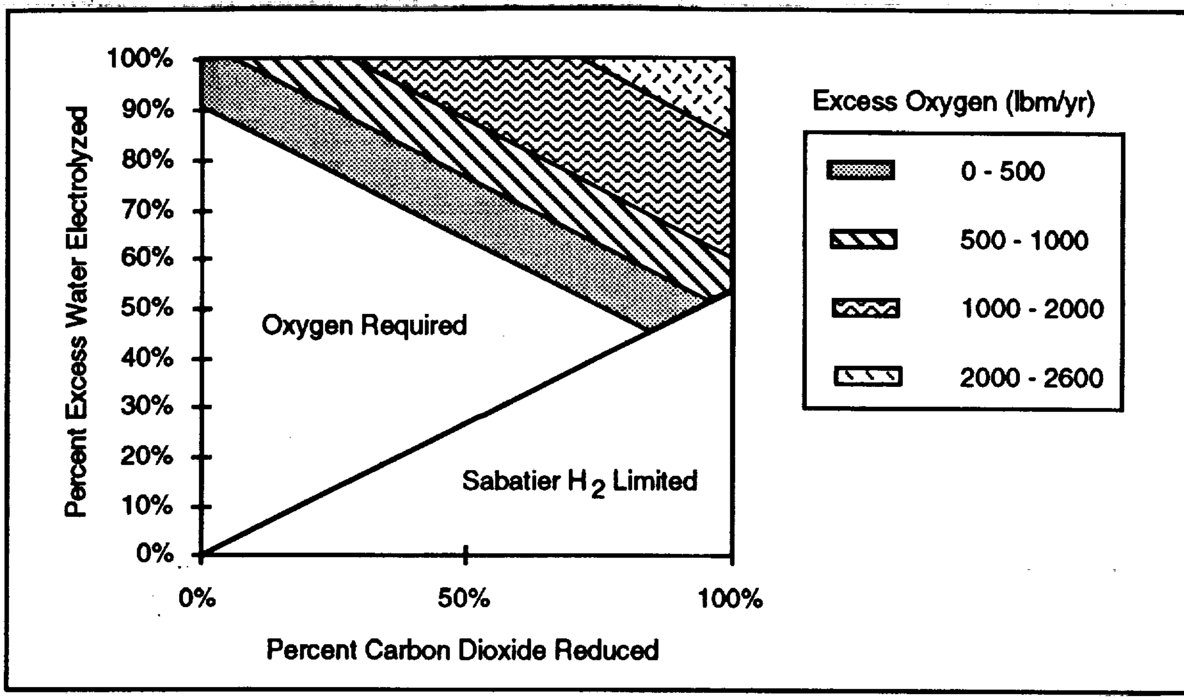

Figure 25 - E

Figure 20 for option 1 illustrates the total fluid logistics requirements for the baseline SSF without any logistics reduction enhancements. The total annual requirement for fluids including propellant, cryogenic oxygen and nitrogen, and food is 24,886 lbms. Figure 21 shows that with the addition of an electrolyzer alone, cryogenic oxygen requirements can be eliminated by processing 91% of the available excess water, a savings of 3900 lbm per year. Electrolyzing the remaining 9% in this option only changes the composition of the waste gases to be vented overboard. Collectively Figures 22 -A - E show the impact of adding both an electrolyzer and a Sabatier. Again all cryogenic oxygen requirements can be eliminated. However, since no resistojet has been added, propellant requirements, as well as food and cryogenic nitrogen requirements remain unchanged. Figure 23 illustrates the impact to fluid logistics for Option 4. In this option, carbon dioxide is fed through the resistojet. While cryogenic oxygen requirements remain unchanged, an annual propellant savings of 1400 lbms is achieved. Option 5 results are shown in Figure 24. Like Option 2, a electrolyzer without a Sabatier is added to station. However, unlike Option 2, Option 5 takes advantage of the waste gases provided by the ECLSS. Therefore cryogenic oxygen requirements can be eliminated and propellant requirements reduced. Maximum benefit, achieved at full electrolysis of excess water, can reduce annual logistics by nearly 6,300 lbm per year. The final option impacts, those for Option 6, are shown in the series of Figures 25 - A-E. While similar to Option 5 in that both cryogenic oxygen requirements can be eliminated and propellant reduced, the amount of waste gas, which is primarily methane and the level of ISP produced by this configuration is less than the benefit achieved from Option 5 using carbon dioxide. In addition Option 5 is a similar system than Option 6.

In the following tables, the total fluid logistics with and without a resistojet are shown based on the level of food dehydration, available Orbiter fuel cell water, carbon dioxide reduction, and water electrolysis.

Table 5

Logistics Savings Based on Food Dehydration, Fuel Cell Water, % CO2 Reduced, % Water Electrolyzed

% Food Dehydrated	% Available STS Fuel Cell H20 Added to Station	% CO2 Reduced	% Excess H2O Electrolyzed	Total Fluid Logistics (w/o R-J)	Total Fluid Logistics (w R-J)	Food	Prop w/o R-J	Prop w/ R-J	Cryo O2	Cryo N2	Average Power (watts)
0%	0%	0%	0%	24886	23467	5616	11914	10495	3906	3450	0
0%	0%	0%	20%	24032	22420	5616	11914	10303	3052	3450	468
0%	0%	0%	40%	23177	21373	5616	11914	10110	2197	3450	936
0%	0%	0%	60%	22323	20326	5616	11914	9917	1343	3450	1404
0%	0%	0%	80%	21468	19279	5616	11914	9724	488	3450	1871
0%	0%	0%	100%	20980	18598	5616	11914	9532	0	3450	2339
0%	0%	20%	11%	23964	22662	5616	11914	10612	2984	3450	287
0%	0%	20%	20%	23571	22180	5616	11914	10523	2591	3450	502
0%	0%	20%	40%	22716	21133	5616	11914	10330	1736	3450	970
0%	0%	20%	60%	21862	20086	5616	11914	10138	882	3450	1438
0%	0%	20%	80%	21008	19038	5616	11914	9945	28	3450	1906
0%	0%	20%	100%	20980	18818	5616	11914	9752	0	3450	2373
0%	0%	40%	22%	23043	21857	5616	11914	10728	2063	3450	573
0%	0%	40%	40%	22256	20892	5616	11914	10551	1276	3450	1004
0%	0%	40%	60%	21401	19845	5616	11914	10358	421	3450	1472
0%	0%	40%	80%	20980	19231	5616	11914	10165	0	3450	1940
0%	0%	40%	100%	20980	19039	5616	11914	9973	0	3450	2408
0%	0%	60%	32%	22121	21052	5616	11914	10845	1141	3450	860
0%	0%	60%	40%	21795	20652	5616	11914	10771	815	3450	1038
0%	0%	60%	60%	20980	19644	5616	11914	10578	0	3450	1506
0%	0%	60%	80%	20980	19452	5616	11914	10386	0	3450	1974
0%	0%	60%	100%	20980	19259	5616	11914	10193	0	3450	2442
0%	0%	80%	43%	21200	20247	5616	11914	10961	220	3450	1146
0%	0%	80%	60%	20980	19865	5616	11914	10799	0	3450	1540
0%	0%	80%	80%	20980	19672	5616	11914	10606	0	3450	2008
0%	0%	80%	100%	20980	19479	5616	11914	10413	0	3450	2476
0%	0%	100%	54%	20980	20144	5616	11914	11078	0	3450	1433
0%	0%	100%	60%	20980	20085	5616	11914	11019	0	3450	1575
0%	0%	100%	80%	20980	19892	5616	11914	10826	0	3450	2043
0%	0%	100%	100%	20980	19700	5616	11914	10634	0	3450	2510
25%	0%	0%	0%	23972	22553	4702	11914	10495	3906	3450	0
25%	0%	0%	20%	23280	21705	4702	11914	10339	3214	3450	379
25%	0%	0%	40%	22588	20857	4702	11914	10183	2522	3450	758
25%	0%	0%	60%	21896	20009	4702	11914	10027	1830	3450	1136
25%	0%	0%	80%	21204	19161	4702	11914	9871	1139	3450	1515
25%	0%	0%	100%	20512	18313	4702	11914	9715	447	3450	1894
25%	0%	20%	13%	23050	21748	4702	11914	10612	2984	3450	287
25%	0%	20%	20%	22819	21465	4702	11914	10560	2753	3450	413
25%	0%	20%	40%	22127	20617	4702	11914	10404	2062	3450	792
25%	0%	20%	60%	21435	19769	4702	11914	10248	1370	3450	1171
25%	0%	20%	80%	20743	18921	4702	11914	10092	678	3450	1550
25%	0%	20%	100%	20066	18087	4702	11914	9935	0	3450	1928
25%	0%	40%	27%	22128	20943	4702	11914	10728	2063	3450	573
25%	0%	40%	40%	21666	20376	4702	11914	10624	1601	3450	826
25%	0%	40%	60%	20974	19528	4702	11914	10468	909	3450	1205
25%	0%	40%	80%	20283	18681	4702	11914	10312	217	3450	1584
25%	0%	40%	100%	20066	18307	4702	11914	10156	0	3450	1963
25%	0%	60%	40%	21207	20137	4702	11914	10845	1141	3450	860
25%	0%	60%	60%	20514	19288	4702	11914	10688	448	3450	1239
25%	0%	60%	80%	20066	18684	4702	11914	10532	0	3450	1618
25%	0%	60%	100%	20066	18528	4702	11914	10376	0	3450	1997
25%	0%	80%	53%	20285	19332	4702	11914	10961	220	3450	1146
25%	0%	80%	60%	20066	19060	4702	11914	10909	0	3450	1273
25%	0%	80%	80%	20066	18904	4702	11914	10753	0	3450	1652
25%	0%	80%	100%	20066	18748	4702	11914	10597	0	3450	2031

% Food Dehydrated	% Available STS Fuel Cell H20 Added to Station	% CO2 Reduced	% Excess H2O Electrolyzed	Total Fluid Logistics (w/o R-J)	Total Fluid Logistics (w R-J)	Food	Prop w/o R-J	Prop w/ R-J	Cryo O2	Cryo N2	Average Power (watts)
25%	0%	100%	67%	20066	19229	4702	11914	11078	0	3450	1433
25%	0%	100%	80%	20066	19125	4702	11914	10973	0	3450	1687
25%	0%	100%	100%	20066	18969	4702	11914	10817	0	3450	2065
50%	0%	0%	0%	23057	21638	3787	11914	10495	3906	3450	0
50%	0%	0%	20%	22528	20990	3787	11914	10376	3377	3450	290
50%	0%	0%	40%	21999	20341	3787	11914	10257	2847	3450	580
50%	0%	0%	60%	21469	19693	3787	11914	10137	2318	3450	869
50%	0%	0%	80%	20940	19044	3787	11914	10018	1789	3450	1159
50%	0%	0%	100%	20411	18395	3787	11914	9898	1260	3450	1449
50%	0%	20%	17%	22136	20833	3787	11914	10612	2984	3450	287
50%	0%	20%	20%	22067	20749	3787	11914	10596	2916	3450	324
50%	0%	20%	40%	21538	20101	3787	11914	10477	2387	3450	614
50%	0%	20%	60%	21009	19452	3787	11914	10358	1857	3450	904
50%	0%	20%	80%	20479	18803	3787	11914	10238	1328	3450	1194
50%	0%	20%	100%	19950	18155	3787	11914	10119	799	3450	1483
50%	0%	40%	35%	21214	20028	3787	11914	10728	2063	3450	573
50%	0%	40%	40%	21077	19860	3787	11914	10697	1926	3450	648
50%	0%	40%	60%	20548	19212	3787	11914	10578	1397	3450	938
50%	0%	40%	80%	20018	18563	3787	11914	10459	867	3450	1228
50%	0%	40%	100%	19489	17914	3787	11914	10339	338	3450	1518
50%	0%	60%	52%	20292	19223	3787	11914	10845	1141	3450	860
50%	0%	60%	60%	20087	18971	3787	11914	10798	936	3450	972
50%	0%	60%	80%	19558	18323	3787	11914	10679	406	3450	1262
50%	0%	60%	100%	19151	17797	3787	11914	10560	0	3450	1552
50%	0%	80%	70%	19371	18418	3787	11914	10961	220	3450	1146
50%	0%	80%	80%	19151	18137	3787	11914	10899	0	3450	1296
50%	0%	80%	100%	19151	18017	3787	11914	10780	0	3450	1586
50%	0%	100%	87%	19151	18315	3787	11914	11078	0	3450	1433
50%	0%	100%	100%	19151	18238	3787	11914	11000	0	3450	1620
75%	0%	0%	0%	22143	20724	2873	11914	10495	3906	3450	0
75%	0%	0%	20%	21776	20275	2873	11914	10413	3539	3450	201
75%	0%	0%	40%	21409	19825	2873	11914	10330	3173	3450	402
75%	0%	0%	60%	21043	19376	2873	11914	10247	2806	3450	602
75%	0%	0%	80%	20676	18926	2873	11914	10164	2439	3450	803
75%	0%	0%	100%	20309	18477	2873	11914	10082	2072	3450	1004
75%	0%	20%	25%	21221	19919	2873	11914	10612	2984	3450	287
75%	0%	20%	40%	20949	19585	2873	11914	10550	2712	3450	436
75%	0%	20%	60%	20582	19135	2873	11914	10468	2345	3450	637
75%	0%	20%	80%	20215	18686	2873	11914	10385	1978	3450	837
75%	0%	20%	100%	19848	18237	2873	11914	10302	1612	3450	1038
75%	0%	40%	50%	20300	19114	2873	11914	10728	2063	3450	573
75%	0%	40%	60%	20121	18895	2873	11914	10688	1884	3450	671
75%	0%	40%	80%	19754	18446	2873	11914	10605	1518	3450	872
75%	0%	40%	100%	19388	17996	2873	11914	10522	1151	3450	1073
75%	0%	60%	75%	19378	18309	2873	11914	10845	1141	3450	860
75%	0%	60%	80%	19294	18205	2873	11914	10826	1057	3450	906
75%	0%	60%	100%	18927	17756	2873	11914	10743	690	3450	1107
75%	0%	80%	60%	19199	18247	2873	11914	10961	963	3450	739
75%	0%	80%	80%	18833	17880	2873	11914	10961	596	3450	940
75%	0%	80%	100%	18466	17513	2873	11914	10961	229	3450	1141
100%	0%	0%	0%	21228	19810	1958	11914	10495	3906	3450	0
100%	0%	0%	20%	21024	19559	1958	11914	10449	3702	3450	112
100%	0%	0%	40%	20820	19309	1958	11914	10403	3498	3450	224
100%	0%	0%	60%	20616	19059	1958	11914	10357	3294	3450	335
100%	0%	0%	80%	20412	18809	1958	11914	10311	3089	3450	447
100%	0%	0%	100%	20208	18559	1958	11914	10265	2885	3450	559
100%	0%	20%	45%	20307	19005	1958	11914	10612	2984	3450	287
100%	0%	20%	60%	20155	18819	1958	11914	10578	2833	3450	370
100%	0%	20%	80%	19951	18568	1958	11914	10531	2629	3450	481
100%	0%	20%	100%	19747	18318	1958	11914	10485	2424	3450	593
100%	0%	40%	90%	19385	18199	1958	11914	10728	2063	3450	573

% Food Dehydrated	% Available STS Fuel Cell H20 Added to Station	% CO2 Reduced	% Excess H2O Electrolyzed	Total Fluid Logistics (w/o R-J)	Total Fluid Logistics (w R-J)	Food	Prop w/o R-J	Prop w/ R-J	Cryo O2	Cryo N2	Average Power (watts)
100%	0%	40%	100%	19286	18078	1958	11914	10706	1964	3450	627
0%	50%	0%	0%	24886	23467	5616	11914	10495	3906	3450	0
0%	50%	0%	20%	23498	21767	5616	11914	10182	2518	3450	760
0%	50%	0%	40%	22111	20066	5616	11914	9869	1131	3450	1520
0%	50%	0%	60%	20980	18622	5616	11914	9556	0	3450	2280
0%	50%	0%	80%	20980	18309	5616	11914	9243	0	3450	3039
0%	50%	0%	100%	20980	17996	5616	11914	8930	0	3450	3799
0%	50%	20%	7%	23964	22662	5616	11914	10612	2984	3450	287
0%	50%	20%	20%	23037	21526	5616	11914	10403	2057	3450	794
0%	50%	20%	40%	21650	19825	5616	11914	10090	670	3450	1554
0%	50%	20%	60%	20980	18843	5616	11914	9777	0	3450	2314
0%	50%	20%	80%	20980	18530	5616	11914	9464	0	3450	3074
0%	50%	20%	100%	20980	18217	5616	11914	9151	0	3450	3834
0%	50%	40%	13%	23043	21857	5616	11914	10728	2063	3450	573
0%	50%	40%	20%	22577	21286	5616	11914	10623	1597	3450	828
0%	50%	40%	40%	21189	19585	5616	11914	10310	209	3450	1588
0%	50%	40%	60%	20980	19063	5616	11914	9997	0	3450	2348
0%	50%	40%	80%	20980	18750	5616	11914	9684	0	3450	3108
0%	50%	40%	100%	20980	18437	5616	11914	9371	0	3450	3868
0%	50%	60%	20%	22121	21052	5616	11914	10845	1141	3450	860
0%	50%	60%	40%	20980	19596	5616	11914	10530	0	3450	1622
0%	50%	60%	60%	20980	19283	5616	11914	10217	0	3450	2382
0%	50%	60%	80%	20980	18970	5616	11914	9904	0	3450	3142
0%	50%	60%	100%	20980	18657	5616	11914	9591	0	3450	3902
0%	50%	80%	27%	21200	20247	5616	11914	10961	220	3450	1146
0%	50%	80%	40%	20980	19817	5616	11914	10751	0	3450	1657
0%	50%	80%	60%	20980	19504	5616	11914	10438	0	3450	2417
0%	50%	80%	80%	20980	19191	5616	11914	10125	0	3450	3176
0%	50%	80%	100%	20980	18878	5616	11914	9812	0	3450	3936
0%	50%	100%	33%	20980	20144	5616	11914	11078	0	3450	1433
0%	50%	100%	40%	20980	20037	5616	11914	10971	0	3450	1691
0%	50%	100%	60%	20980	19724	5616	11914	10658	0	3450	2451
0%	50%	100%	80%	20980	19411	5616	11914	10345	0	3450	3211
0%	50%	100%	100%	20980	19098	5616	11914	10032	0	3450	3971
25%	50%	0%	0%	23972	22553	4702	11914	10495	3906	3450	0
25%	50%	0%	20%	22746	21051	4702	11914	10219	2681	3450	671
25%	50%	0%	40%	21521	19550	4702	11914	9943	1456	3450	1342
25%	50%	0%	60%	20296	18048	4702	11914	9666	230	3450	2013
25%	50%	0%	80%	20066	17542	4702	11914	9390	0	3450	2683
25%	50%	0%	100%	20066	17265	4702	11914	9114	0	3450	3354
25%	50%	20%	8%	23050	21748	4702	11914	10612	2984	3450	287
25%	50%	20%	20%	22286	20811	4702	11914	10439	2220	3450	705
25%	50%	20%	40%	21060	19309	4702	11914	10163	995	3450	1376
25%	50%	20%	60%	20066	18038	4702	11914	9887	0	3450	2047
25%	50%	20%	80%	20066	17762	4702	11914	9610	0	3450	2718
25%	50%	20%	100%	20066	17486	4702	11914	9334	0	3450	3389
25%	50%	40%	15%	22128	20943	4702	11914	10728	2063	3450	573
25%	50%	20%	40%	21060	19309	4702	11914	10163	995	3450	1376
25%	50%	40%	40%	20600	19069	4702	11914	10383	534	3450	1410
25%	50%	40%	60%	20066	18259	4702	11914	10107	0	3450	2081
25%	50%	40%	80%	20066	17982	4702	11914	9831	0	3450	2752
25%	50%	40%	100%	20066	17706	4702	11914	9554	0	3450	3423
25%	50%	60%	23%	21207	20137	4702	11914	10845	1141	3450	860
25%	50%	60%	40%	20139	18829	4702	11914	10604	73	3450	1444
25%	50%	60%	60%	20066	18479	4702	11914	10327	0	3450	2115
25%	50%	60%	80%	20066	18203	4702	11914	10051	0	3450	2786
25%	50%	60%	100%	20066	17926	4702	11914	9775	0	3450	3457
25%	50%	80%	30%	20285	19332	4702	11914	10961	220	3450	1146
25%	50%	80%	40%	20066	18976	4702	11914	10824	0	3450	1479
25%	50%	80%	60%	20066	18699	4702	11914	10548	0	3450	2150
25%	50%	80%	80%	20066	18423	4702	11914	10271	0	3450	2820

% Food Dehydrated	% Available STS Fuel Cell H20 Added to Station	% CO2 Reduced	% Excess H2O Electrolyzed	Total Fluid Logistics (w/o R-J)	Total Fluid Logistics (w R-J)	Food	Prop w/o R-J	Prop w/ R-J	Cryo O2	Cryo N2	Average Power (watts)
25%	50%	80%	100%	20066	18147	4702	11914	9995	0	3450	3491
25%	50%	100%	38%	20066	19229	4702	11914	11078	0	3450	1433
25%	50%	100%	40%	20066	19196	4702	11914	11045	0	3450	1513
25%	50%	100%	60%	20066	18920	4702	11914	10768	0	3450	2184
25%	50%	100%	80%	20066	18643	4702	11914	10492	0	3450	2855
25%	50%	100%	100%	20066	18367	4702	11914	10216	0	3450	3526
50%	50%	0%	0%	23057	21638	3787	11914	10495	3906	3450	0
50%	50%	0%	20%	21995	20336	3787	11914	10256	2843	3450	582
50%	50%	0%	40%	20932	19034	3787	11914	10016	1781	3450	1164
50%	50%	0%	60%	19869	17732	3787	11914	9776	718	3450	1746
50%	50%	0%	80%	19151	16774	3787	11914	9537	0	3450	2327
50%	50%	0%	100%	19151	16534	3787	11914	9297	0	3450	2909
50%	50%	20%	9%	22136	20833	3787	11914	10612	2984	3450	287
50%	50%	20%	20%	21534	20096	3787	11914	10476	2383	3450	616
50%	50%	20%	40%	20471	18794	3787	11914	10236	1320	3450	1198
50%	50%	20%	60%	19409	17491	3787	11914	9997	257	3450	1780
50%	50%	20%	80%	19151	16994	3787	11914	9757	0	3450	2362
50%	50%	20%	100%	19151	16755	3787	11914	9517	0	3450	2943
50%	50%	40%	17%	21214	20028	3787	11914	10728	2063	3450	573
50%	50%	40%	20%	21073	19855	3787	11914	10696	1922	3450	650
50%	50%	40%	40%	20010	18553	3787	11914	10457	859	3450	1232
50%	50%	40%	60%	19151	17454	3787	11914	10217	0	3450	1814
50%	50%	40%	80%	19151	17215	3787	11914	9977	0	3450	2396
50%	50%	40%	100%	19151	16975	3787	11914	9738	0	3450	2978
50%	50%	60%	26%	20292	19223	3787	11914	10845	1141	3450	860
50%	50%	60%	40%	19550	18313	3787	11914	10677	398	3450	1266
50%	50%	60%	60%	19151	17675	3787	11914	10437	0	3450	1848
50%	50%	60%	80%	19151	17435	3787	11914	10198	0	3450	2430
50%	50%	60%	100%	19151	17195	3787	11914	9958	0	3450	3012
50%	50%	80%	35%	19371	18418	3787	11914	10961	220	3450	1146
50%	50%	80%	40%	19151	18135	3787	11914	10897	0	3450	1301
50%	50%	80%	60%	19151	17895	3787	11914	10658	0	3450	1883
50%	50%	80%	80%	19151	17655	3787	11914	10418	0	3450	2464
50%	50%	80%	100%	19151	17416	3787	11914	10178	0	3450	3046
50%	50%	100%	43%	19151	18315	3787	11914	11078	0	3450	1433
50%	50%	100%	60%	19151	18115	3787	11914	10878	0	3450	1917
50%	50%	100%	80%	19151	17876	3787	11914	10639	0	3450	2499
50%	50%	100%	100%	19151	17636	3787	11914	10399	0	3450	3080
75%	50%	0%	0%	22143	20724	2873	11914	10495	3906	3450	0
75%	50%	0%	20%	21243	19621	2873	11914	10292	3006	3450	493
75%	50%	0%	40%	20343	18518	2873	11914	10089	2106	3450	986
75%	50%	0%	60%	19443	17415	2873	11914	9886	1206	3450	1479
75%	50%	0%	80%	18543	16312	2873	11914	9683	306	3450	1971
75%	50%	0%	100%	18237	15803	2873	11914	9480	0	3450	2464
75%	50%	20%	10%	21221	19919	2873	11914	10612	2984	3450	287
75%	50%	20%	20%	20782	19381	2873	11914	10513	2545	3450	527
75%	50%	20%	40%	19882	18278	2873	11914	10310	1645	3450	1020
75%	50%	20%	60%	18982	17175	2873	11914	10107	745	3450	1513
75%	50%	20%	80%	18237	16226	2873	11914	9904	0	3450	2006
75%	50%	20%	100%	18237	16023	2873	11914	9701	0	3450	2498
75%	50%	40%	20%	20300	19114	2873	11914	10728	2063	3450	573
75%	50%	40%	40%	19421	18037	2873	11914	10530	1184	3450	1054
75%	50%	40%	60%	18521	16934	2873	11914	10327	284	3450	1547
75%	50%	40%	80%	18237	16447	2873	11914	10124	0	3450	2040
75%	50%	40%	100%	18237	16244	2873	11914	9921	0	3450	2533
75%	50%	60%	31%	19378	18309	2873	11914	10845	1141	3450	860
75%	50%	60%	40%	18960	17797	2873	11914	10750	723	3450	1088
75%	50%	60%	60%	18237	16870	2873	11914	10547	0	3450	1581
75%	50%	60%	80%	18237	16667	2873	11914	10344	0	3450	2074
75%	50%	60%	100%	18237	16464	2873	11914	10141	0	3450	2567
75%	50%	80%	41%	18456	17503	2873	11914	10961	220	3450	1146

% Food Dehydrated	% Available STS Fuel Cell H20 Added to Station	% CO2 Reduced	% Excess H2O Electrolyzed	Total Fluid Logistics (w/o R-J)	Total Fluid Logistics (w R-J)	Food	Prop w/o R-J	Prop w/ R-J	Cryo O2	Cryo N2	Average Power (watts)
75%	50%	80%	60%	18237	17091	2873	11914	10768	0	3450	1615
75%	50%	80%	80%	18237	16888	2873	11914	10565	0	3450	2108
75%	50%	80%	100%	18237	16685	2873	11914	10362	0	3450	2601
75%	50%	100%	51%	18237	17400	2873	11914	11078	0	3450	1433
75%	50%	100%	60%	18237	17311	2873	11914	10988	0	3450	1650
75%	50%	100%	80%	18237	17108	2873	11914	10785	0	3450	2143
75%	50%	100%	100%	18237	16905	2873	11914	10582	0	3450	2635
100%	50%	0%	0%	21228	19810	1958	11914	10495	3906	3450	0
100%	50%	0%	20%	20491	18906	1958	11914	10329	3169	3450	404
100%	50%	0%	40%	19753	18002	1958	11914	10163	2431	3450	808
100%	50%	0%	60%	19016	17098	1958	11914	9996	1694	3450	1211
100%	50%	0%	80%	18278	16194	1958	11914	9830	956	3450	1615
100%	50%	0%	100%	17541	15291	1958	11914	9664	219	3450	2019
100%	50%	20%	12%	20307	19005	1958	11914	10612	2984	3450	287
100%	50%	20%	20%	20030	18665	1958	11914	10549	2708	3450	438
100%	50%	20%	40%	19293	17762	1958	11914	10383	1970	3450	842
100%	50%	20%	60%	18555	16858	1958	11914	10217	1233	3450	1246
100%	50%	20%	80%	17818	15954	1958	11914	10050	495	3450	1650
100%	50%	20%	100%	17322	15292	1958	11914	9884	0	3450	2053
100%	50%	40%	25%	19385	18199	1958	11914	10728	2063	3450	573
100%	50%	40%	40%	18832	17521	1958	11914	10603	1509	3450	876
100%	50%	40%	60%	18094	16617	1958	11914	10437	772	3450	1280
100%	50%	40%	80%	17357	15714	1958	11914	10271	34	3450	1684
100%	50%	40%	100%	17322	15513	1958	11914	10104	0	3450	2088
100%	50%	60%	37%	18464	17394	1958	11914	10845	1141	3450	860
100%	50%	60%	40%	18371	17281	1958	11914	10824	1049	3450	910
100%	50%	60%	60%	17634	16377	1958	11914	10657	311	3450	1314
100%	50%	60%	80%	17322	15899	1958	11914	10491	0	3450	1718
100%	50%	60%	100%	17322	15733	1958	11914	10325	0	3450	2122
100%	50%	80%	50%	17542	16589	1958	11914	10961	220	3450	1146
100%	50%	80%	60%	17322	16286	1958	11914	10878	0	3450	1348
100%	50%	80%	80%	17322	16120	1958	11914	10711	0	3450	1752
100%	50%	80%	100%	17322	15954	1958	11914	10545	0	3450	2156
100%	50%	100%	62%	17322	16486	1958	11914	11078	0	3450	1433
100%	50%	100%	80%	17322	16340	1958	11914	10932	0	3450	1787
100%	50%	100%	100%	17322	16174	1958	11914	10766	0	3450	2190
0%	100%	0%	0%	24886	23467	5616	11914	10495	3906	3450	0
0%	100%	0%	20%	22965	21113	5616	11914	10062	1985	3450	1052
0%	100%	0%	40%	21044	18759	5616	11914	9629	64	3450	2104
0%	100%	0%	60%	20980	18261	5616	11914	9195	0	3450	3156
0%	100%	0%	80%	20980	17828	5616	11914	8762	0	3450	4208
0%	100%	0%	100%	20980	17395	5616	11914	8329	0	3450	5260
0%	100%	20%	5%	23964	22662	5616	11914	10612	2984	3450	287
0%	100%	20%	20%	22504	20873	5616	11914	10282	1524	3450	1086
0%	100%	20%	40%	20980	18915	5616	11914	9849	0	3450	2138
0%	100%	20%	60%	20980	18482	5616	11914	9416	0	3450	3190
0%	100%	20%	80%	20980	18049	5616	11914	8983	0	3450	4242
0%	100%	20%	100%	20980	17615	5616	11914	8549	0	3450	5294
0%	100%	40%	10%	23043	21857	5616	11914	10728	2063	3450	573
0%	100%	40%	40%	20980	19135	5616	11914	10069	0	3450	2172
0%	100%	40%	60%	20980	18702	5616	11914	9636	0	3450	3224
0%	100%	40%	80%	20980	18269	5616	11914	9203	0	3450	4276
0%	100%	40%	100%	20980	17836	5616	11914	8770	0	3450	5328
0%	100%	60%	14%	22121	21052	5616	11914	10845	1141	3450	860
0%	100%	60%	40%	20980	19356	5616	11914	10290	0	3450	2207
0%	100%	60%	60%	20980	18923	5616	11914	9857	0	3450	3258
0%	100%	60%	80%	20980	18489	5616	11914	9423	0	3450	4310
0%	100%	60%	100%	20980	18056	5616	11914	8990	0	3450	5362
0%	100%	80%	19%	21200	20247	5616	11914	10961	220	3450	1146
0%	100%	80%	60%	20980	19143	5616	11914	10077	0	3450	3293
0%	100%	80%	80%	20980	18710	5616	11914	9644	0	3450	4345

% Food Dehydrated	% Available STS Fuel Cell H20 Added to Station	% CO2 Reduced	% Excess H2O Electrolyzed	Total Fluid Logistics (w/o R-J)	Total Fluid Logistics (w R-J)	Food	Prop w/o R-J	Prop w/ R-J	Cryo O2	Cryo N2	Average Power (watts)
0%	100%	80%	100%	20980	18276	5616	11914	9210	0	3450	5397
0%	100%	100%	24%	20980	20144	5616	11914	11078	0	3450	1433
0%	100%	100%	60%	20980	19363	5616	11914	10297	0	3450	3327
0%	100%	100%	80%	20980	18930	5616	11914	9864	0	3450	4379
0%	100%	100%	100%	20980	18497	5616	11914	9431	0	3450	5431
25%	100%	0%	0%	23972	22553	4702	11914	10495	3906	3450	0
25%	100%	0%	20%	22213	20398	4702	11914	10099	2147	3450	963
25%	100%	0%	40%	20455	18243	4702	11914	9702	389	3450	1926
25%	100%	0%	60%	20066	17457	4702	11914	9305	0	3450	2889
25%	100%	0%	80%	20066	17060	4702	11914	8909	0	3450	3852
25%	100%	0%	100%	20066	16664	4702	11914	8512	0	3450	4814
25%	100%	20%	5%	23050	21748	4702	11914	10612	2984	3450	287
25%	100%	20%	20%	21752	20157	4702	11914	10319	1687	3450	997
25%	100%	20%	40%	20066	18074	4702	11914	9922	0	3450	1960
25%	100%	20%	60%	20066	17677	4702	11914	9526	0	3450	2923
25%	100%	20%	80%	20066	17281	4702	11914	9129	0	3450	3886
25%	100%	20%	100%	20066	16884	4702	11914	8733	0	3450	4849
25%	100%	40%	10%	22128	20943	4702	11914	10728	2063	3450	573
25%	100%	20%	20%	21752	20157	4702	11914	10319	1687	3450	997
25%	100%	40%	40%	20066	18294	4702	11914	10143	0	3450	1994
25%	100%	40%	60%	20066	17898	4702	11914	9746	0	3450	2957
25%	100%	40%	80%	20066	17501	4702	11914	9350	0	3450	3920
25%	100%	40%	100%	20066	17105	4702	11914	8953	0	3450	4883
25%	100%	60%	16%	21207	20137	4702	11914	10845	1141	3450	860
25%	100%	60%	20%	20831	19677	4702	11914	10760	765	3450	1066
25%	100%	60%	40%	20066	18515	4702	11914	10363	0	3450	2029
25%	100%	60%	60%	20066	18118	4702	11914	9967	0	3450	2991
25%	100%	60%	80%	20066	17722	4702	11914	9570	0	3450	3954
25%	100%	60%	100%	20066	17325	4702	11914	9173	0	3450	4917
25%	100%	80%	21%	20285	19332	4702	11914	10961	220	3450	1146
25%	100%	80%	40%	20066	18735	4702	11914	10584	0	3450	2063
25%	100%	80%	60%	20066	18339	4702	11914	10187	0	3450	3026
25%	100%	80%	80%	20066	17942	4702	11914	9790	0	3450	3989
25%	100%	80%	100%	20066	17545	4702	11914	9394	0	3450	4951
25%	100%	100%	26%	20066	19229	4702	11914	11078	0	3450	1433
25%	100%	100%	40%	20066	18956	4702	11914	10804	0	3450	2097
25%	100%	100%	60%	20066	18559	4702	11914	10407	0	3450	3060
25%	100%	100%	80%	20066	18162	4702	11914	10011	0	3450	4023
25%	100%	100%	100%	20066	17766	4702	11914	9614	0	3450	4986
50%	100%	0%	0%	23057	21638	3787	11914	10495	3906	3450	0
50%	100%	0%	20%	21461	19683	3787	11914	10135	2310	3450	874
50%	100%	0%	40%	19865	17727	3787	11914	9775	714	3450	1748
50%	100%	0%	60%	19151	16653	3787	11914	9415	0	3450	2622
50%	100%	0%	80%	19151	16293	3787	11914	9055	0	3450	3496
50%	100%	0%	100%	19151	15933	3787	11914	8696	0	3450	4369
50%	100%	20%	6%	22136	20833	3787	11914	10612	2984	3450	287
50%	100%	20%	20%	21000	19442	3787	11914	10356	1849	3450	908
50%	100%	20%	40%	19405	17486	3787	11914	9996	253	3450	1782
50%	100%	20%	60%	19151	16873	3787	11914	9636	0	3450	2656
50%	100%	20%	80%	19151	16513	3787	11914	9276	0	3450	3530
50%	100%	20%	100%	19151	16153	3787	11914	8916	0	3450	4404
50%	100%	40%	12%	21214	20028	3787	11914	10728	2063	3450	573
50%	100%	20%	20%	21000	19442	3787	11914	10356	1849	3450	908
50%	100%	40%	40%	19151	17453	3787	11914	10216	0	3450	1816
50%	100%	40%	60%	19151	17093	3787	11914	9856	0	3450	2690
50%	100%	40%	80%	19151	16733	3787	11914	9496	0	3450	3564
50%	100%	40%	100%	19151	16373	3787	11914	9136	0	3450	4438
50%	100%	60%	17%	20292	19223	3787	11914	10845	1141	3450	860
50%	100%	60%	20%	20079	18961	3787	11914	10796	928	3450	977
50%	100%	60%	40%	19151	17674	3787	11914	10437	0	3450	1850
50%	100%	60%	60%	19151	17314	3787	11914	10077	0	3450	2724

% Food Dehydrated	% Available STS Fuel Cell H20 Added to Station	% CO2 Reduced	% Excess H2O Electrolyzed	Total Fluid Logistics (w/o R-J)	Total Fluid Logistics (w R-J)	Food	Prop w/o R-J	Prop w/ R-J	Cryo O2	Cryo N2	Average Power (watts)
50%	100%	60%	80%	19151	16954	3787	11914	9717	0	3450	3598
50%	100%	60%	100%	19151	16594	3787	11914	9357	0	3450	4472
50%	100%	80%	23%	19371	18418	3787	11914	10961	220	3450	1146
50%	100%	80%	40%	19151	17894	3787	11914	10657	0	3450	1885
50%	100%	80%	60%	19151	17534	3787	11914	10297	0	3450	2759
50%	100%	80%	80%	19151	17174	3787	11914	9937	0	3450	3633
50%	100%	80%	100%	19151	16814	3787	11914	9577	0	3450	4506
50%	100%	100%	29%	19151	18315	3787	11914	11078	0	3450	1433
50%	100%	100%	40%	19151	18114	3787	11914	10877	0	3450	1919
50%	100%	100%	60%	19151	17755	3787	11914	10517	0	3450	2793
50%	100%	100%	80%	19151	17395	3787	11914	10157	0	3450	3667
50%	100%	100%	100%	19151	17035	3787	11914	9797	0	3450	4541
75%	100%	0%	0%	22143	20724	2873	11914	10495	3906	3450	0
75%	100%	0%	20%	20709	18967	2873	11914	10172	2473	3450	785
75%	100%	0%	40%	19276	17211	2873	11914	9849	1039	3450	1570
75%	100%	0%	60%	18237	15848	2873	11914	9525	0	3450	2355
75%	100%	0%	80%	18237	15525	2873	11914	9202	0	3450	3139
75%	100%	0%	100%	18237	15202	2873	11914	8879	0	3450	3924
75%	100%	20%	6%	21221	19919	2873	11914	10612	2984	3450	287
75%	100%	20%	20%	20249	18727	2873	11914	10392	2012	3450	819
75%	100%	20%	40%	18815	16970	2873	11914	10069	578	3450	1604
75%	100%	20%	60%	18237	16069	2873	11914	9746	0	3450	2389
75%	100%	20%	80%	18237	15745	2873	11914	9423	0	3450	3174
75%	100%	20%	100%	18237	15422	2873	11914	9099	0	3450	3959
75%	100%	40%	13%	20300	19114	2873	11914	10728	2063	3450	573
75%	100%	40%	20%	19788	18487	2873	11914	10613	1551	3450	853
75%	100%	40%	40%	18354	16730	2873	11914	10289	118	3450	1638
75%	100%	40%	60%	18237	16289	2873	11914	9966	0	3450	2423
75%	100%	40%	80%	18237	15966	2873	11914	9643	0	3450	3208
75%	100%	40%	100%	18237	15642	2873	11914	9320	0	3450	3993
75%	100%	60%	40%	18237	16833	2873	11914	10510	0	3450	1672
75%	100%	60%	60%	18237	16509	2873	11914	10187	0	3450	2457
75%	100%	60%	100%	18237	15863	2873	11914	9540	0	3450	4027
75%	100%	80%	26%	18456	17503	2873	11914	10961	220	3450	1146
75%	100%	80%	40%	18237	17053	2873	11914	10730	0	3450	1707
75%	100%	80%	60%	18237	16730	2873	11914	10407	0	3450	2492
75%	100%	80%	80%	18237	16406	2873	11914	10084	0	3450	3276
75%	100%	80%	100%	18237	16083	2873	11914	9760	0	3450	4061
75%	100%	100%	32%	18237	17400	2873	11914	11078	0	3450	1433
75%	100%	100%	40%	18237	17273	2873	11914	10951	0	3450	1741
75%	100%	100%	60%	18237	16950	2873	11914	10627	0	3450	2526
75%	100%	100%	80%	18237	16627	2873	11914	10304	0	3450	3311
75%	100%	100%	100%	18237	16304	2873	11914	9981	0	3450	4096
100%	100%	0%	0%	21228	19810	1958	11914	10495	3906	3450	0
100%	100%	0%	20%	19958	18252	1958	11914	10209	2635	3450	696
100%	100%	0%	40%	18687	16695	1958	11914	9922	1364	3450	1392
100%	100%	0%	60%	17416	15137	1958	11914	9635	94	3450	2088
100%	100%	0%	80%	17322	14757	1958	11914	9349	0	3450	2783
100%	100%	0%	100%	17322	14471	1958	11914	9062	0	3450	3479
100%	100%	20%	7%	20307	19005	1958	11914	10612	2984	3450	287
100%	100%	20%	20%	19497	18012	1958	11914	10429	2174	3450	730
100%	100%	20%	40%	18226	16454	1958	11914	10142	904	3450	1426
100%	100%	20%	60%	17322	15264	1958	11914	9856	0	3450	2122
100%	100%	20%	80%	17322	14978	1958	11914	9569	0	3450	2818
100%	100%	20%	100%	17322	14691	1958	11914	9283	0	3450	3514
100%	100%	40%	15%	19385	18199	1958	11914	10728	2063	3450	573
100%	100%	40%	20%	19036	17771	1958	11914	10649	1714	3450	764
100%	100%	40%	40%	17765	16214	1958	11914	10363	443	3450	1460
100%	100%	40%	60%	17322	15485	1958	11914	10076	0	3450	2156
100%	100%	40%	80%	17322	15198	1958	11914	9790	0	3450	2852
100%	100%	40%	100%	17322	14911	1958	11914	9503	0	3450	3548

% Food Dehydrated	% Available STS Fuel Cell H20 Added to Station	% CO2 Reduced	% Excess H2O Electrolyzed	Total Fluid Logistics (w/o R-J)	Total Fluid Logistics (w R-J)	Food	Prop w/o R-J	Prop w/ R-J	Cryo O2	Cryo N2	Average Power (watts)
100%	100%	60%	22%	18464	17394	1958	11914	10845	1141	3450	860
100%	100%	60%	40%	17322	15992	1958	11914	10583	0	3450	1494
100%	100%	60%	60%	17322	15705	1958	11914	10297	0	3450	2190
100%	100%	60%	80%	17322	15418	1958	11914	10010	0	3450	2886
100%	100%	60%	100%	17322	15132	1958	11914	9723	0	3450	3582
100%	100%	80%	29%	17542	16589	1958	11914	10961	220	3450	1146
100%	100%	80%	40%	17322	16212	1958	11914	10804	0	3450	1529
100%	100%	80%	60%	17322	15925	1958	11914	10517	0	3450	2225
100%	100%	80%	80%	17322	15639	1958	11914	10230	0	3450	2920
100%	100%	80%	100%	17322	15352	1958	11914	9944	0	3450	3616
100%	100%	100%	36%	17322	16486	1958	11914	11078	0	3450	1433
100%	100%	100%	40%	17322	16432	1958	11914	11024	0	3450	1563
100%	100%	100%	60%	17322	16146	1958	11914	10737	0	3450	2259
100%	100%	100%	80%	17322	15859	1958	11914	10451	0	3450	2955
100%	100%	100%	100%	17322	15572	1958	11914	10164	0	3450	3651

From the calculated data, the maximum reduction in fluid logistics can be achieved with the addition of an electrolyzer operating at full efficiency, a resistojet utilizing the available waste gas, transfer of all available STS fuel cell water to station, and full dehydration of the crew's food. This would amount to an annual savings of 10415 lbms/year over the baseline configuation. The only remaining consideration for choosing a logistics reduction option is that of power requirements. Figure 26 illustrates the power cost and logistics savings for each of the options considered.

Total Integrated Fluid Logistics as a Function of Available Power

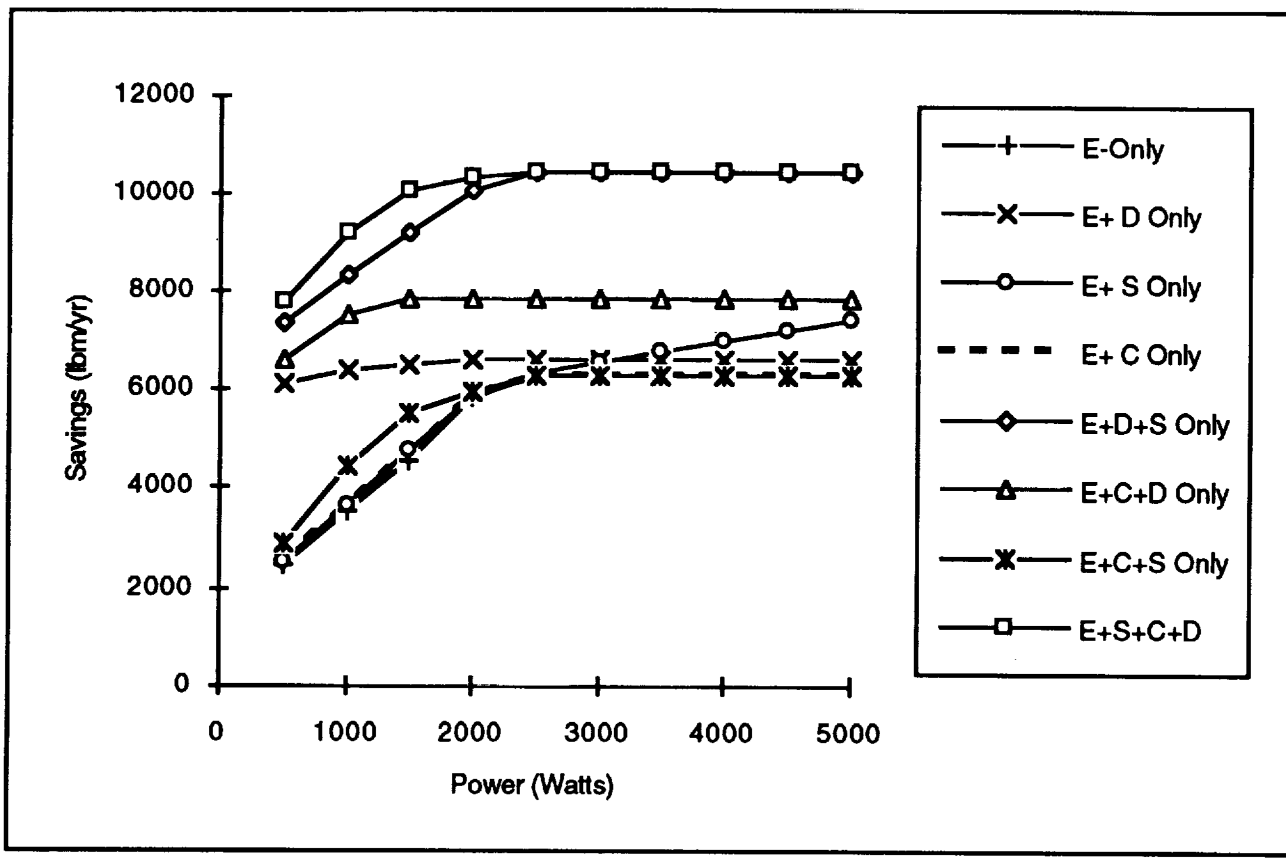

Figure 26

The options are categorized using "E" for electrolysis available, "D" for food dehydration, "S" for STS fuel cell water available, and "C" for carbon dioxide reduction available. Values for savings were generated at 500 watt power increments over the entire range of operational efficiencies available for each configuration. From the figure it can be seen that in all cases the most savings can be achieved using the SFE, STS fuel cell water, food dehydration, and the Sabatier. However for power usage above 2.5 kW, no additional savings are achieved using the Sabatier. Even below 2.5 kW, the added savings of using a Sabatier are only marginal. Without STS fuel cell water available, the use of both a Sabatier and the SFE provides the greatest savings. Without the Sabatier, this savings drops by 100 - 700 lbm/yr over the entire power range. The remaining options provide nearly identical savings below 3 kW. Above 3 kW the use of the SFE with STS fuel cell water does provide a slight benefit.

Since Options 4-6, those with a resistojet, provide much greater savings than Options 1-3 without a resistojet, Options 1-3 are eliminated from further consideration. Option 4 is eliminated on the basis of this configuation's inability to eliminate oxygen requirements in addition to reducing propellant resupply. While Option 6 can provide equal or greater savings over Option 5 over the entire power range, this savings would be at most marginal. The added savings would be outweighed by the development, scaring, and integration of the Sabatier on station. Therefore, Option 5, which provides for the elimination of oxygen resupply through the electrolysis of excess water and a reduction in propellant resupply through the use of a resistojet and hydrogen and carbon dioxide waste gases is recommened.

Evolution Impacts

The last major consideration is that of the impact of Space Station evolution. The data in Table 4 illustrates the planned assembly flights, milestones and elements for station growth between PMC and the Eight Crew Capability (ECC) phase. It also shows the corresponding increase in spacecraft mass and the change in ballistic number.

Table 6

Space Station Freedom Build-up				
Assembly Flight	Milestone	Elements	Spacecraft Mass (lbm)	Spacecraft Ballistic No.
MB-17	PMC	ACRV	590,315	11.45
MB-18		Centrifuge	612,310	11.71
MB-19		4th PV Array	638,614	10.76
MB-20		Resource Node 3	664,348	11.39
MB-21		Resource Node 4	690,083	12.02
MB-22	SCC-Option	U.S. Hab B	729,468	12.98
MB-23		U.S. Lab B	766,568	13.88
MB-24	ECC	ACRV, Cupola 2	787,648	14.39

In order to quantify the requirements during this evolution, the rate of build-up must be known. Table 7 lists three possible manifest scenarios.

Table 7

Space Station Freedom Manifest Options			
Date	Slow Build-up Rate	Medium Build-up Rate	Fast Build-up Rate
	1 flight /2 yr	2 flight / 3 yr	1 flight/yr
5/29/00	PMC	PMC	PMC
8/10/00			
10/22/00			
1/3/01			
3/17/01			
5/29/01			MB-18
8/10/01			
10/22/01		MB-18	
1/3/02			
3/17/02			
5/29/02	MB-18		MB-19
8/10/02			
10/22/02			
1/3/03			
3/17/03			
5/29/03		MB-19	MB-20
8/10/03			
10/22/03			
1/3/04			
3/16/04			
5/28/04	MB-19		MB-21
8/9/04			
10/21/04		MB-20	
1/2/05			
3/16/05			
5/28/05			MB-22
8/9/05			
10/21/05			
1/2/06			
3/16/06			
5/28/06	MB-20	MB-21	MB-23
8/9/06			
10/21/06			
1/2/07			
3/16/07			
5/28/07			MB-24
8/9/07			
10/21/07			
1/2/08		MB-22	
3/15/08			
5/27/08	MB-21		
8/8/08			
10/20/08			
1/1/09			
3/15/09			
5/27/09		MB-23	
8/8/09			
10/20/09			
1/1/10			

Figures 27-30 illustrate the increase in annual resupply requirements during the evolution build-up sequence for food, oxygen, nitrogen, and propellant. Figure 31 shows the amount of excess water available during the same period.

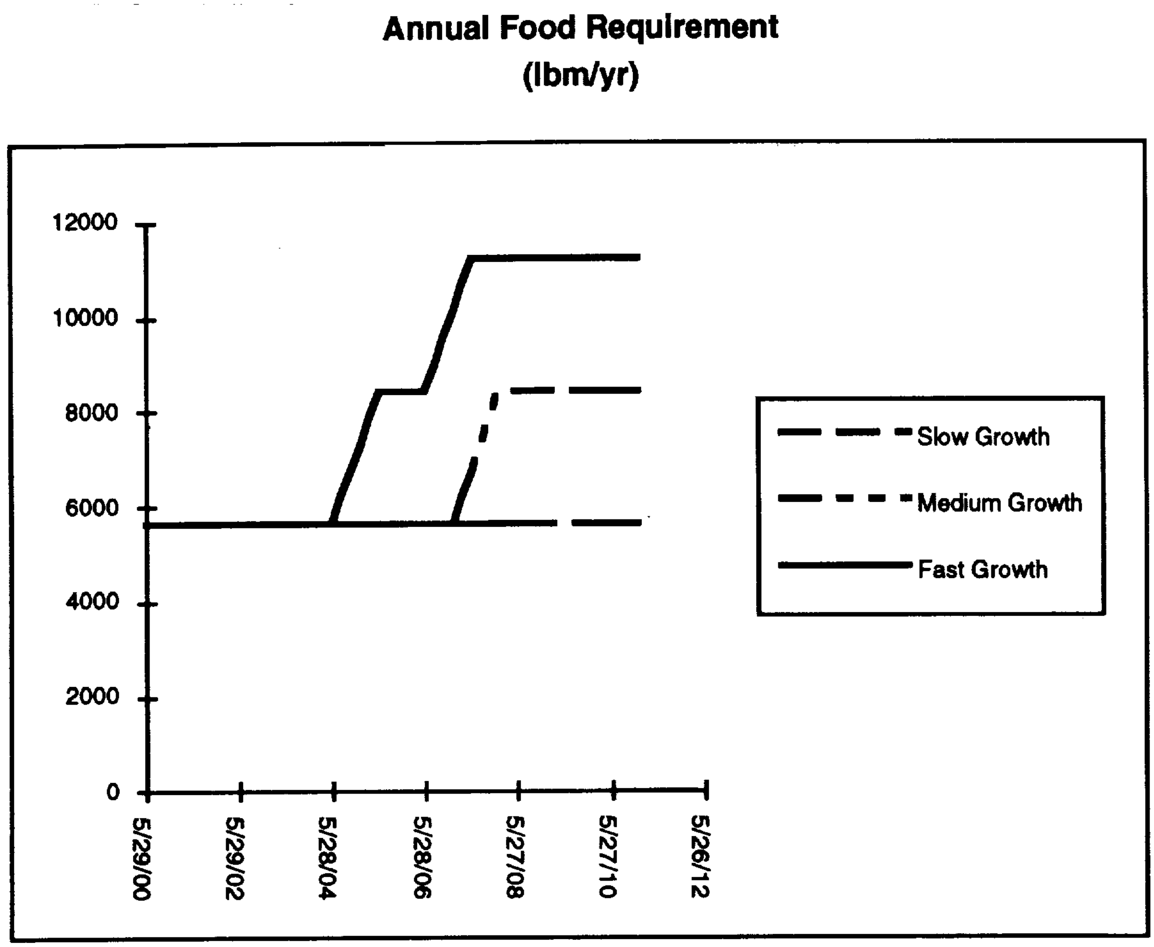

Figure 27

Annual Oxygen Requirement
(lbm/yr)

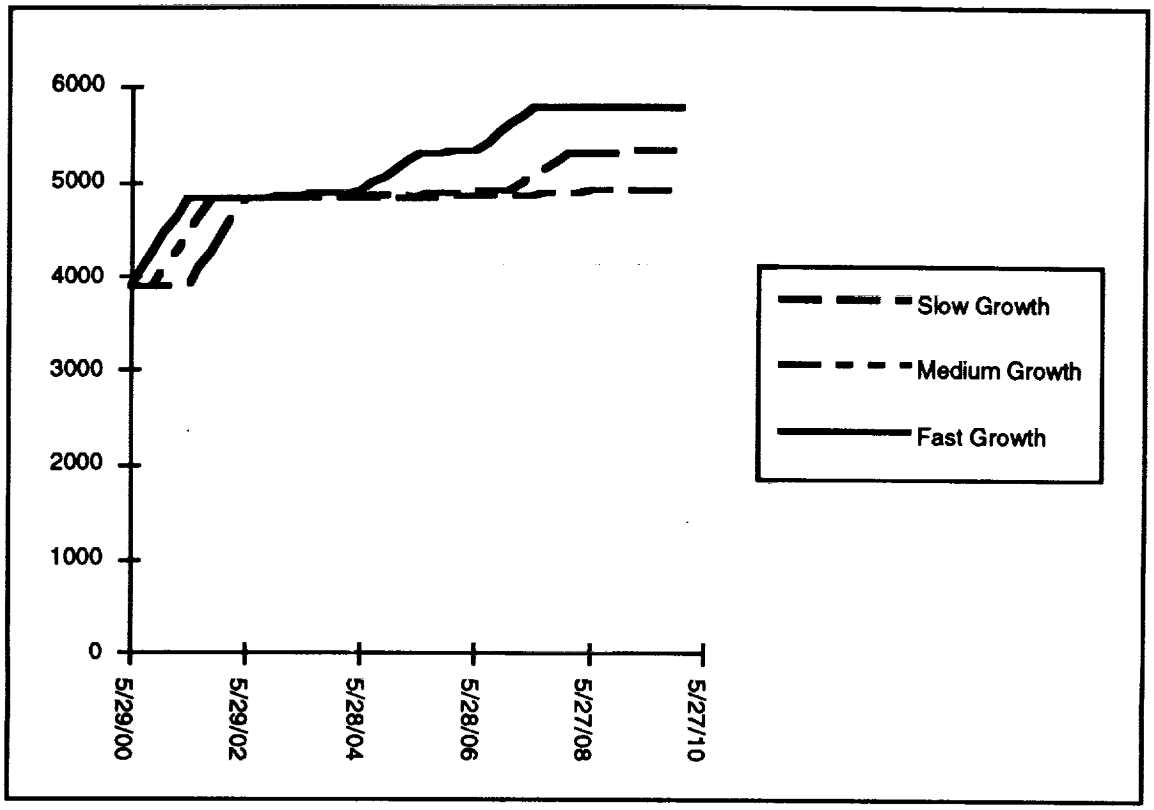

Figure 28

Annual Nitrogen Requirement
(lbm/yr)

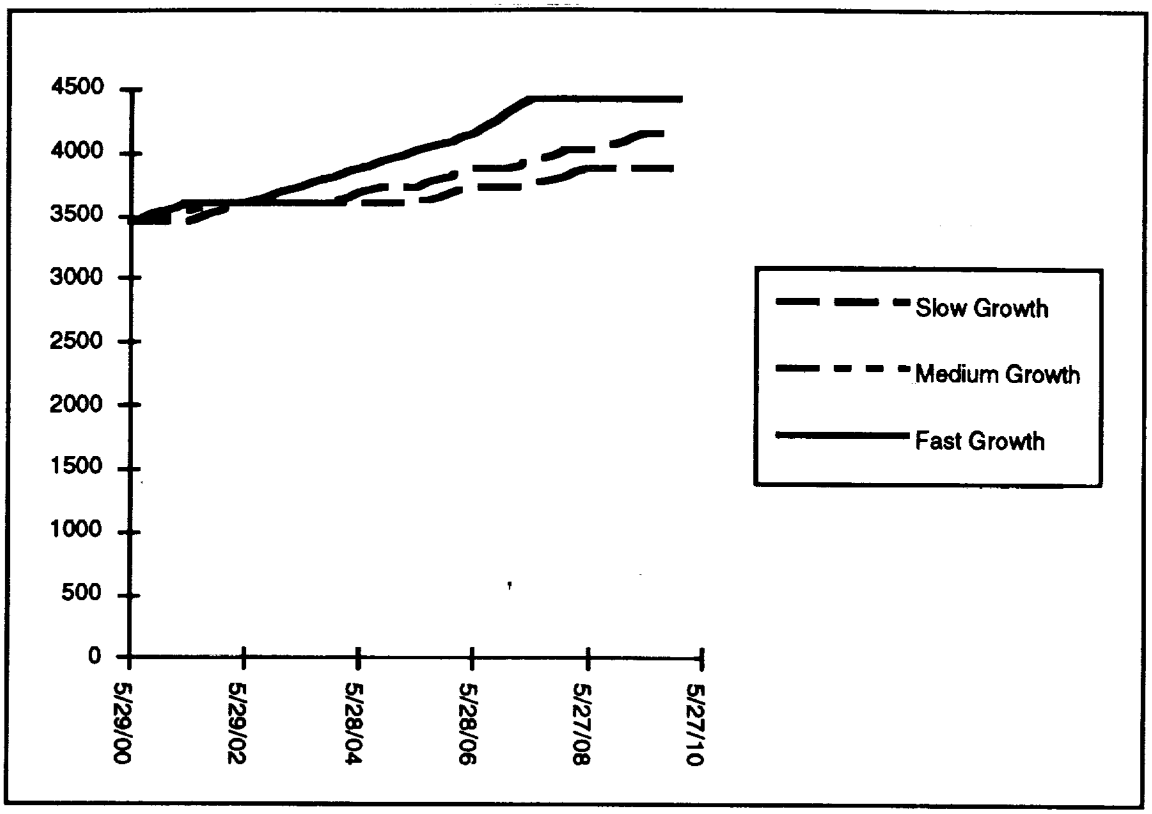

Figure 29

Annual Propellant Requirements
(lbm/yr)

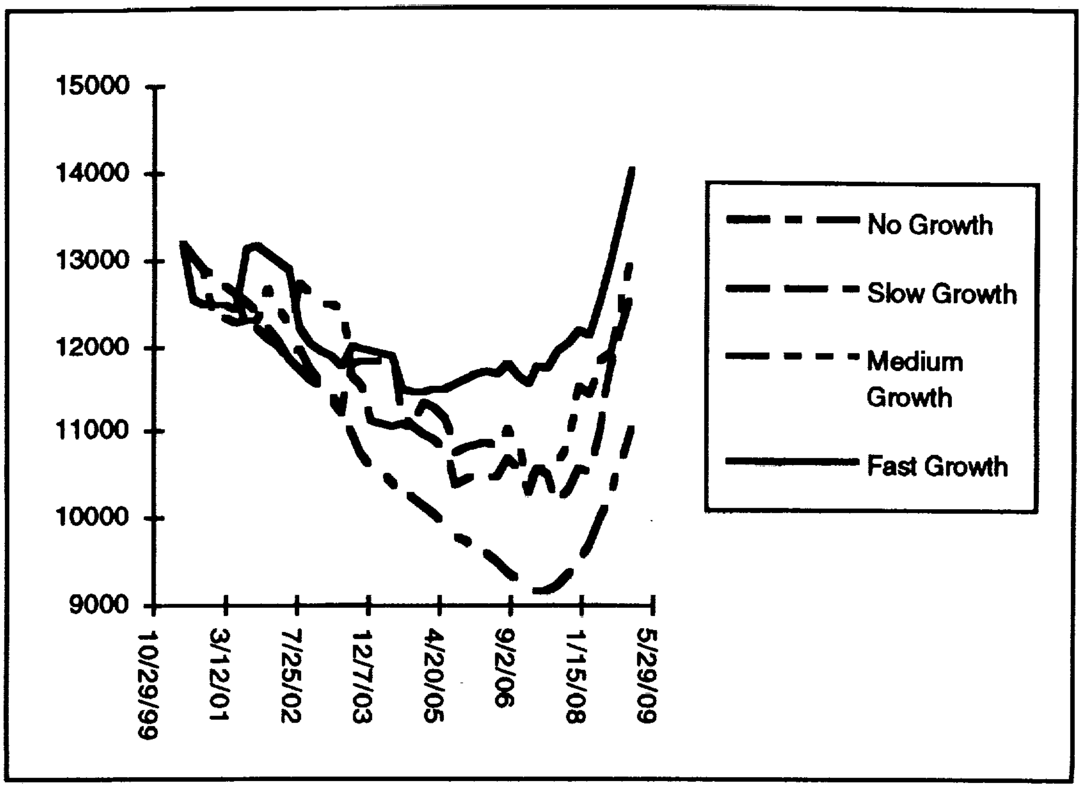

Figure 30

Annual Excess Water
(lbm/yr)

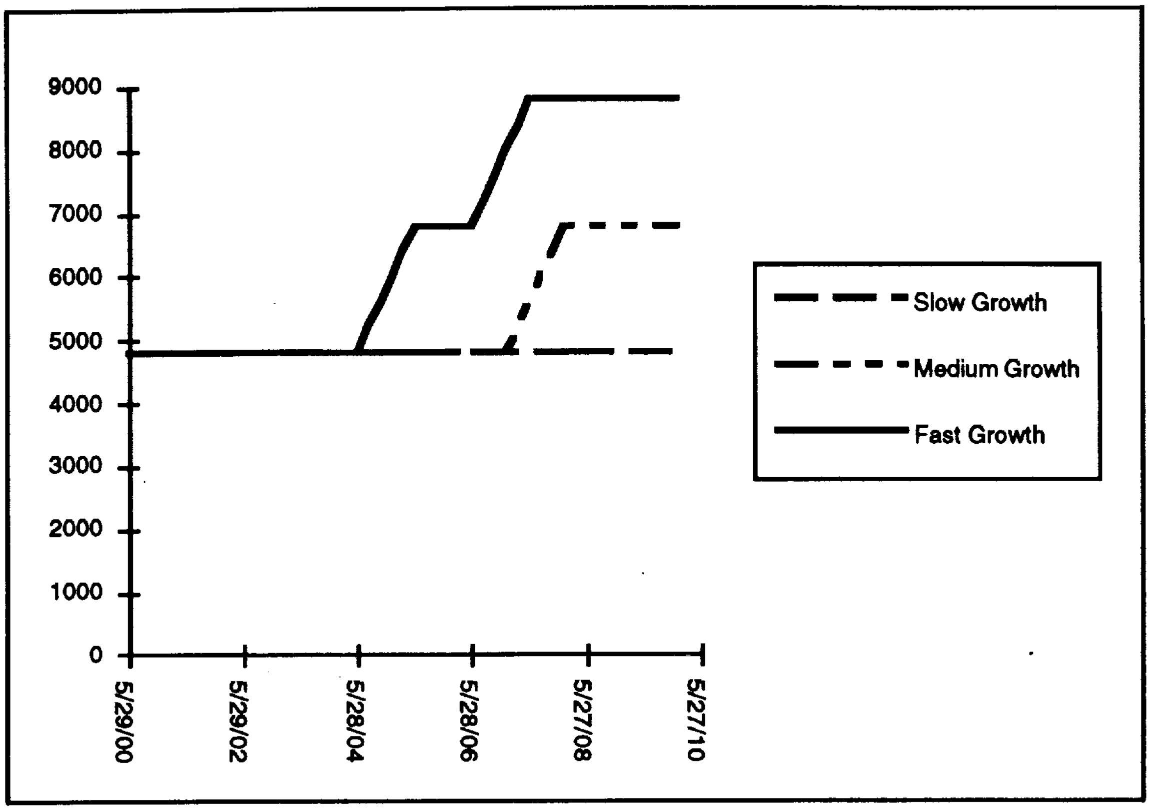

Figure 31

Figures 32-35 illustrate the average annual requirements for fluid logistics and the available excess water based on the build-up rate from PMC to ECC.

Average Annual Food Requirement Based on Build-up Rate

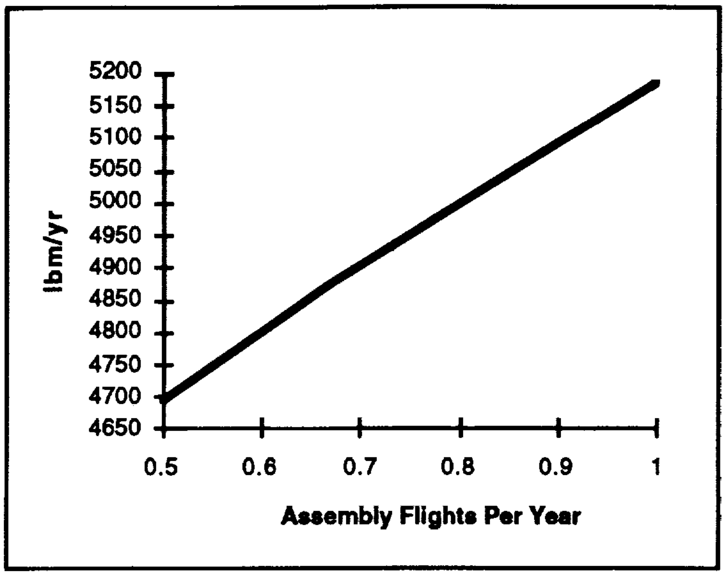

Figure 32

Average Annual Oxygen Requirement Based On Build-Up Rate

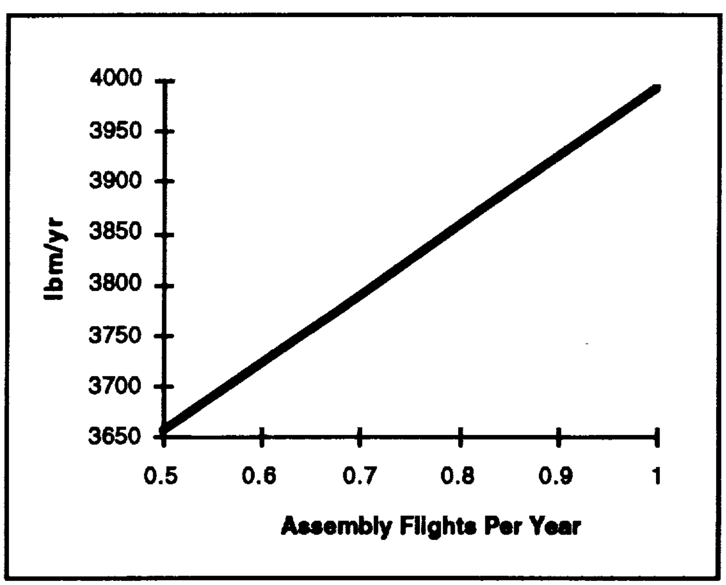

Figure 33

Average Annual Nitrogen Requirement Based On Build-Up Rate

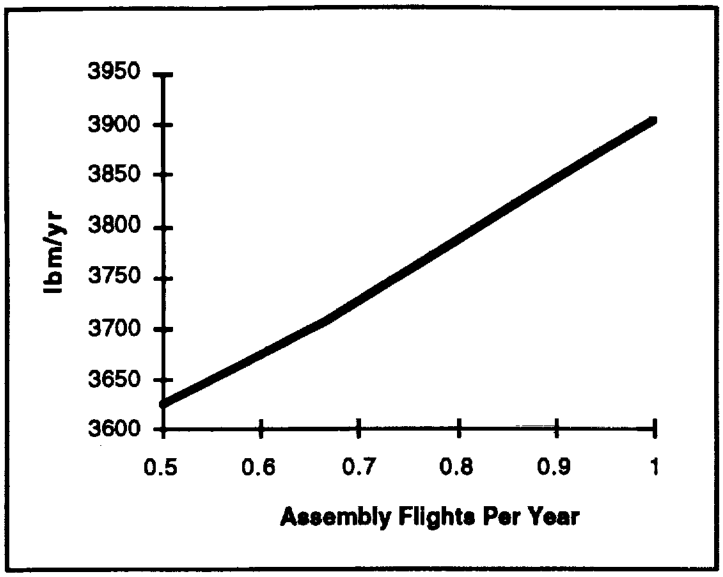

Figure 34

Average Annual Propellant Requirements Based On Build-Up Rate

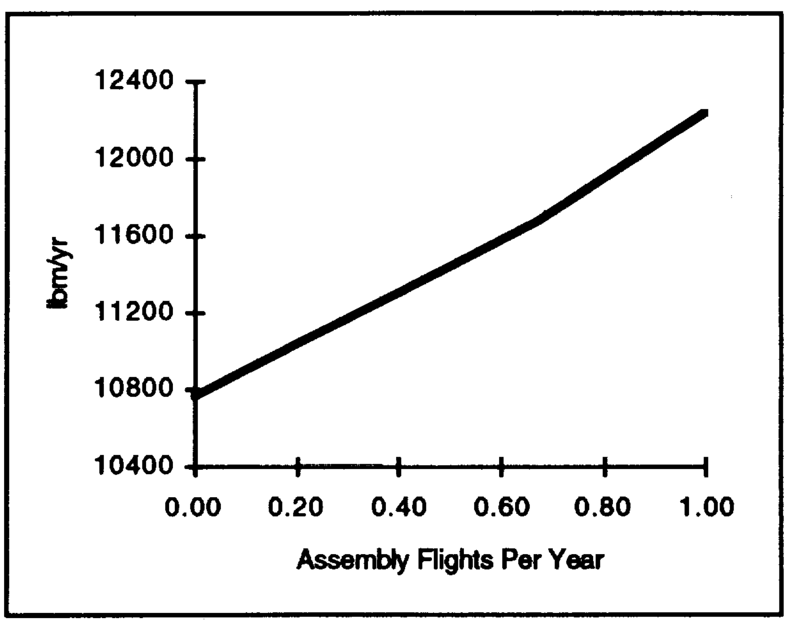

Figure 35

Average Annual Excess Water Available Based On Build-up Rate

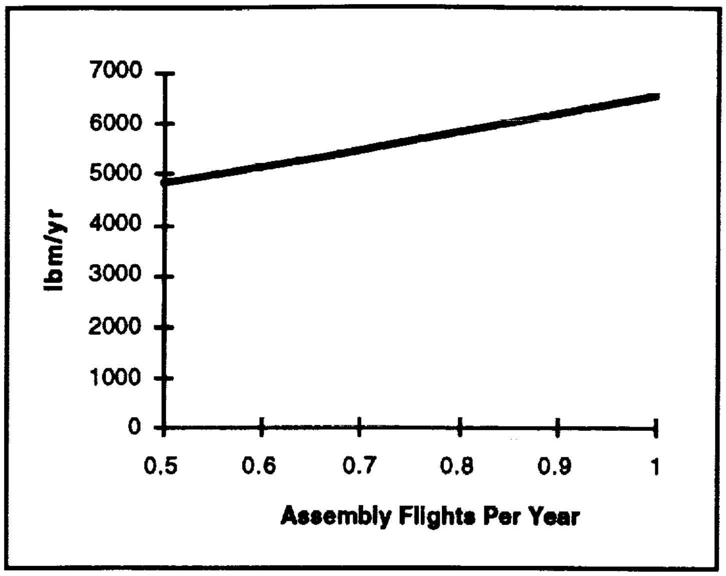

Figure 36

In all cases a nearly linear relationship exists for each of the resupply fluids. This simplifies the determination of the impact of variable build-up rates on total fluid logistics. Figure 37 shows the effect of utilizing the Option 5 configuration during the evolution of the Space Station Freedom. Net savings can be as high as 50% or 15,000 lbm per year of fluid logisitics if all excess water is electrolyzed including available STS fuel cell water and the crew's food is dehydrated. Figure 38 show the savings as a function of the build-up rate.

Comparison of Total Annual Fluid Resupply Requirements Based On Baseline (Option 1) and Option 5

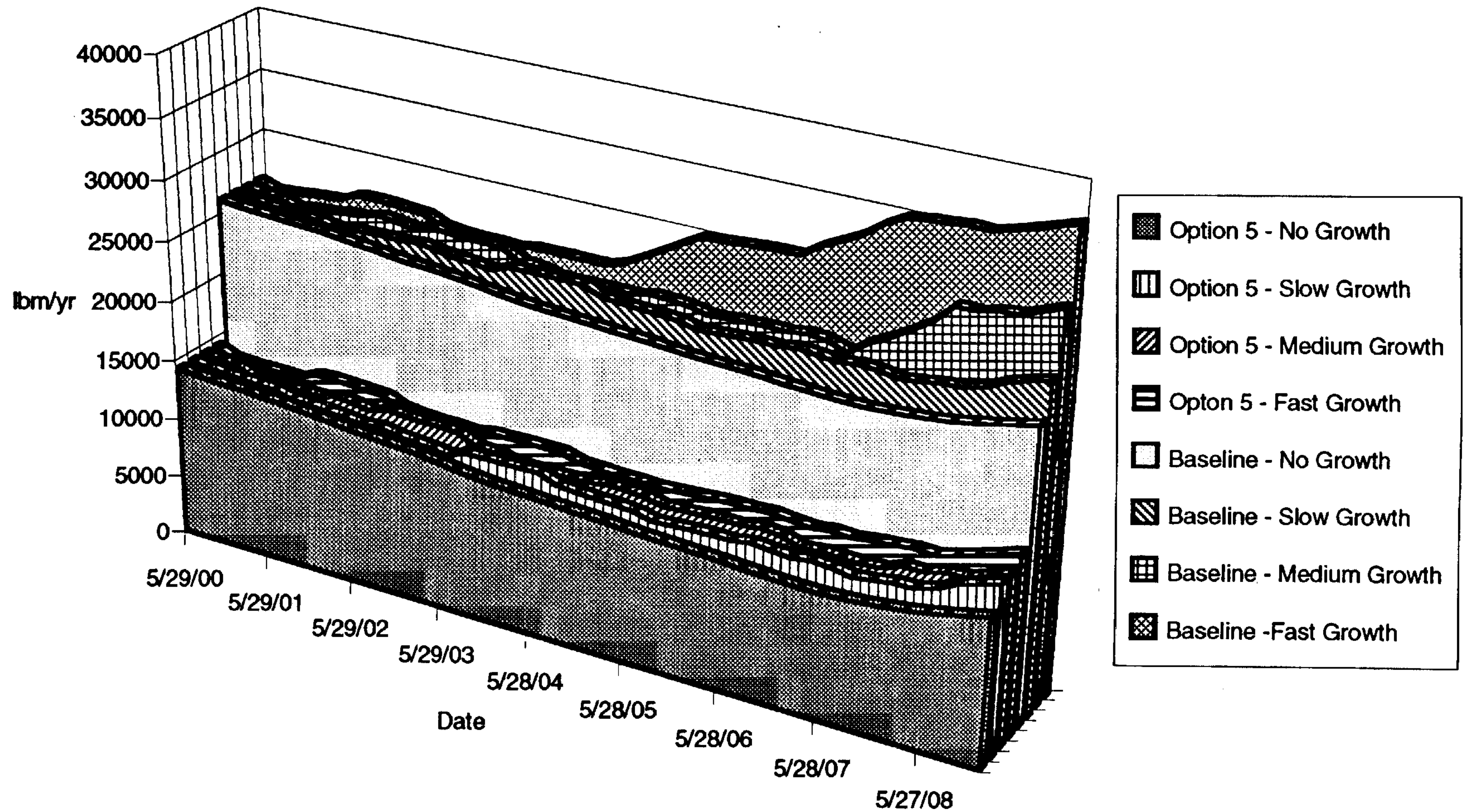

Figure 37

Comparison of Average Annual Fluid Resupply Requirements Based On Assembly Flight Rate for Baseline (Option 1) and Option 5

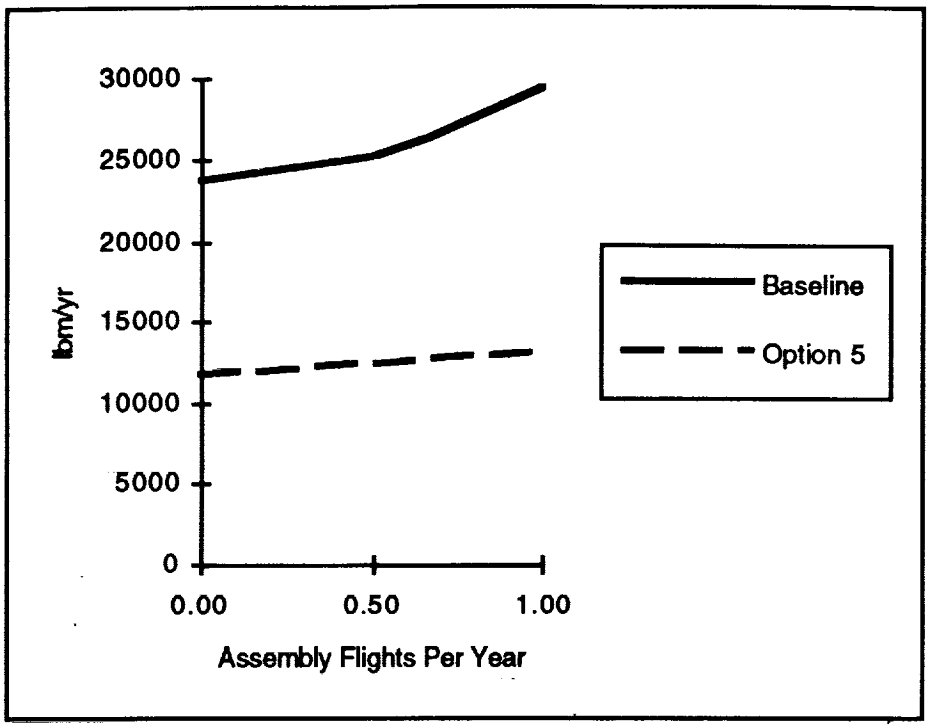

Figure 38

Conclusions

From the analysis of the various options utilizing a resistojet, the Static Feed Electrolyzer, and the Sabatier the greatest savings in total integrated fluid logistics can be achieved when only the Static Feed Electrolyzer and the resistojet are used. While in some instances of low power availability the addition of a Sabatier could provide an added benefit, this increased savings is marginal. Therefore the cost of development, scaring, and integration of the Sabatier would be prohibitive based on the possible benefit. This paper also described the impact of evolution build-up rate on the expected savings of using the SFE and resistojet during the PMC to ECC time period.

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13. ABSTRACT *(Maximum 200 words)*

The use of an integrated environmental control and life support system (ECLSS) and secondary propulsion system (SRS) on the Space Station Freedom (SSF) has many potential advantages. Through the metabolism of food, the crew on-board the station will produce carbon dioxide as a waste gas and an excess of water in the form of urine and condensate. The processing of these waste fluids by the ECLSS could produce quantities of oxygen that would eliminate the need for cryogenic oxygen resupply and hydrogen, carbon dioxide, and/or methane that could be used with the addition of a resistojet system to provide a constant low thrust for station. This additional thrust would represent significant savings in required hydrazine resupply.

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