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PREPARED UNDER
CONTRACT NO. NAS3-23353
IR&D
OTHER

PREPARED ON
FILED UNDER

DOCUMENT NO. D483-10060-1
MODEL

TITLE Space Station Propulsion-ECLSS Interaction Study

ORIGINAL RELEASE DATE 2/14/86

ISSUE NO. TO DATE

ADDITIONAL LIMITATIONS IMPOSED ON THIS DOCUMENT
WILL BE FOUND ON A SEPARATE LIMITATIONS SHEET.

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PREFACE

The Space Station Propulsion-ECLSS Interaction Study, NASA Contract NAS3-23353, Modification 4, was managed by the NASA Lewis Research Center (LERC) and was performed by the Flight Technology organization under the Advanced Development Program of the Boeing Aerospace Company in Kent, Washington. The LERC contract monitor was Richard M. Donovan.

This final report is an extension of the NASA Contract NAS3-23353, Boeing Document D180-28264-1.

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LIST OF ACRONYMS AND OTHER ABBREVIATIONS

ACT	Augmented Catalytic Thruster
CCA	Coolant Control Assembly
CEC	Chemical Equilibrium Computer
CH_4	Methane
CO_2	Carbon Dioxide
CS_2CO_3	Cesium Carbonate
ECLS	Environmental Control and Life Support
ECLSS	Environmental Control and Life Support System
EDC	Electrochemical Desorbed Concentrator
EVA	External Vehicular Activity
IOC	Initial Operation Capability
LiOH	Lithium Hydroxide
N_2H_4	Hydrazine
$0_2/H_2$	Oxygen/Hydrogen
PCA	Pressure Control Assembly
SAWD	Solid Amine-Water Desorbed
SFWES	Static Feed Water Electrolysis System

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1.0 INTRODUCTION

Past studies of Space Station propulsion and environmental control/life support (ECLS) systems have focused on examining proven concepts for each system primarily in terms of development risk for the IOC station and up/down logistics. From these studies it can be generally concluded that system development risk increases as logistic requirements decrease. In the ECLS system this increased risk results from the advanced technologies needed for increased closure, whereas in propulsion it is associated with going from a storable N_2H_4 system to a cryogenic or water electrolysis H_2/O_2 system.

For the most part, synergistic operation of the propulsion and ECLS system has not been considered and, therefore, benefits from synergism have not been illuminated. Specifically, 1) what level of ECLS closure is optimum when considering propulsion synergy, 2) what concept modifications or changes to the N_2H_4 reference design are needed to accommodate synergistic operation and, 3) what are the logistic benefits of synergistic operation which have not been quantified. To scope the problem, Boeing under the direction of the Lewis Research Center initiated the Space Station Propulsion - ECLSS Interaction Study, NAS 3-23353. The results of this work are reported herein.

1.1 Study Objective

The primary objective of this study is to determine the benefits that the ECLSS system could experience by using its effluents to augment or even supplement the propulsion system. The potential benefits which both the ECLS and propulsion systems could experience include: reductions in logistic weight and volume; fixed weight and volume; power requirements; and overall system cost. Four different ECLS systems with various levels of closure are analyzed for their use in conjunction with cold or warm gas thrusters. Missions and available technologies used in this study are applicable for the time frame 1985-2003.

1.2 Scope of Work

The work performed in this study consists of four primary tasks. These tasks, which are shown in figure 1-1, define ECLS requirements for four different systems, propulsion requirements for orbit maintenance, collection and storage requirements, and compare each of the ECLS-propulsion system combinations against a baseline system for the time frame 1992-2003. For those ECLS systems that do not ordinarily supply enough impulse for propulsion, modifications are made to generate additional impulse. All

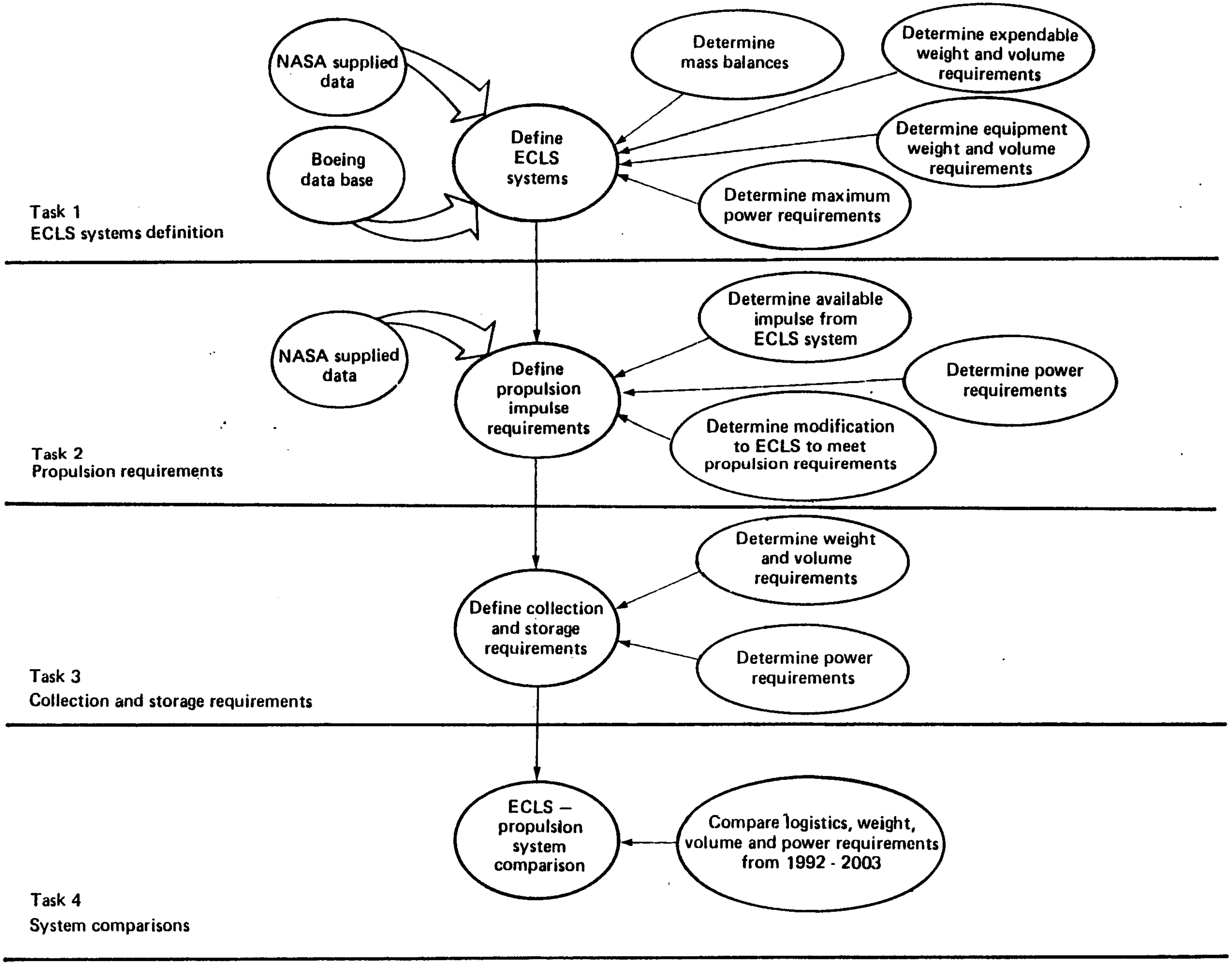

Figure 1-1. Task Flow Diagram

1.2 Continued

system combinations will be compared against an ECLS system using OPEN CO_2 loop with Electrochemical Depolarized CO_2 Collection (EDC) in conjunction with a modular hydrazine propulsion system as the baseline case.

1.3 Mission Profile

Analyses assume, 1) a 28½° - 270-nm orbit Space Station with an eight-man crew and with a docked orbiter for 14 of every 90-day resupply period, 2) NASA two-sigma atmosphere for sizing the propulsion system (ref. 1), 3) NASA nominal atmosphere for determining resupply requirements, 4) results from Space Station Propulsion Requirements Study, Tasks 1, 2, & 3, NASA 3-23353 and, 5) that non-propulsive venting of ECLS effluents is not acceptable but propulsive thrusting using ECLS effluents is acceptable.

2.0 ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS DEFINITION

The major functions of the Environmental Control and Life Support (ECLS) system include atmospheric pressure and composition control, temperature and humidity control, atmospheric revitalization, water management, waste management, and EVA support. In accomplishing the processes associated with these functions, effluents are produced which must be stored and periodically returned to earth or vented propulsively. The type and quantity of effluents depends primarily upon the methods used to accomplish atmosphere revitalization.

2.1 Atmosphere Revitalization Subsystems

The primary functions of the Atmosphere Revitalization system include oxygen generation by water electrolysis, regenerable carbon dioxide removal and concentration, and carbon dioxide reduction. The first two of these functions play a vital part in maintaining the breatheable atmosphere within the limits prescribed in Table 2-1, whereas the third function (CO_2 reduction) has a major influence on ECLSS fixed weight and volume, and logistic requirements. All three functions impact the amount and chemical makeup of the ECLSS effluents. The following three sections provide a synopsis of how each subsystem functions.

2.1.1 Oxygen Generation

There are a variety of methods that may be used to generate oxygen from water. These include: 1) water electrolysis, 2) sulfur-iodine thermochemistry, 3) photosynthesis and, 4) thermal decomposition through solar radiation. Based upon constraints such as power, mass, volume, cost, and potential production rates water electrolysis is the preferred method. A functional schematic of a static feed water electrolysis system (SFWES) is shown in figure 2-1. This unit generates oxygen for atmospheric makeup and hydrogen, as a by-product, from water supplied from the water management subsystem of the ECLS system.

The SFWES consists of three main components; the electrochemical module, a coolant control assembly (CCA), and a pressure control assembly (PCA). The module consists of a series of electrochemical cells connected electrically in series with fluid inlet and outlet passages in parallel. The CCA and PCA provide the necessary supporting functions to regulate the temperature and operating pressures of the system. In addition, the SFWES must have an inlet water pump and accumulator and a constant current power supply to apply conditioned power to the electrolysis module.

Table 2-1. ECLSS Atmosphere Requirements

Parameter	Units	Operational	90-day degraded*	21-day emergency
CO_2 partial pressure	mmHg	3.0 maximum	7.6 maximum	12 maximum
Temperature	°F	65 - 75	60 - 85	60 - 90
Dew point**	°F	40 - 60	35 - 70	35 - 70
Ventilation	ft/min	15 - 40	10 - 100	5 - 200
O_2 partial pressure***	psia	2.7 - 3.2	2.4 - 3.8	2.3 - 3.9
Total pressure****	psia	14.7	10 - 14.7	10 - 14.7
Trace contaminants	——	24 hour industrial standard	8 hour industrial standard	8 hour industrial standard

* Degraded levels meet "fail operational" reliability criteria

** In no case shall relative humidities exceed the range of 25 - 75%

*** In no case shall the O_2 partial pressure be below 2.3 psia, or the O_2 concentration exceed 26.9%. Controlled within ± 0.11 psia

**** Diluent is N_2. Controlled within ± 0.2 psia

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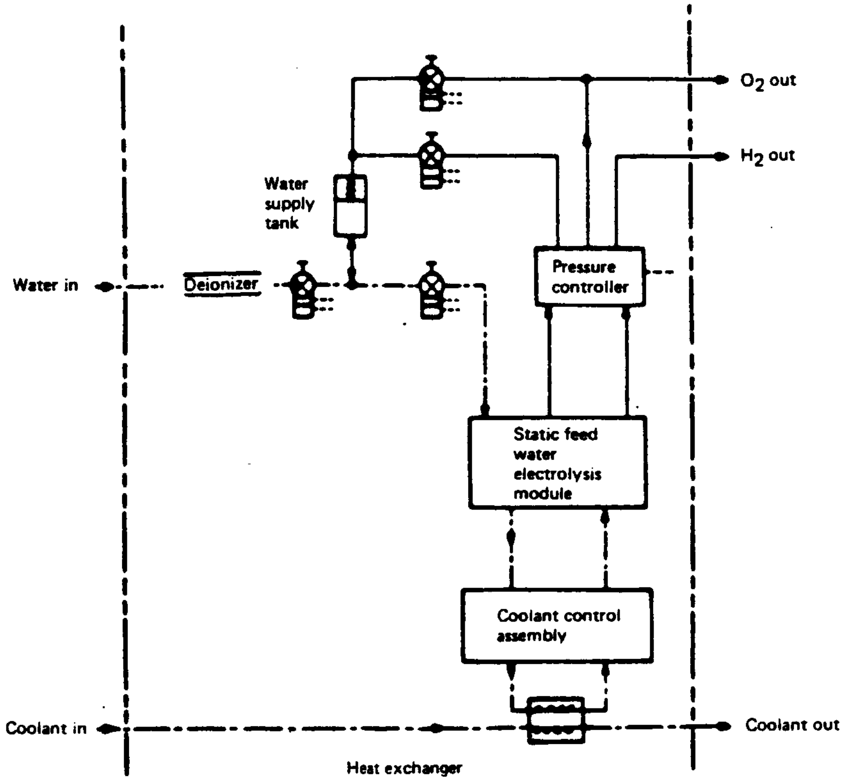


Figure 2.1. Static Feed Water Electrolysis Subsystem (SFWE)

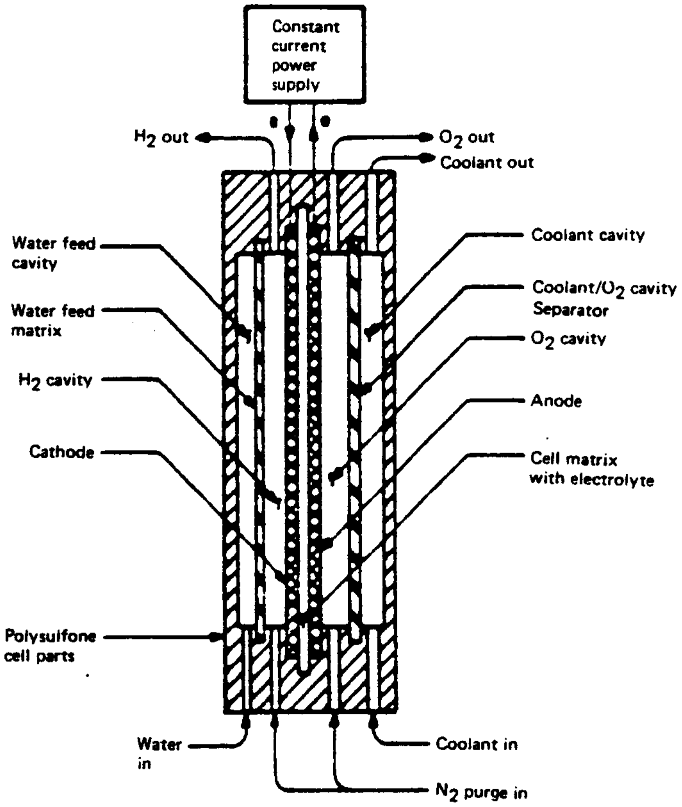


Figure 2.2. SFWE Cell Functional Schematic

2.1.1 Continued

Figure 2-2 is a functional schematic of a SFWE cell. When not operating, both the water feed cavity and the cell matrix have an electrolyte solution consisting of equal concentrations of water in potassium hydroxide. When electrical power is supplied to the electrodes, a current flows and water is electrolyzed in the cell matrix, causing H_2 to form at the cathode and oxygen at the anode. This depletion of water in the cell matrix solution creates a concentration gradient relative to the water feed cavity causing water vapor to diffuse into the cell matrix to make up the water usage. Concurrently, the water from the water feed cavity is replenished statically from the external water supply tank. (Ref. 2)

2.1.2 Carbon Dioxide Removal and Collection

Both expendable and regenerable methods for CO_2 removal have been developed. Expendable chemical canisters such as LiOH, though acceptable for short missions with few crew members, become increasingly unacceptable as mission duration and/or number of crew increase. This has led to the development of regenerable methods such as non-hydrophobic molecular sieves, the solid amine-water desorbed (SAWD) concept and the electrochemical desorbed concentrator (EDC). Only the SAWD and EDC have been considered in the present study. Non-hydrophobic molecular sieves were considered not cost effective for the required 3.0 nm Hg CO_2 maximum partial pressure, and expendable chemical canisters are too heavy.

Solid Amine-Water Desorption

The SAWD process uses as an absorbent a solid amine material known as amberlite (RA-45) which is a weak base ion exchange resin that is deposited on a high surface area granular substrate. In absorbing CO_2, the amine first combines with water vapor from the atmosphere to form a hydrated amine, then with the CO_2 to form a bicarbonate. The amine is regenerated by heating with steam, breaking the bicarbonate bond and replacing the absorbed CO_2 with water.

A typical SAWD system is shown in Figure 2.3. This is a two canister system, with one absorbing while the other is desorbing. While the CO_2 saturated canister is isolated from the cabin air and desorbed, cabin air is routed to the absorbing canister for CO_2 removal. An electrically heated steam generator built into the head of the canister produces low pressure steam for the desorbing process. The steam heats the bed and

2.1.2 Continued

at first pushes ullage air out of the canister at a low flow rate, which is returned to the cabin. As the steam advances into the bed, a wave of high purity (99%) CO_2 is evolved, resulting in a sharp increase in effluent flow rate. A sensor detects this increase and diverts the CO_2 into a storage system. A back pressure regulator in the CO_2 outlet controls the saturation temperature of the steam and thereby the desorption temperature of the bed. After desorption is completed, the process air flow is re-directed through the bed, cooling it and making it ready for an absorption period. The steam used for desorption is evaporated into the process air stream and then condensed out in the cabin humidity control heat exchanger.

Electrochemical Desorbed Concentrator

The EDC concept is shown schematically in Figure 2-4. CO_2 is removed from the atmosphere by passing atmospheric air through a module consisting of electrochemical cells. Each cell consists of two electrodes separated by a process matrix containing an aqueous solution of cesium carbonate (CS_2CO_3). As shown in Figure 2-5, cabin air is passed through the cavity adjacent to the cathode, and Hydrogen, from the SFWES, is passed by the anode. As a result, a fuel-cell reaction occurs, transfering some of the hydrogen through the electrolyte matrix to combine with oxygen from the air stream to form water vapor which shows up in the effluent air stream. Concurrently, an electrical current is generated across a load connected between the anode and cathode. The reaction and the power available from the reaction is controlled by this load impedance.

As the H_2 - O_2 fuel cell reaction occurs, a corresponding transfer of CO_2 occurs from the air side of the matrix to the H_2 side. The rate of this transfer depends upon the partial pressure of CO_2 in the air stream and the cell current density. Unused hydrogen exits the cell mixed with the transferred CO_2 and is then stored or further processed in the CO_2 reduction system.

2.1.3 Carbon Dioxide Reduction

Two concepts have been studied to perform CO_2 reduction: the Sabatier process, and the Bosch process. The primary advantage of using a CO_2 reduction process is that it reduces the amount of effluent generated by the oxygen generation and CO_2 collection units. It does this by breaking down and combining the CO_2 with H_2 to form water vapor and carbon or methane depending on the reduction process. The water vapor is then sent back into the ECLS system thus enabling a higher level of closure.

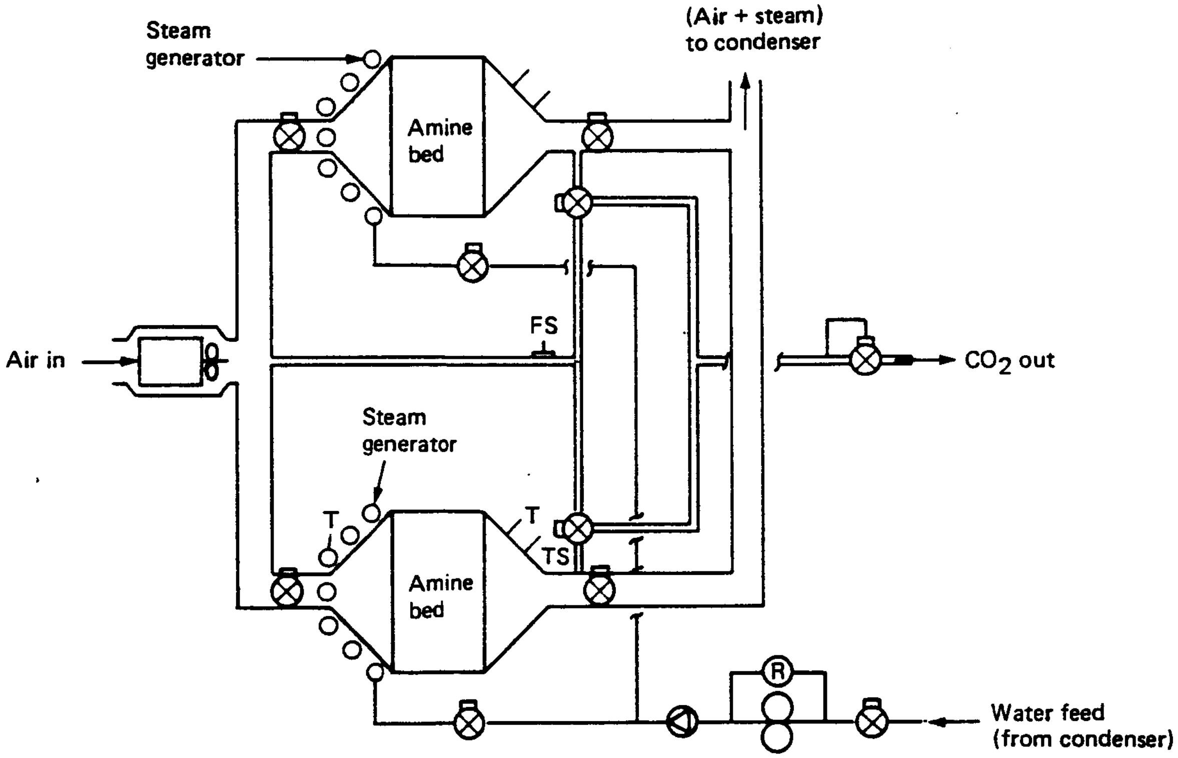


Figure 2-3. SAWD Concept Schematic

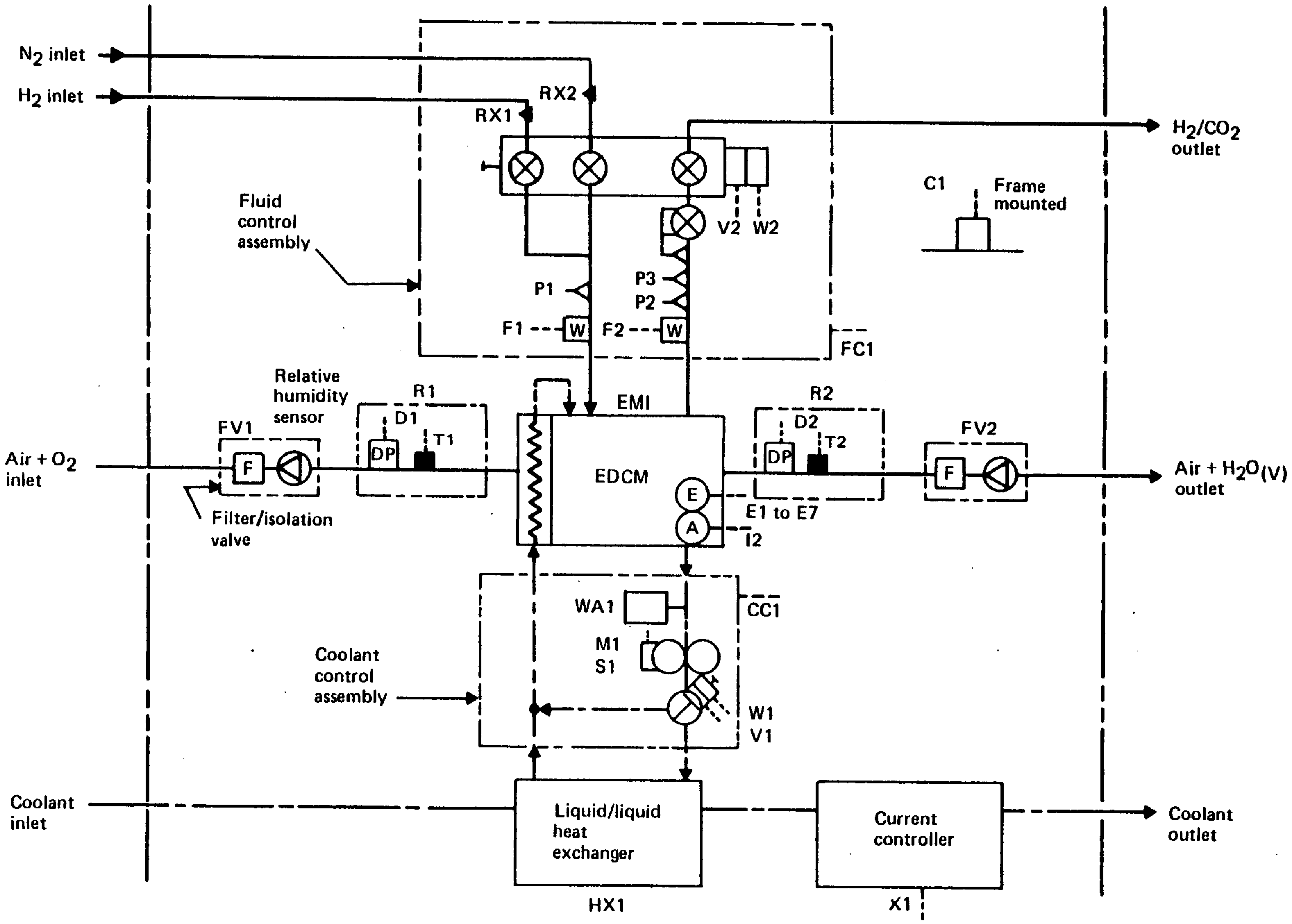


Figure 2-4. EDC CO_2 Removal Subsystem Schematic

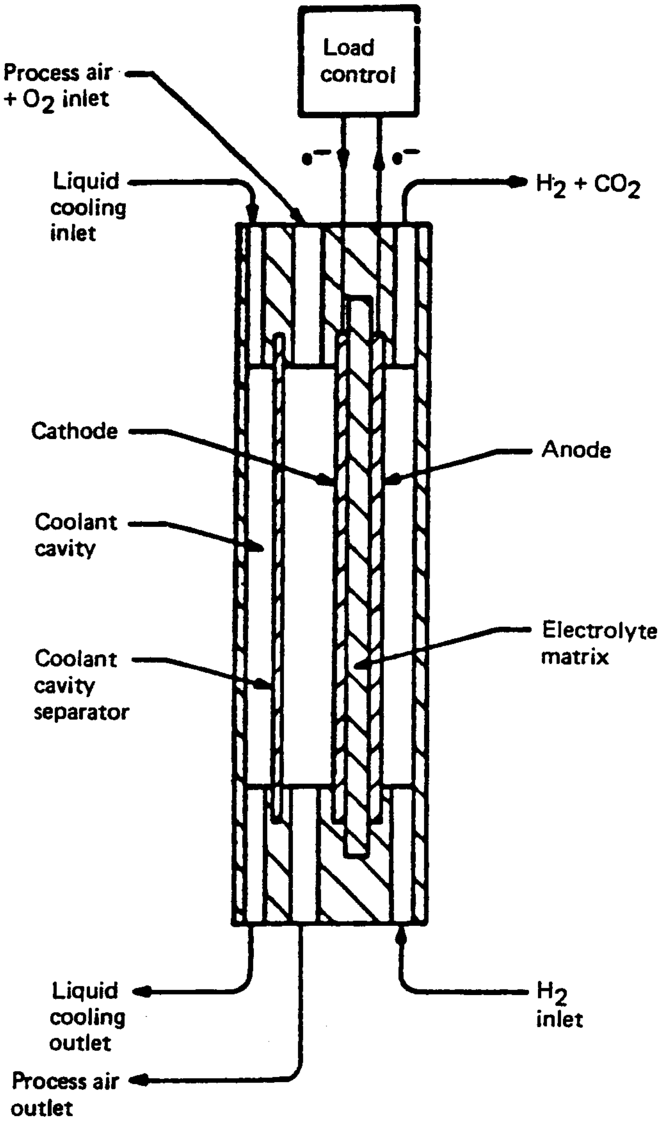


Figure 2-5. EDC Single Cell Functional Schematic

Sabatier Process

The Sabatier process takes a mixed stream of H_2 and CO_2 and passes it through a heated catalyst bed to produce methane (CH_4) and water vapor. Typically, a single pass through the bed will convert at least 99 percent of the H_2 in the stream. Normally there is excess CO_2 in the process, leaving an effluent gas stream of mixed CO_2 and CH_4 which is stored. Water vapor is condenced, separated from the gas stream and pumped to the potable water tank.

Figures 2-6 and 2-7 show a schematic of a Sabatier subsystem and a cross section of a typical reactor respectively. The reaction occurs at 860 to 1060°R (477 to 588°K) and produces enough heat to make the reaction self-sustaining after a start-up heater is used to initiate it. Excess heat is removed either by liquid cooling or by compartment air. An activated charcoal absorption bed ahead of the catalyst bed is used to remove any trace contaminants from the incoming gas stream. The preferred catalyst is 20% Ruthenium on an alumina substrate.

Bosch Process

The Bosch process takes a gas mixture of H_2 and CO_2, heats it to between 1460 and 1810°R (811 and 1006°K) and then passes it through a steel wool catalyst to produce carbon and water vapor. Each pass over the steel wool typically converts only 5 to 10 percent of the reactants. As a result, a recycling system with close control on the H_2/CO_2 mixture in the system is required to obtain complete reduction of the CO_2. Effluents consist of water vapor, a small amount of H_2, and carbon deposited on the steel wool. The water vapor after cooling is pumped to potable water tanks. Only about 60% of the water produced in the reduction process is needed to close the water cycle. Storage capacity is required to handle the excess water. The H_2 after cooling is compressed and stored. The steel wool reactor with deposited carbon is periodically replaced and stored.

Figure 2-8 is a simplified flow schematic of a Bosch system. Two expendable reactor beds are used so that one may be operated while the other is cooled prior to change out. A compressor circulates the gases through a regenerative heat exchanger and heater to preheat the gases entering the reactor bed. During each pass through the the reactor, some of the gases are converted to water vapor, and carbon which is deposited in the steel wool matrix. Upon leaving the reactor the gases pass through

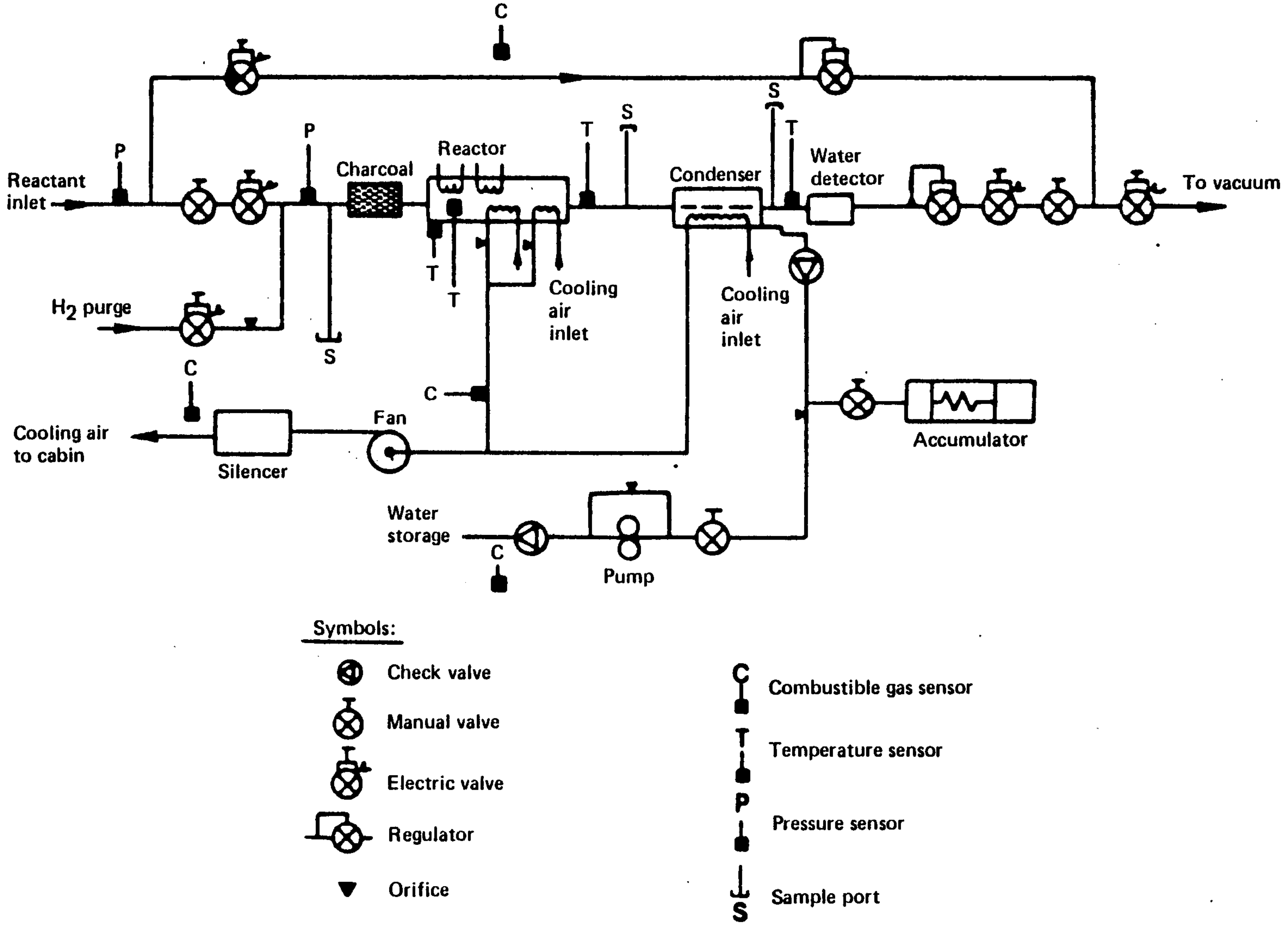


Figure 2-6. Sabatier Subsystem

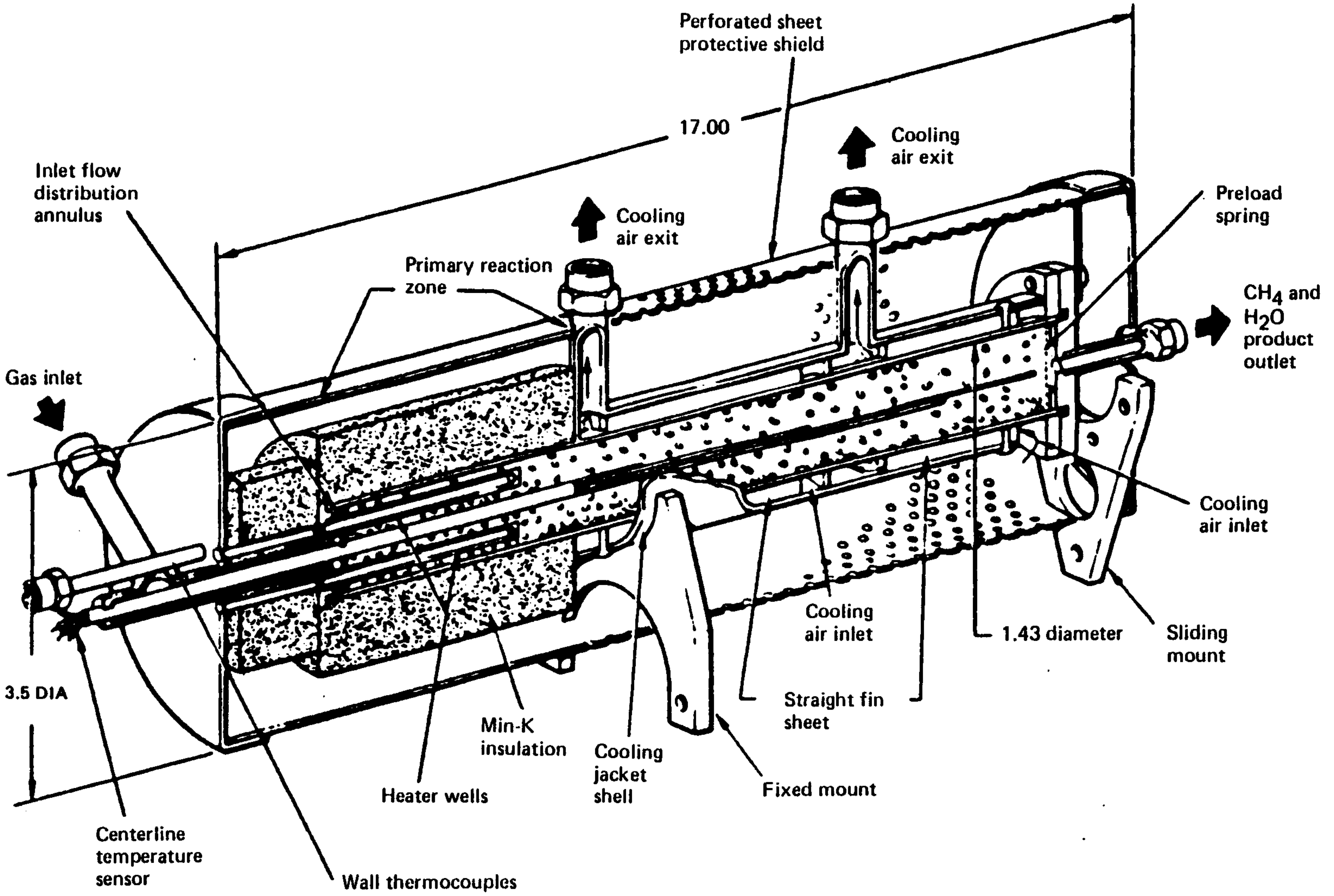
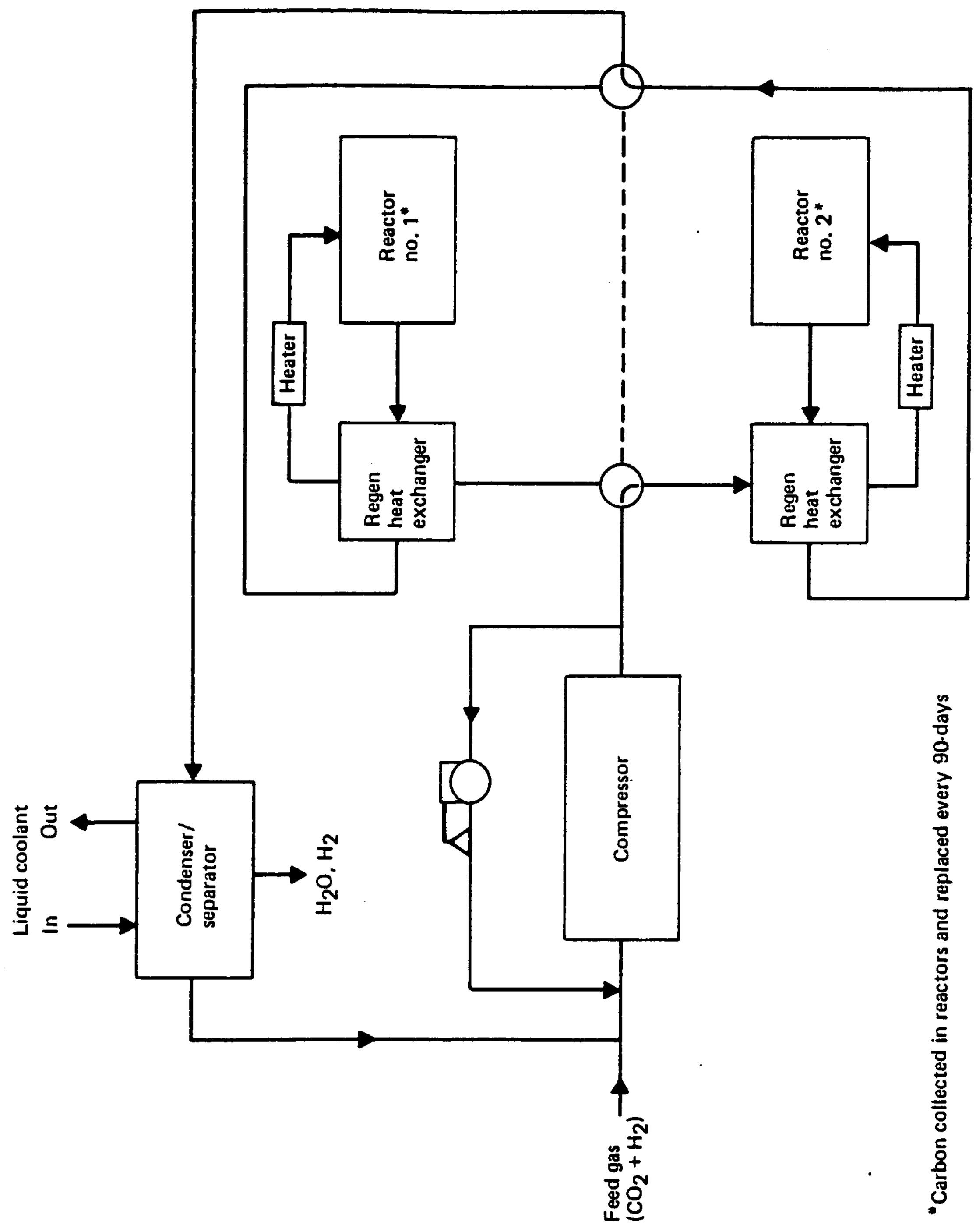


Figure 2-7. Sabatier Reactor – Cross Section



*Carbon collected in reactors and replaced every 90-days

Figure 2-8. *Bosch Subsystem*

2.1.3 Continued

a regenerative heat exchanger, transferring heat to the incoming gas stream, and then through a liquid cooled condenser separator before returning to the compressor. Feed gases are introduced into the loop at the compressor inlet.

2.2 ECLSS Options Analyzed

Four ECLS systems were analyzed for (1) gaseous and liquid effluents, (2) fixed weight and volume of major atmosphere revitalization subsystems, (3) power required by major atmosphere revitalization subsystems, and (4) equivalent weight penalties for power and thermal cooling. They are:

- Open Loop system using water electrolysis (WES) for O_2 generation, and electrochemical depolarizer concentrator (EDC) for CO_2 concentration. Useable effluent includes CO_2 and H_2.
- Open Loop system using water electrolysis for O_2 generation, and solid amine water desorbed (SAWD) concentrator for CO_2 concentration. Useable effluent includes CO_2 and H_2.
- Closed Loop - Sabatier system using water electrolysis for O_2 generation, EDC for CO_2 concentration and Sabatier carbon dioxide reduction. Useable effluent includes CO_2 and CH_4.
- Closed Loop - Bosch system using water electrolysis for O_2 generation, EDC for CO_2 concentration and Bosch carbon dioxide reduction. Useable effluent includes H_2 and H_2O.

It should be emphasized that the weights, volumes, powers, and equivalent weights for power and thermal cooling in this section are for only the major subsystems of the atmosphere revitalization system i.e., EDC or SAWD, Sabatier or Bosch, WES.

Subsystems common to all the analyzed systems such as:

- Waste water collection, pretreatment and storage
- Waste water recovery and post-treatment
- Product water collection and storage
- Trace contaminant
- Temperature and humidity control
- Atmosphere pressure and composition control

are not included in these data. Also not included, at least in this section, is storage tankage unique to an ECLSS option. This tankage and associated compressors are included in section 5.0, where total comparisons of ECLSS-Propulsion combinations are made.

Figures 2-9 through 2-12 show material balances for each of the four ECLS systems. Input materials, material flows within the system, and output materials are shown in units of lbm/day.

There are two important aspects of these figures that are of interest. The first is that the inputs to the system are equal to the outputs from the system (i.e. the system is balanced). The second is the type and quantity of effluents being generated by each system. If the effluent can be used in another Space Station subsystem or even one of the free-flying platforms, then it can alleviate the need to be returned to earth. The quantity is important since it determines how much can be used in another subsystem or how much has to be brought back to earth. Obviously, if the effluent needs to be brought back down in the Shuttle, the lesser the amount the cheaper the cost to the ECLS system.

Figure 2-9 shows the baseline Open Loop system material balance in which an EDC is used for CO_2 removal. Input materials are 8.5 lbm/day of water, 8.8 lbm/day of water in the food, 10.9 lbm/day of dry food, 1.9 lbm/day of N_2, and 0.35 lbm/day of urine pretreat chemicals. Output materials are 2.4 lbm/day of (station leakage) N_2 and O_2, 6.3 lbm/day of brine, 2.2 lbm/day of fecal waste and 19.5 lbm/day of CO_2 and H_2.

The system requires the electrolysis of 24.3 lbm/day of water to generate 21.6 lbm/day of O_2, of which 15.2 lbm/day are required for crew respiration and O_2 leakage make-up. The remaining 6.4 lbm/day of O_2 plus 2.7 lbm/day of H_2 are used in the EDC CO_2 concentration process. EDC outputs consist of 7.2 lbm/day of water vapor which is condensed and returned to the WES and 19.5 lbm/day of CO_2 and H_2 which cannot be further used in the ECLS system.

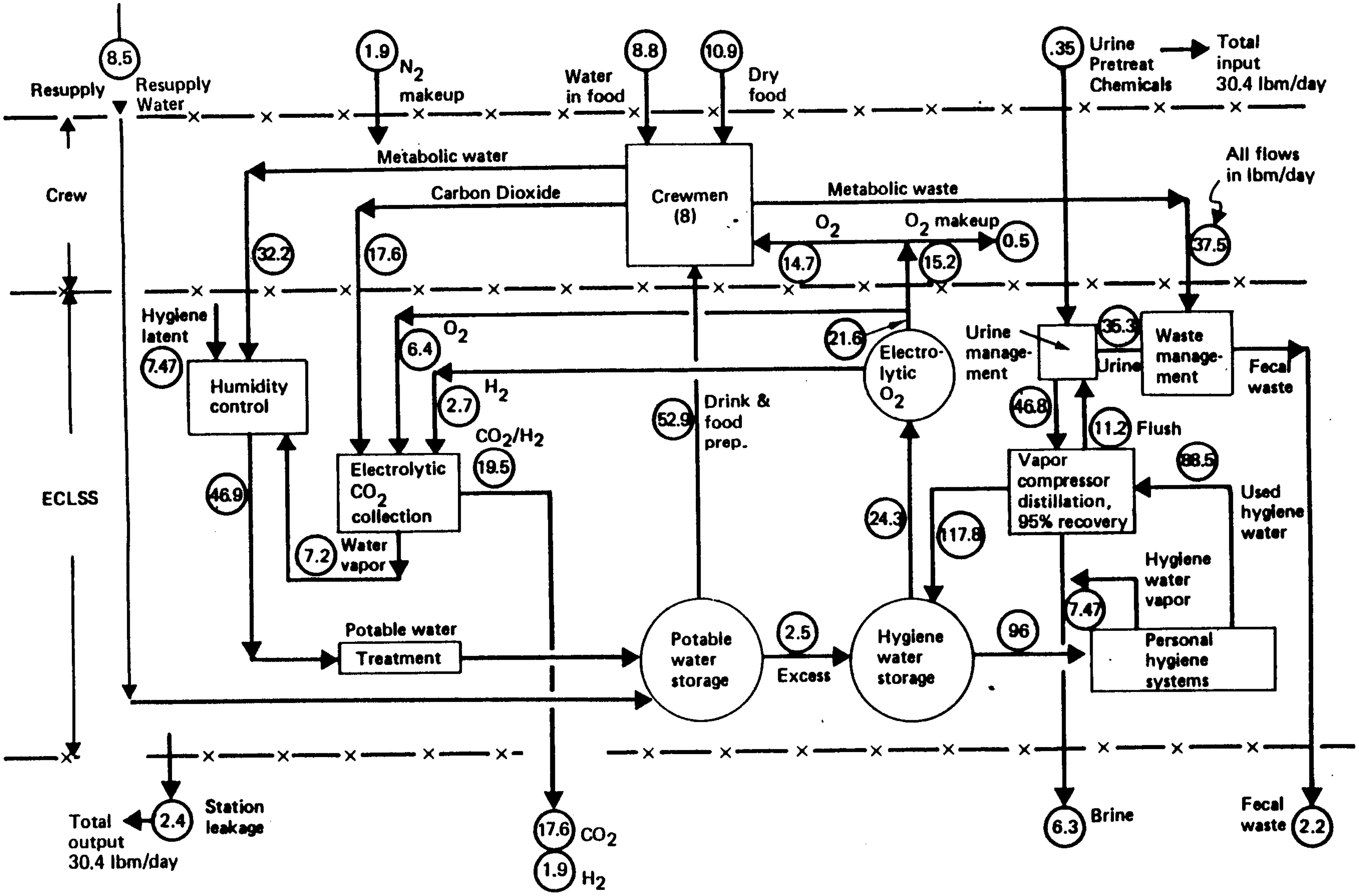


Figure 2-9. Open CO_2 Loop Using EDC ECLSS Material Balance

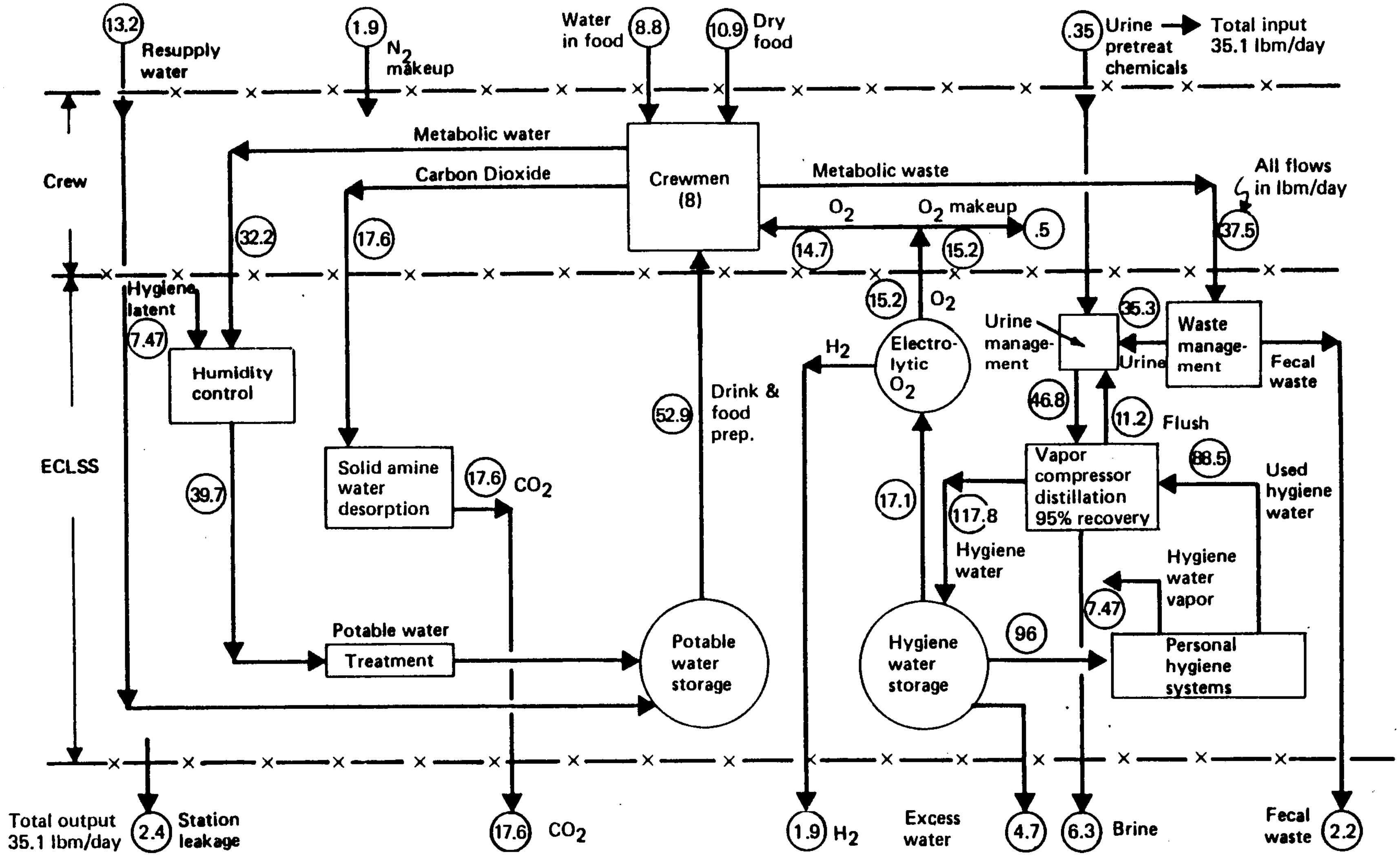


Figure 2-10. Open CO_2 Loop Using SAWD ECLSS Material Balance

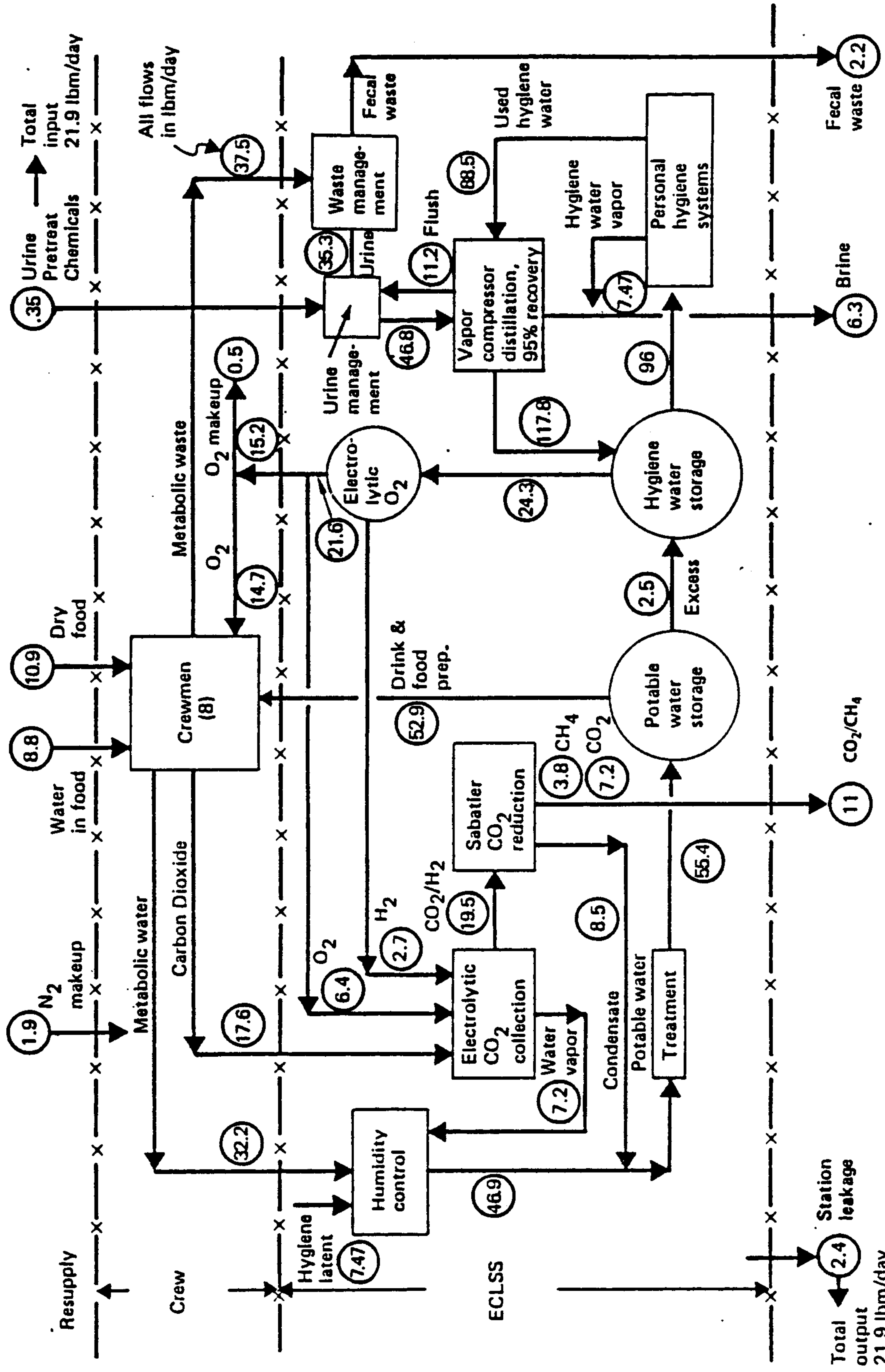


Figure 2-11. ECLSS Material Balance With Sabatier CO_2 Reduction

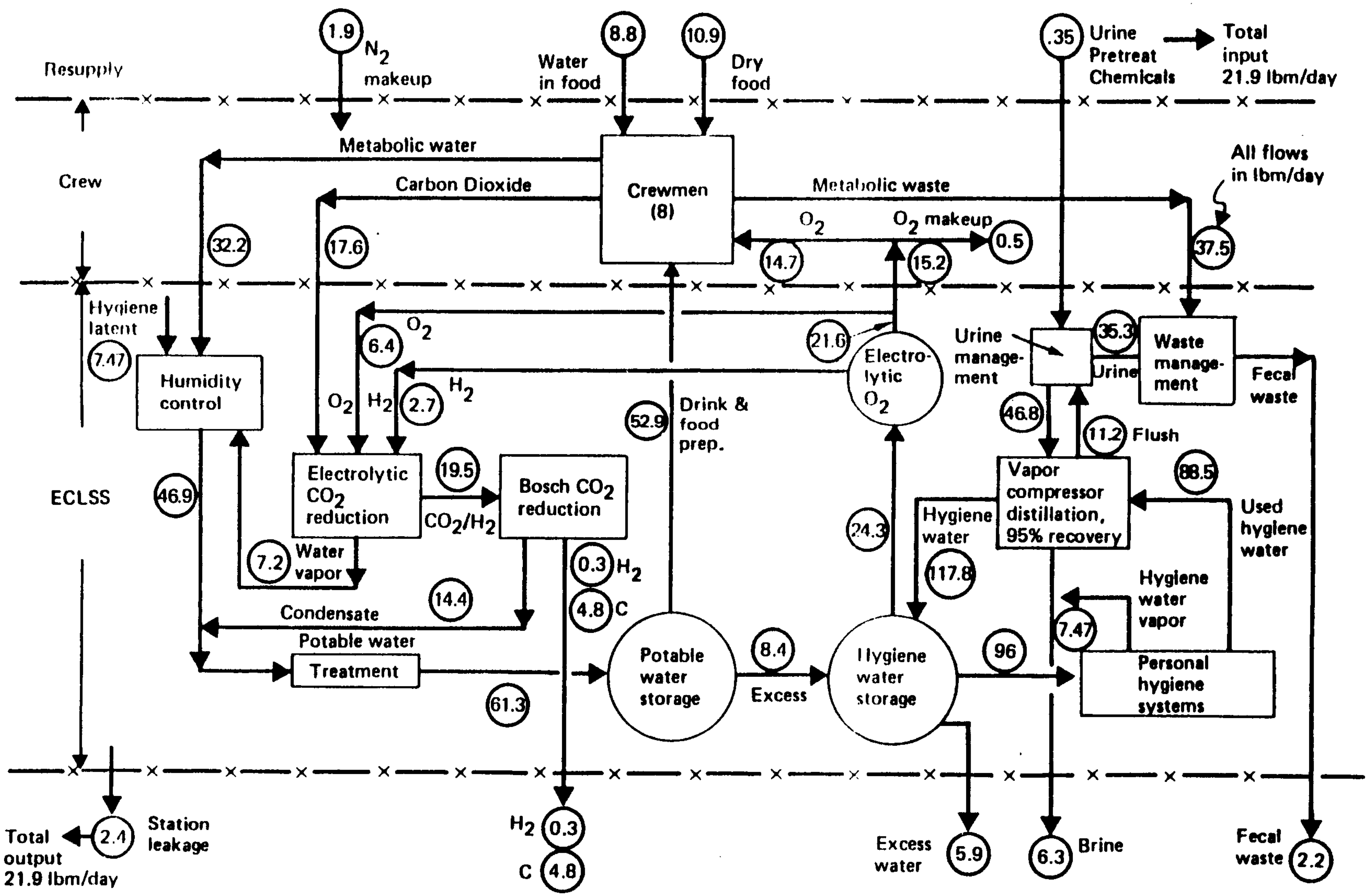


Figure 2-12. Bosch ECLSS Material Balance

2.2 Continued

Figure 2-10 shows the Open Loop system material balance using a SAWD. It produces the same amount of CO_2 and H_2 effluent as the Open CO_2 Loop system using EDC. However, in the SAWD system the CO_2 and H_2 effluents are separate.

The SAWD system requires 13.2 lbm/day of water resupply which is 4.7 lbm/day more than the EDC system. This is caused by the difference between how the hygiene and potable water supplies can be used. Excess potable water can be used for hygiene, but the opposite is not true. Hence, the SAWD system generates an excess of 4.7 lbm/day of hygiene water which cannot be further used by the ECLS system.

Figure 2-11 shows the Closed Loop - Sabatier system material balance. The Sabatier subsystem reduces a portion of the 17.6 lbm/day of CO_2 and 1.9 lbm/day of H_2 leaving the EDC unit. Effluents consist of 8.5 lbm/day of water, 3.8 lbm/day of CH_4, and 7.2 lbm/day of unreduced CO_2. No resupply water is required and no excess water is generated. The CO_2/CH_4 effluent cannot be further used in the ECLSS. If stored, the storage weight and volume penalties are significantly reduced from those of the Open Loop system because of the lower mass and higher density effluents.

Figure 2-12 shows the Closed Loop - Bosch system material balance. The system generates 5.9 lbm/day of excess water, 0.3 lbm/day of gaseous hydrogen and 4.8 lbm/day of solid carbon. The solid carbon (and filters) must be returned every resupply period, while the excess hydrogen must be continuously eliminated or stored and periodically eliminated from the Space Station. The Bosch system, like the Sabatier, has zero water resupply requirements.

The weight, volume, power and thermal cooling for major components of the ECLS systems are shown in Appendix A Figures A-1 through A-5. The schematics on each of the figures illustrates inputs and outputs of each unit operation, mass flow rates in lbm/day, thermal (heat rejection) loads, and power requirements. Station numbers indicate entrance and exit points. The table in the upper right corner of each figure summarizes the fixed weight and volume and resupply requirements of the major components. Resupply requirements include water plus tankage when required (i.e. open loop systems) or, in the case of the Bosch system, the weight of the filters and canisters to store the carbon.

The shown fixed weight and volume, weight penalty for power, and weight penalty for thermal cooling are based on (1) light-side operation of the systems, (2) the daily material balances shown in Figures 2-9 through 2-12 after the continuous internal material flows were adjusted for light-side operation, (3) relationships given in Appendix A Tables A-1 and A-2, and in Figure A-6. Appendix A expands further on these figures and tables and their relationships.

Table 2-2 summarizes the weight, volume, and expendable penalties for each ECLS system considered and how they compare to the baseline system. As stated previously, the baseline system in this study is the Open CO_2 loop using EDC in conjunction with a hydrazine propulsion system.

The first column of Table 2-2 correlates the ECLS system with the appropriate figure in Appendix A. The second and third columns show the absolute fixed weights of the main components in each ECLS system and then how that weight compares to the baseline system. The fixed weights include the weight of the water electrolysis unit. EDC (or SAWD) unit, Sabatier (or Bosch) unit when applicable, equivalent weight for power, and equivalent weight for the thermal heat. Of the four ECLS systems, the baseline system is the lightest while the Bosch is the heaviest.

Columns four and five show the absolute fixed volume of each system and their corresponding differences with the baseline system. The fixed volumns include the same components as the fixed weights excluding the equivalent power and thermal heat. Again, the baseline ECLS system is the smallest with the Bosch system being the largest. A special note should be mentioned and that is if the accumulator tank required to store the effluents were included, then for both cases of fixed weight and fixed volume, the Open CO_2 loop using SAWD would be the heaviest and largest system.

Columns six and seven show the resupply weight required for each system and the corresponding comparison with the baseline ECLS system. The resupply weight includes the required water and tankage or, in the case of the Bosch system, the required canisters and filters to collect and store the accummulated carbon. The Sabatier system is the only one that does not require any resupply water or canisters.

Table 2-2. *ECLSS Options Weight and Volume Penalties*

[1] ECLSS components	Figure	Fixed and equivalent weight lbs	[2] Δ lbs fixed weight	Fixed volume ft^3	Δ ft^3 fixed volume	[3] Resupply lbs	Δ lbs resupply	Resupply volume ft^3	Δ ft^3 resupply	Available effluent, lbm/day
EDC CO_2 collection only	A-1	1930	––	11.4	––	841	––	13.5	––	19.5
SAWD CO_2 collection only	A-2	2275	+345	16.6	+5.2	1307	+466	20.9	+7.4	19.5
EDC CO_2 collection SABATIER CO_2 reduction	A-3	2339	+409	31.9	+20.5	none	-841	none	-13.5	11.0
EDC CO_2 collection BOSCH CO_2 reduction	A-4	3085	+1155	138	+127	360	-481	45	+31.5	6.2

[1] Oxygen supplied for all options by a static feed, solid polymer electrolytic O_2 cell (Hamilton Standard)

[2] Delta weight and volume is relative to the baseline ECLSS using EDC only, no CO_2 reduction (Figure A-1)

[3] 90-day resupply cycle

2.2 Continued

Columns eight and nine show the resupply volumes of those water tanks or canisters and filters discussed previously and their differences compared to the baseline system. Obviously, the Sabatier has no resupply volume requirements and hence has the smallest volume requirements of the four systems.

Finally, column ten shows the generated effluent that if not stored and brought back to Earth could be used for some other purpose (i.e. propulsion). These effluents consist of either CO_2, CH_4, H_2, and/or H_2O. Figures 2-9 through 2-12 show the combinations and quantities of effluents for each system.

2.3 ECLS Systems Summary

Four ECLS systems have been looked at:

(1) Open CO_2 loop using EDC, which is considered the baseline for this study;
(2) Open CO_2 loop using SAWD;
(3) Sabatier CO_2 reduction using EDC;
(4) Bosch CO_2 reduction using EDC;

to determine how they function as stand alone systems on-board the Space Station. The main components of each system have been examined and their functional capabilities determined. For each system it was determined the type and quantity of effluents generated. Of these effluents, some can be used for other functions on the Space Station. By using these effluents in other Space Station subsystems, it is possible to reduce the amount and frequency of bringing ECLS by-products back to earth. The next section examines the Space Station propulsion system requirement and determines how the ECLS waste gases can reduce and at times eliminate propulsion resupply requirements by supplementing or replacing the primary fuel.

3.0 PROPULSION REQUIREMENTS FOR ORBIT MAINTENANCE

Space Station propulsion requirements (Ref. 11) include thrust and total impulse requirements for drag makeup, desaturation of momentum storage devices, back-up support for attitude control, and cancellation of docking disturbances. In the reference 11, the latter three functions require a small amount of propellant compared to that needed for orbit maintenance. Hence, only drag makeup requirements are considered when examining the impact of ECLSS effluents on propulsion.

3.1 Impulse Requirements

The Space Station propulsion system 90-day impulse requirements are determined using two types of atmospheric models. The first is a 2-sigma model, shown in figure 3-1A, which encompasses 97.5% of the "estimated" possible atmospheres that could occur over an 11-year solar cycle. The 2-sigma atmospheric model is used to size the tanks, thrusters, lines, etc...of the propulsion system.

The second is a zero-sigma (or nominal) atmospheric model, shown in figure 3-1B, which encompasses 50% of the "estimated" possible atmospheres that could occur over an 11-year solar cycle. The nominal atmospheric model is used to determine the expected resupply schedule over the 10-year mission of the station. Both figures 3-1A and 3-1B show how the density models fluctuate over 11-year and annual cycles. Daily and orbital fluctuations due to light and dark side variations and geomagnetic disturbances have been averaged out.

The aerodynamic drag used in determining impulse requirements is a function of the coefficient of drag, atmospheric density, velocity (squared), and the effective cross sectional area of the station. For a given altitude only the atmospheric density changes significantly over time (figure 3-1A). The velocity (24931 ft/sec) is for 270 n.m. altitude.

The effective cross sectional area is based on the average frontal area of the station over one orbit. Since, the solar arrays are Sun-pointing, their area, projected along the velocity vector, changes cyclically. Figure 3-2 illustrates these effects. At point A, the arrays are "flat" to the wind and the array area is reduced by the cosine of the beta angle only. At point B, the arrays remained essentially fixed in inertial space while the body has rotated between the arrays. Effective array area at point B has been reduced to zero. Figure 3-3 illustrates the array angle of attack history from which an average 47.5 degree angle of attack was determined. The cross sectional

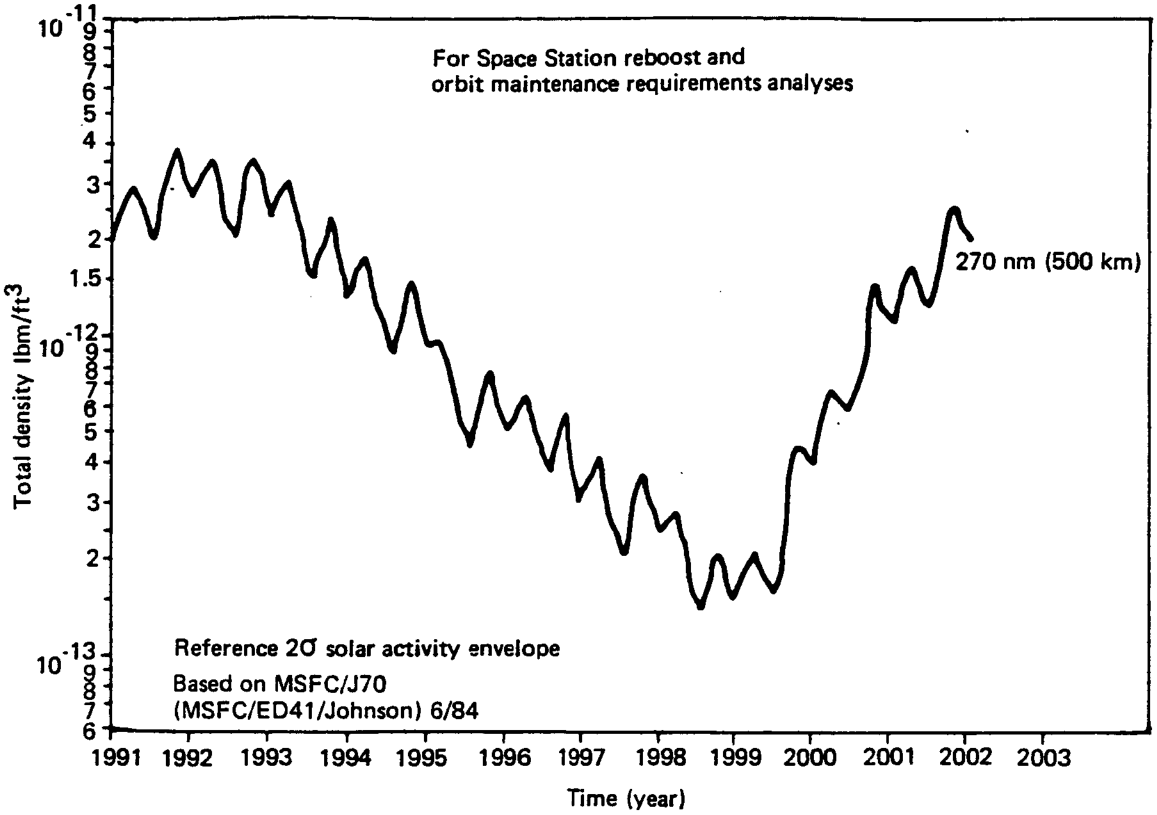


Figure 3-1A. Design Reference Orbit Maintenance Steady State Total Density (Low Inclination Orbit)

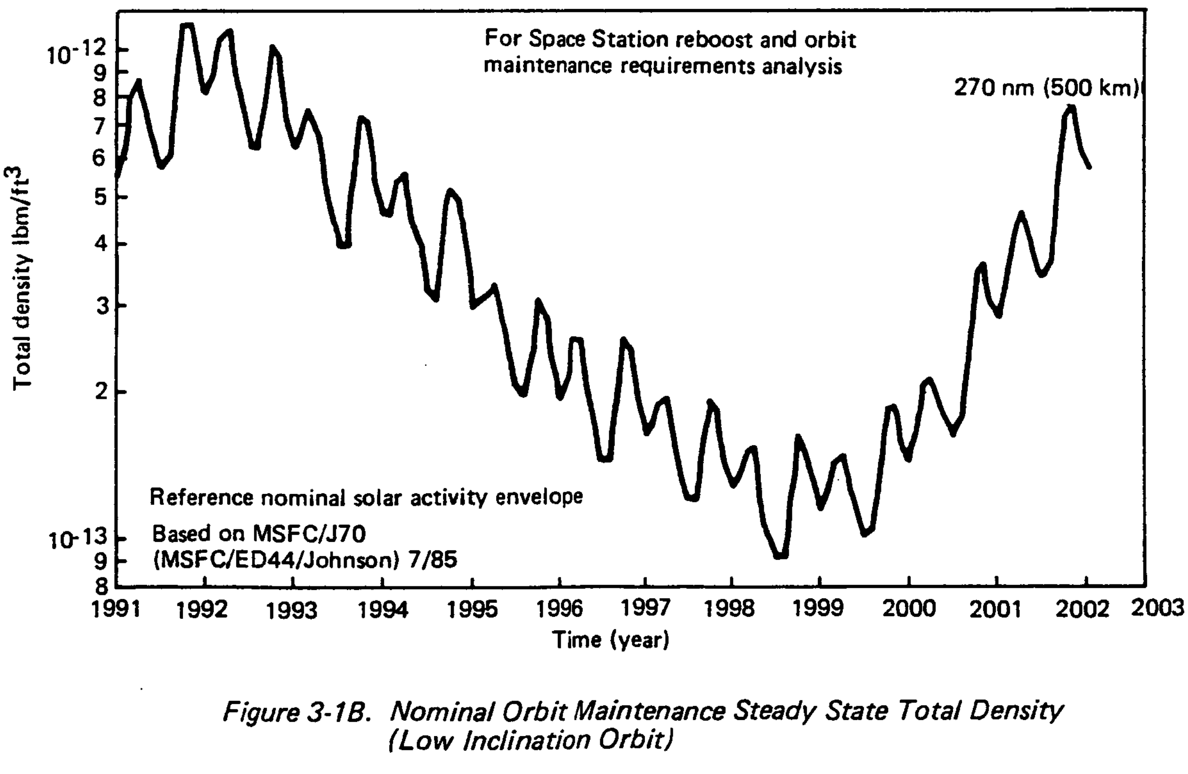


Figure 3-1B. Nominal Orbit Maintenance Steady State Total Density (Low Inclination Orbit)

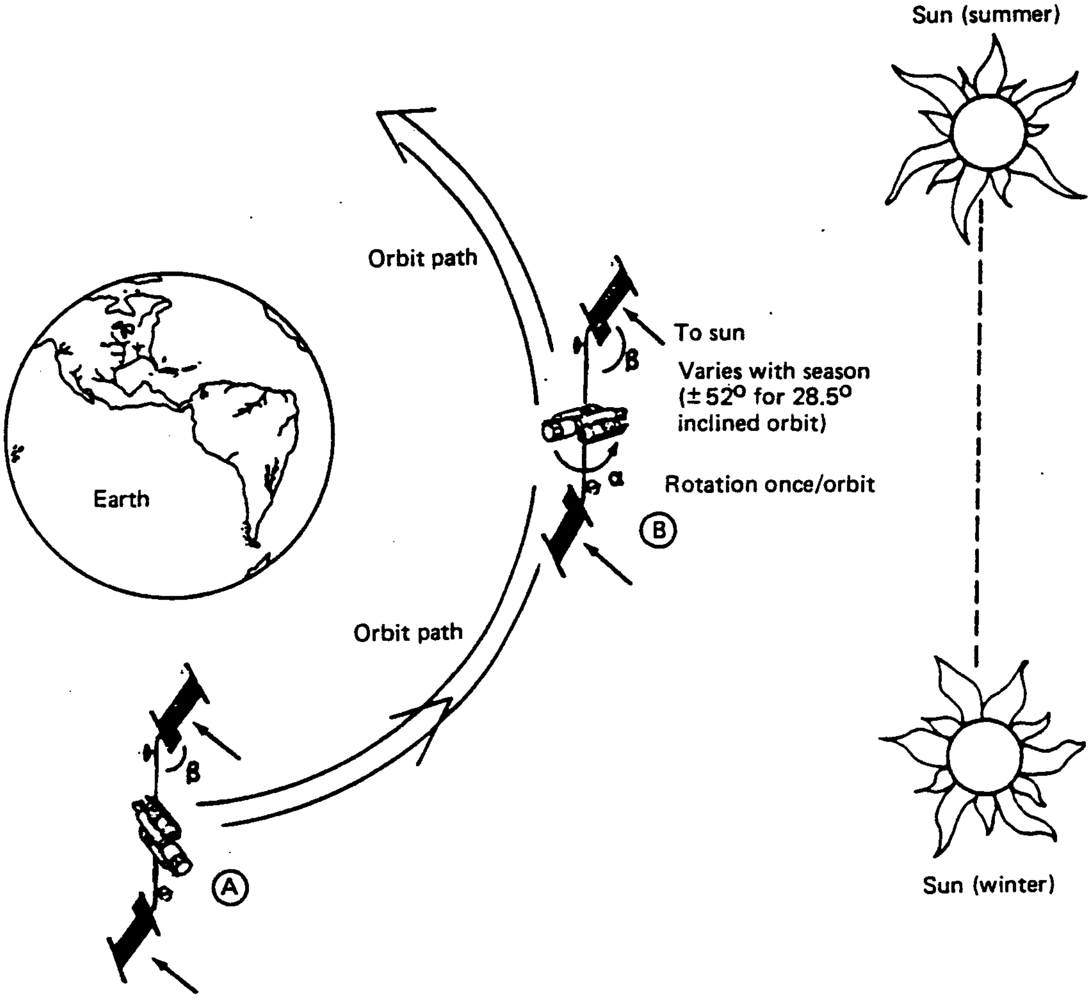


Figure 3-2. Earth-Oriented Solar Array Angle Variation

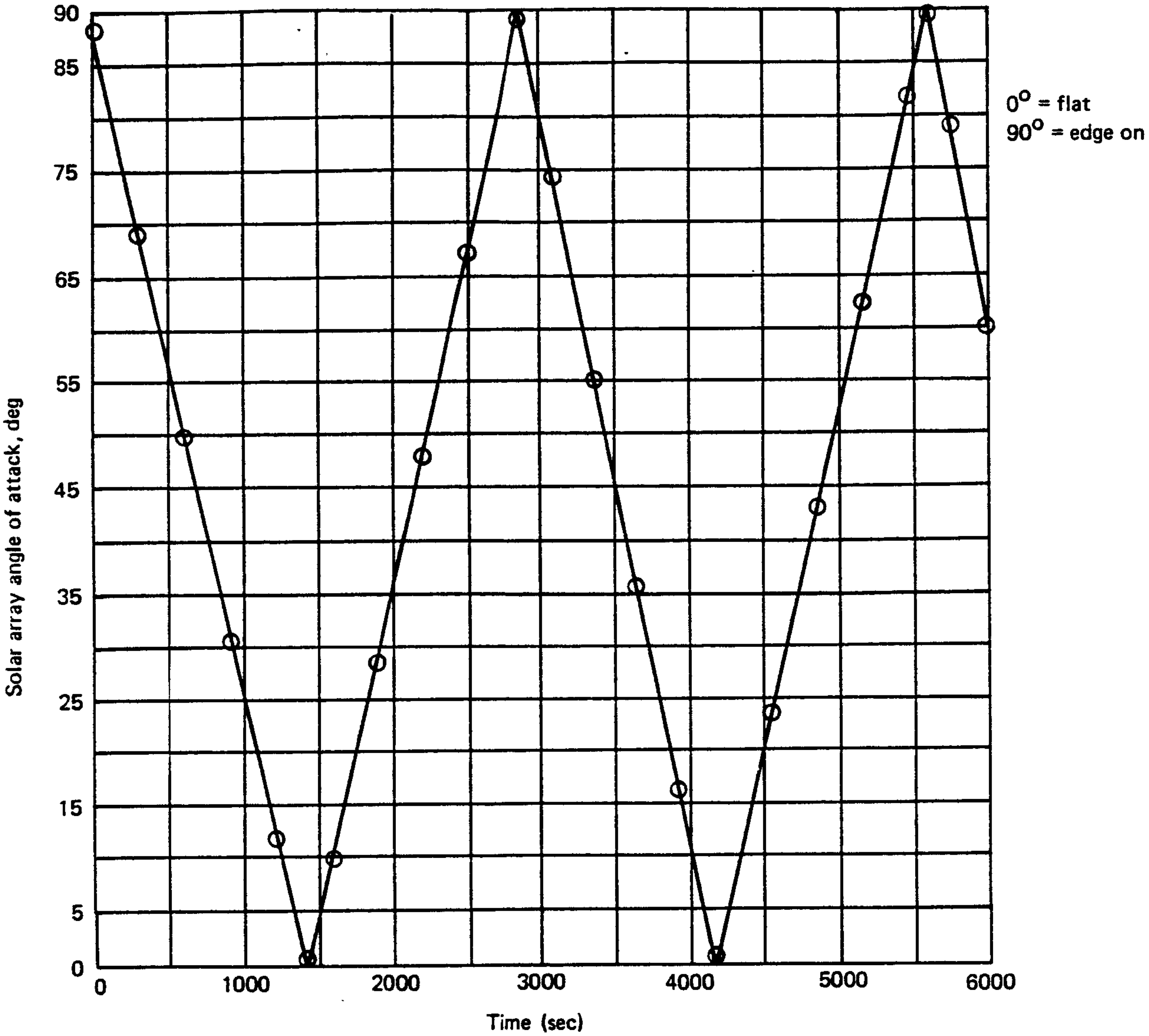


Figure 3-3. Solar Array Angle of Attack

3.1 Continued

area of the station is determined with the orbiter docked for 14 days of every 90-day resupply period. This results in a total effective cross sectional area of 31775 ft^2. Tables 3-1a and b and 3-2a and b show the drag and required 90-day impulse values for the 2-sigma and nominal atmospheres of an 8- to 12-man, $28\frac{1}{2}^\circ$ - inclination, 270-n.m., Sun-pointing array, earth-oriented core Space Station.

Figure 3-4 illustrates the difference in magnitude between the 2-sigma and nominal atmospheres. During the initial and latter years of the Space Station 10-year mission, the 2-sigma impulse model is as much as three times the requirement as the nominal impuse model. This plays a significant role in determining which propulsion and ECLS system is chosen as will be made clear further in the text.

The 1992 2-sigma 90-day impulse requirement is used throughout this study in sizing all aspects of the propulsion system as well as imparting the resupply scheme. The nominal 90-day impulse requirements are used solely to determine the expected 90-day fuel consumption over the 10-year mission of the station.

Possible thrusting strategies are examined using the 1992 2-sigma, 90-day impulse requirements to better understand what thrust levels are most appropriate for propulsion systems using resistojets, warm gas thrusters, or combustion jets. These are shown in table 3-3. Thrust levels and burn times assume no loss of altitude between thrusting periods. Actual thrust levels and/or burn times would be larger for longer thrusting frequencies. For example, a 45-day thrusting frequency results in approximately a 16 nmi (20 kw) drop in altitude. Hence, a reboost would require either a higher thrust level, longer burn time, or some combination of the two than is shown in table 3-3.

3.2 Available Specific and 90-Day Impulses

Specific impulse performance data is generated using a Chemical Equilibrium Computer program (CEC) (Ref. 12) for the different propellant combinations produced by the Open Loop (EDC and SAWD), Sabatier and Bosch ECLS systems

Figures 3-5 through 3-7 show the variation of specific impulse versus chamber pressure for CO_2/H_2 and CO_2/CH_4 resistojets and specific impulse versus mixture ratio for O_2/CH_4 and O_2/H_2 combustion jets. For the resistojet curve a maximum chamber

Table 3-1A. Drag Data (2σ Atmosphere)

	Year					
Drag (lb_f)	1992	1993	1994	1995	1996	1997
Mean	.115	.081	.053	.030	.019	.013
	1998	1999	2000	2001	2002	2003
Mean	.008	.013	.038	.074	.108	.115

- 8 - 12 man station
- 28½° inclination
- 270 nmi altitude
- Orbiter docked 14/90 days

- Mean drag (11 years) = .055 lb_f

Table 3-1B. Drag Data (Nominal Atmosphere)

	Year					
Drag (lb_f)	1992	1993	1994	1995	1996	1997
Mean	.0360	.0266	.0187	.0116	.0087	.0068
	1998	1999	2000	2001	2002	2003
Mean	.0055	.0058	.0095	.0197	.0332	.0360

- 8 - 12 man station
- 28½° inclination
- 270 nmi altitude
- Orbiter docked 14/90 days

- Mean drag (11 years) = .0166 lb_f

Table 3-2A. *90-Day Required Impulse (2σ Atmosphere)*

	Year					
Impulse (lb_f-sec)	1992	1993	1994	1995	1996	1997
90-day	894,000	630,000	412,000	233,000	148,000	101,000
	1998	1999	2000	2001	2002	2003
90-day	62,000	101,000	295,000	575,000	840,000	894,000

- 8 - 12 man station
- 28½° inclination
- 270 nmi altitude
- Orbiter docked 14/90 days

- Mean impulse (11 years)* = 428,000 lb_f-sec

* Per 90-day resupply cycle

Table 3-2B. *90-Day Required Impulse (Nominal Atmosphere)*

	Year					
Impulse (lb_f-sec)	1992	1993	1994	1995	1996	1997
90-day	280,000	207,000	145,000	90,000	67,700	52,900
	1998	1999	2000	2001	2002	2003
90-day	42,800	45,100	73,900	153,000	258,000	280,000

- 8 - 12 man station
- 28½° inclination
- 270 nmi altitude
- Orbiter docked 14/90 days

- Mean impulse (11 years)* = 129,000 lb_f-sec

* Per 90-day resupply cycle

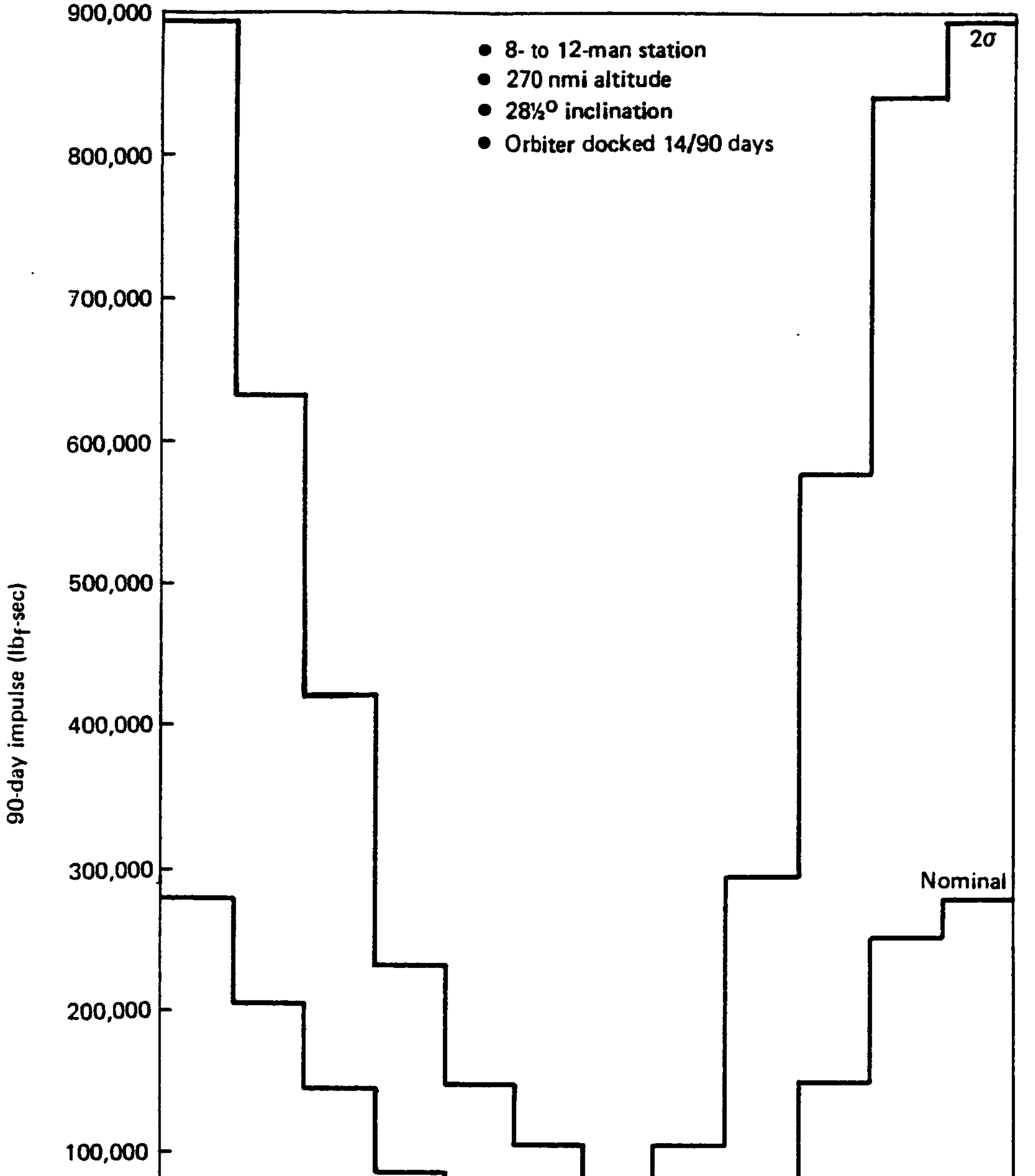


Figure 3-4. 90-Day Required Impulse for 2σ and Nominal Atmospheres

Table 3-3. *Orbit Maintenance Thrust Levels for Various Thrusting Strategies*

Thrust level (lb_f)	Thrust duration (sec)	Thrusting frequency			
		Per orbit*	Per day	Per 10 days	Per 45 days
.11	Continuous	X			
.17	3792**	X			
.54	1200 (20 min)	X			
1.1	600 (10 min)	X			
1.7	5688 (1.58 hrs)		X		
2.6	3792		X		
8.3	1200		X		
16	600		X		
17	5688			X	
26	3792			X	
83	1200			X	
170	600			X	
79	5688				X
120	3792				X
370	1200				X
750	600				X

*One orbit = 1.58 hours

**Sunlit portion or 2/3 of orbit

- 1992 90-day impulse = 894,000 lb_f-sec
- Z - sigma atmosphere
- Altitude = 270 nmi
- 8- to 12-man station

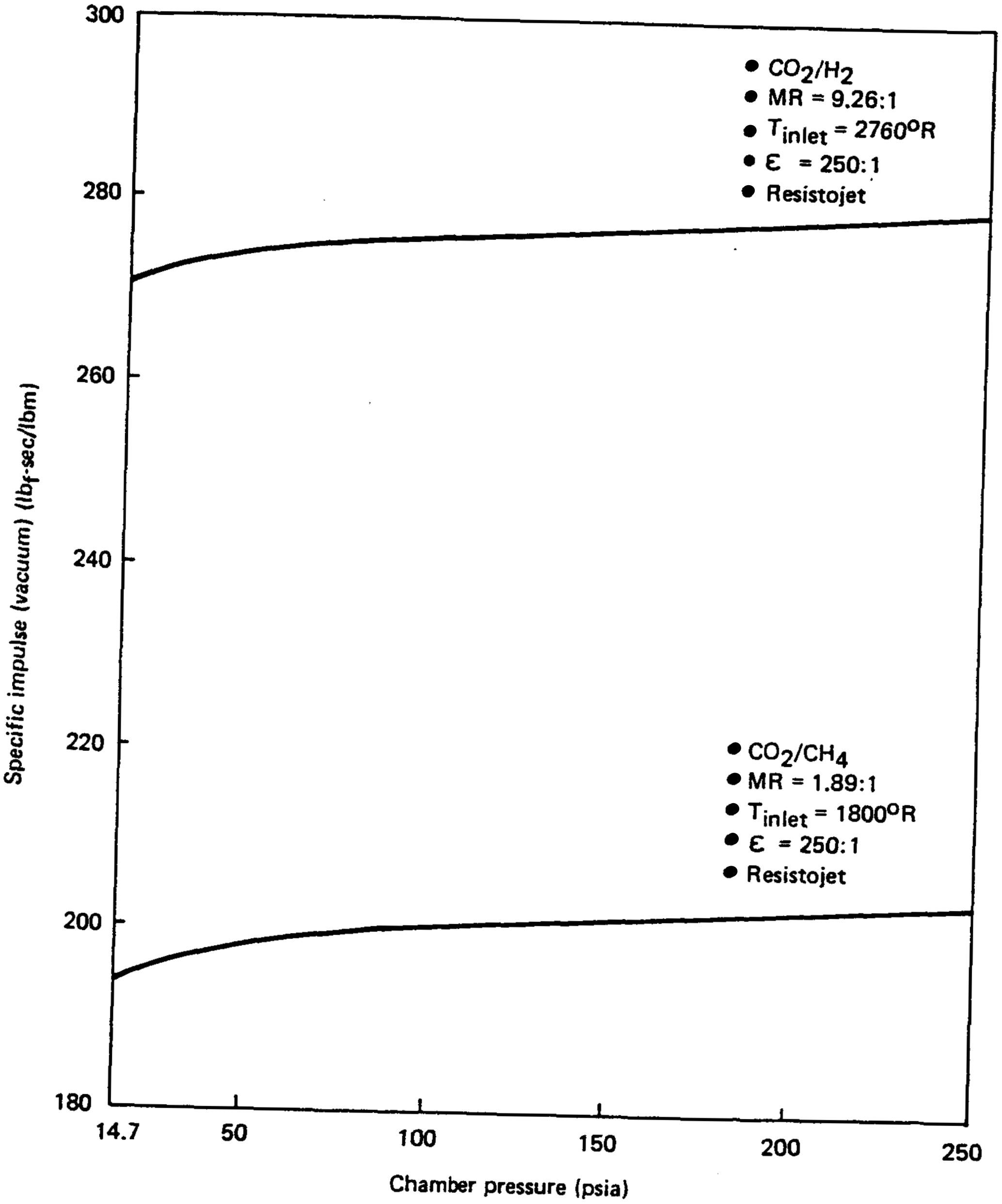


Figure 3-5. CO_2/H_2 *and* CO_2/CH_4 *Ideal Specific Impulse Performance*

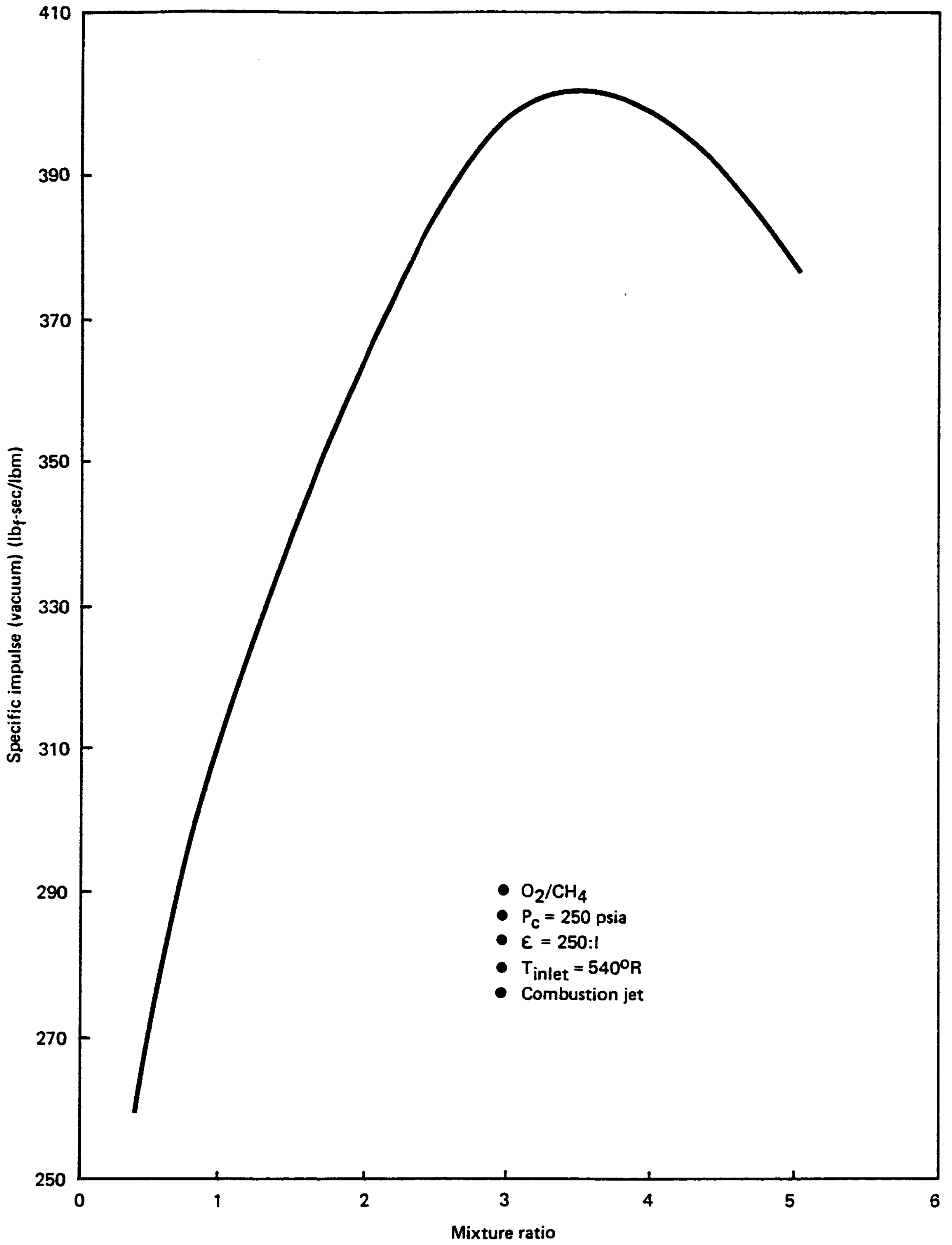


Figure 3-6. O_2/CH_4 Ideal Specific Impulse Performance

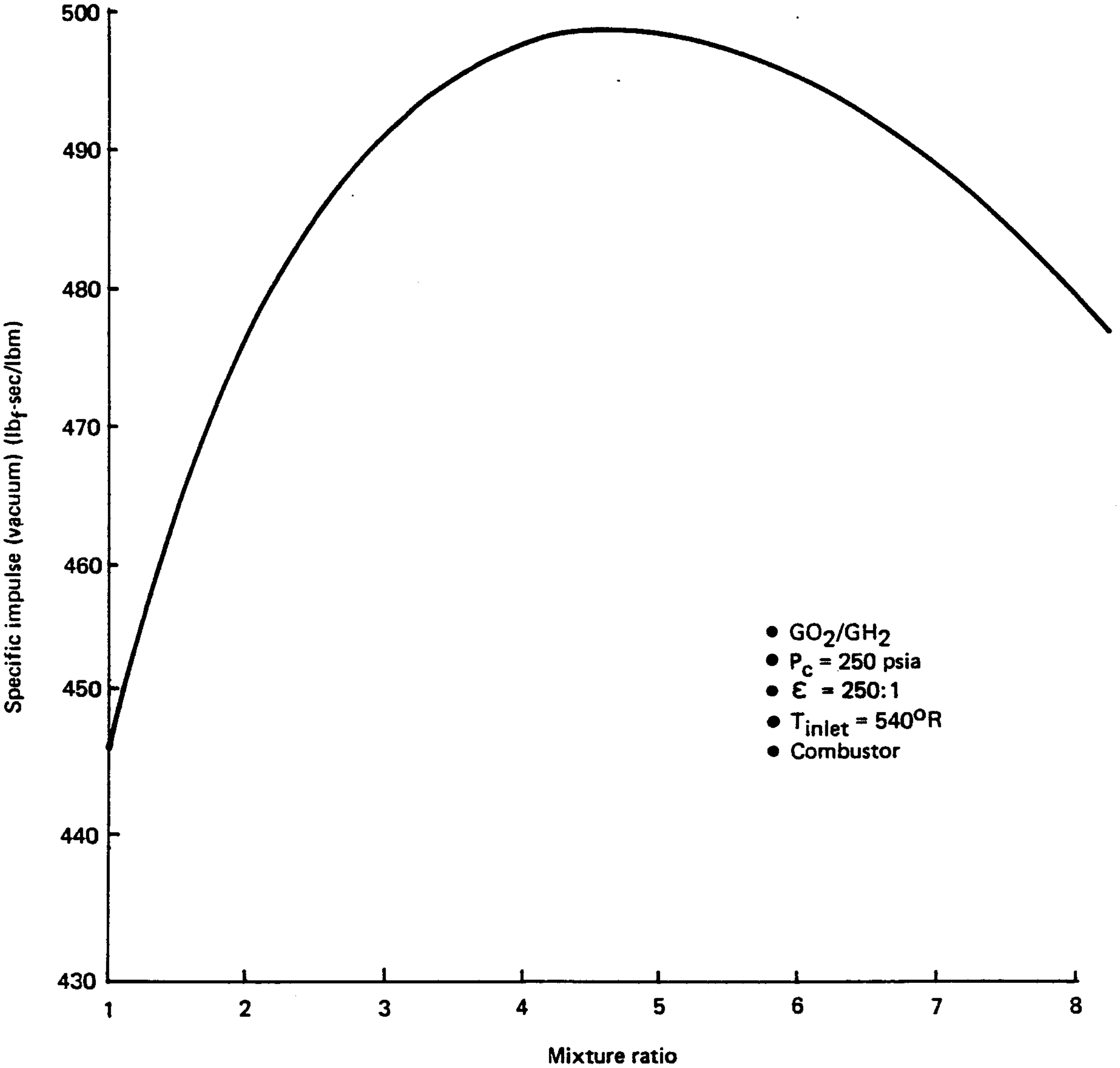


Figure 3-7. O_2/H_2 Ideal Specific Impulse Performance

temperature based on the dissociation values of CO_2 (2760°R) and $C0_2CH_4$ (1800°R) is used. From these curves, the available 90-day total impulse of the effluents from each ECLSS is determined (Table 3-4).

For each ELCS system option there exists one or more propellant combinations that can be created. In table 3-4 six propellant combinations are used from the four ECLS systems. The effluents (propellants) generated by the different ECLS systems are fixed based on the crew, hence the mixture ratios shown in table 3-4 can only change if the crew size changes or if additional water is electrolyzed to generate more propellant. This latter option is discussed in section 3.5. For those propellant combinations that are used in warm gas thrusters or resistojets, temperature ranges are used based on the characteristics of the propellants. For example, CO_2 will solidify in a nozzle unless it is heated to at least 760°R. Likewise, CO_2 begins to dissociate at approximately 2760°R. It is these temperature ranges which dictates the specific impulse of the propellants and, coupled with the available mass, the 90-day specific impulse.

In the case of the Open CO_2 loop ECLS system using SAWD and the Bosch CO_2 reduction system, two propellant combinations were used. In both cases excess water is generated. If, in the case of the SAWD system, the excess water is electrolyzed and combined with the available H_2 from the EDC unit a mixture ratio of 1.72 is obtained. This propellant could then be combusted while injecting the available CO_2 into the nozzle downstream of the combustion chanber. This provides about 73,000 lb_f-sec of additional impulse over the CO_2/H_2 at 2760°R.

In the case of the Bosch, the excess water could be electrolyzed and combined with the available H_2 from the Bosch unit. This would provide a mixture ratio of 5.9:1 and generates an additional 75,000 lb_f-sec of impulse every 90-days.

Figures 3-8 through 3-11 compare the available impulse from the basic ECLSS options; against the impulse values required over the 11-year cycle for the 2-sigma model (Table 3-2A). Maximum and minimum available impulses are shown for each option based on alternative thrusting concepts e.g. warm gas and resistojet.

Table 3-4. 90-Day Available Impulse

ECLS system	Propellant	Mixture ratio	Thruster type	Available mass (lbm) 90-days	Inlet temperature (^oR)	Specific impulse $\frac{(lbf\text{-}sec)}{(lbm)}$	90-day impulse (lbf-sec)
Open CO_2 loop – EDC	CO_2/H_2	9.26	Warm gas	1755	760+	143	251,000
			Resistojet	1755	2760++	280	491,400
Open CO_2 loop – SAWD	CO_2/H_2	9.26	Warm gas	1755	760+	143	251,000
			Resistojet	1755	2760	280	491,400
	$O_2/H_2 - CO_2$*	1.72	Combustor	2178	540	259	564,100
SABATIER CO_2 reduction	CO_2/CH_4	1.89	Warm gas	990	760+	106	105,000
			Resistojet	990	1800+++	203	201,000
BOSCH CO_2 reduction	Steam/H_2	19.67	Resistojet	558	960	162	90,400
			Resistojet	558	2760	281	157,000
	O_2/H_2	5.9	Combustor	558	540	417	232,700

- 8 crew members
- P_c = 250 psia
- ϵ = 250:1

\+ All propellant combinations containing CO_2 are heated to 760°R (300°F) to avoid solidification in nozzle

++ CO_2 dissociates at ~2760°R

+++ CH_4 dissociates at ~1800°R

* CO_2 injected into nozzle downstream of combustion chamber

Figure 3-8 shows how under 2-sigma atmospheric conditions the CO_2/H_2 from an Open Loop ECLS system using an EDC can reduce and even eliminate, for some years, propellant requirements and the need to store/return-to-earth ECLS system effluents. For example, in 1992, 90-day impulse requirements for the primary propulsion system can be reduced by 400,000 lb_f-sec from about 900,000 to 500,000 lb_f-sec. This represents a saving of about 1670 lb_m every 90-days for a hydrazine propulsion system. This saving is equivalent to a longer resupply period for the system when it is sized for non augmented operation. In 1994 through 2000, 90-day impulse requirements can be completely met with the available CO_2/H_2 impulse from a resistojet operating at temperatures between 2760°R and 760°R or by a warm gas thruster operating at 760°R. It should be noted that for the years between 1995 to 2000 some storage/return-to-earth of CO_2/H_2 will be required if the reboost impulse is not increased by deliberately performing reboost inefficiently since the minimum available impulse is greater than the required impulse. Another alternative would be to allow the station to drop to a lower altitude thus requiring a higher impulse. This method would in turn enable the Shuttle to bring up larger payloads.

Under nominal atmospheric conditions, shown in figure 3-4; the available impulse from the Open CO_2 loop ECLS system using EDC is sufficient to meet all the 90-day impulse requirements (table 3-2B). Consequently it provides too much impulse for all but three years. Hence, some type of inefficient thrusting would be required or, as mentioned above, the station could be flown at a lower altitude.

Figure 3-9 shows similar information for the Open CO_2 Loop ECLS system using SAWD. The Open CO_2 Loop system using SAWD generates 4.7 lbm/day of excess water which must be either stored/returned-to-earth or used for propulsion. Since the propulsive capabilities of the effluents from the EDC and SAWD systems are the same when the excess water is returned to earth, only the case of using the water to provide O_2 and H_2 for propulsion was considered for the maximum available impulse shown in Figure 3-9. This maximum impulse is based on electrolyzing the water into O_2 and H_2, combining the stored products with stored H_2 from water electrolysis for crew O_2, combusting the combined products in an O_2/H_2 gas burner, injecting stored CO_2 effluent into the combusted stream, and then expanding the total mixture through thrusters. The resulting impulse is approximately 73,000 lb_f-sec higher than the CO_2/H_2 resistojet at 2760°R.

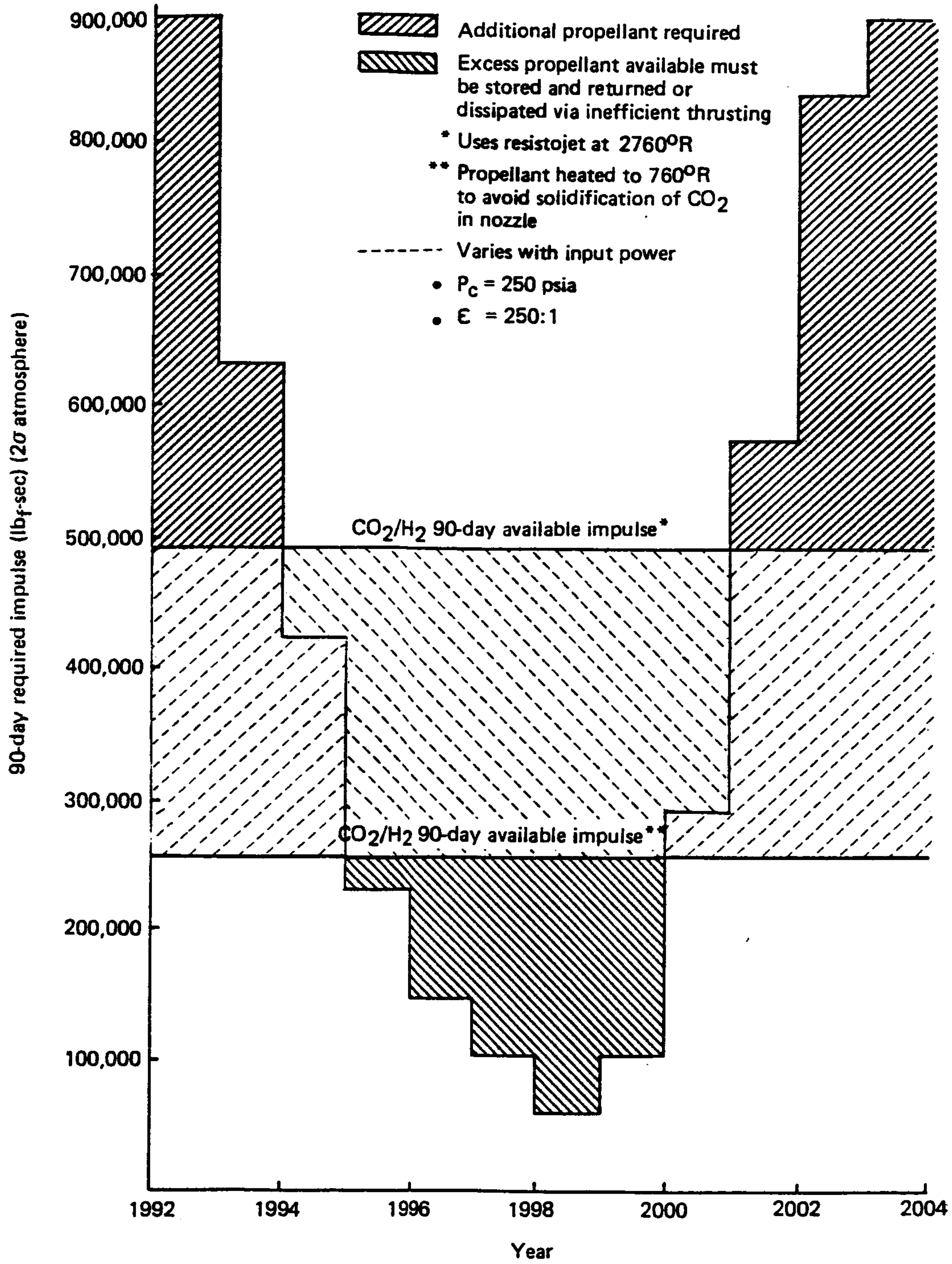


Figure 3-8. 90-Day Impulse Capability of Open CO_2 Loop Using EDC Effluents

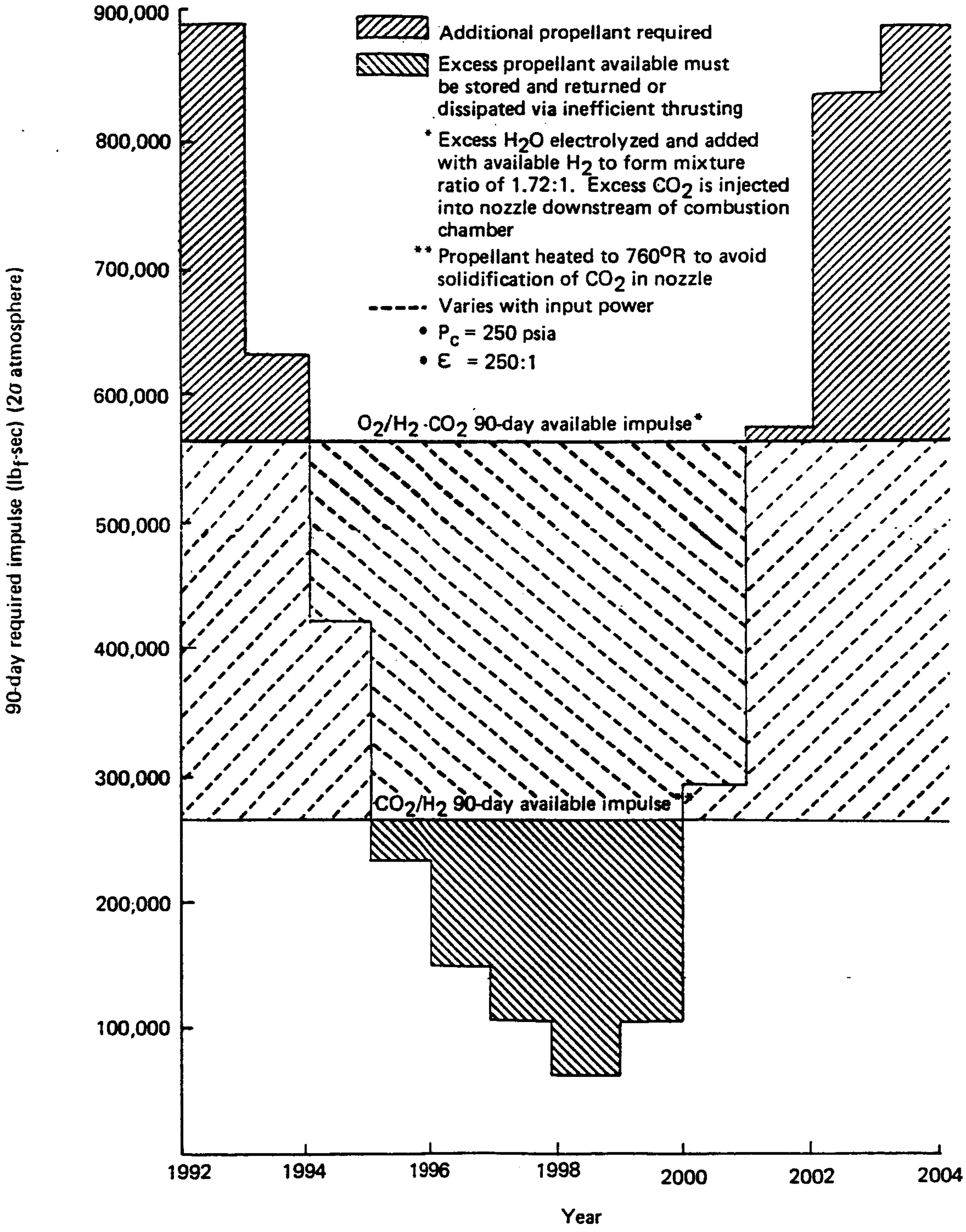


Figure 3-9. 90-Day Impulse Capability of Open CO_2 Loop Using SAWD Effluents

3.2 Continued

The subject system, though interesting, expecially for the higher impulse years and when O_2/H_2 primary propulsion is used, has significant problems not encountered by the Open CO_2 Loop system using EDC. These problems center on purity requirements for electrolysis water, higher power requirements for electrolysis and gas compression, gas storage weight and volume penalties, complex combustion - thruster system, and on an inability to reduce available impulse as easily as the Open CO_2 Loop system using EDC. However, in contrast to the CO_2/H_2 resistojet concept of the Open Loop - EDC, the O_2/H_2-CO_2 combustion jet concept does not require continuous or very long duration thrusting and can counteract much larger disturbances.

Figure 3-10 continues the comparison of required versus available impulse, for the Closed Loop Sabatier system. As can be seen, this system does not provide the available impulse of either Open Loop system. A maximum available 90-day impulse of about 210,000 lb_f-sec is all that can be attained using the CO_2/CH_4 effluents in a resistojet at 1800°R.

As shown, the maximum available impulse is less than the required impulse for all but 4 years of the 10-year 2-sigma cycle. During these deficient years primary propulsion is required to augment CO_2/CH_4 impulse capability. Two types of hydrazine thrusters were considered for this function. The first was a continuous low thrust level augmented catalytic thruster (ACT) using $N_2H_4/CO_2/CH_4$. The second was a periodically fired higher thrust level (25 lb_f) catalytic thruster using $N_2H_4/CO_2/CH_4$.

For the maximum impulse year of 1992, the ACT approach would require 2475 lbm of N_2H_4 every 90 days plus about 0.6 KW, and the catalytic thruster approach would require 3590 lbm of N_2H_4 every 90 days. This is in contrast to a straight N_2H_4 system in which 4096 lbm is required every 90 days and 990 lbm of CO_2/CH_4 must be compressed, stored and returned-to-earth every 90 days.

Only during the years 1997 through 1999 is there a small excess of CO_2/CH_4. This excess can be eliminated by once again operating the reboost cycle slightly inefficiently or allowing the station to drop to a lower altitude.

When compared to the nominal atmospheric model, the CO_2/CH_4 effluent can meet almost all of the impulse requirements over the 10-year mission. During the middle years there is excess CO_2/CH_4 available, however, this again can be eliminated by the techniques mentioned above.

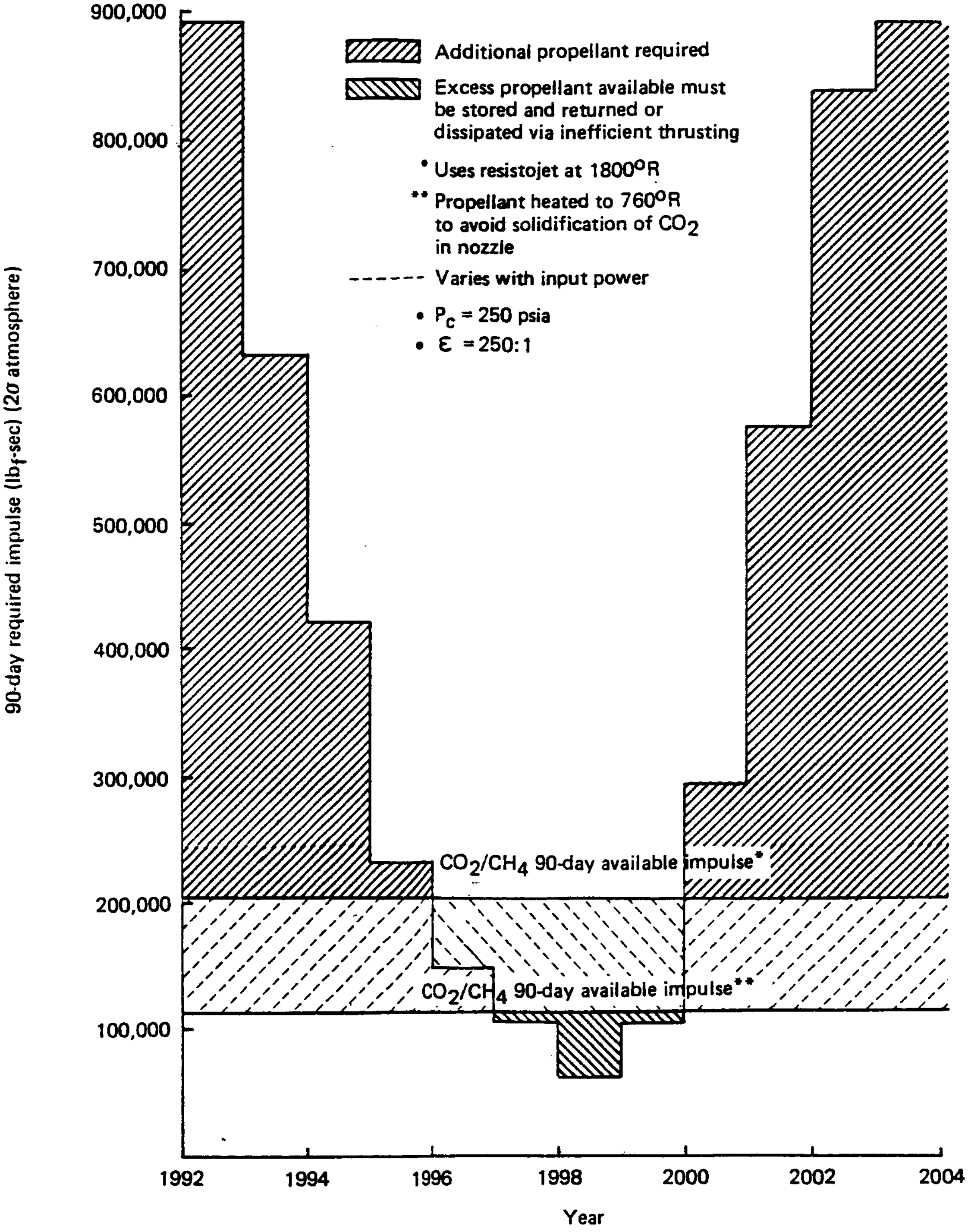


Figure 3-10. 90-Day Impulse Capability of Sabatier Effluents

3.2 Continued

Figure 3-11 shows the 90-day impulse capability for the Closed Loop - Bosch system. Like the Closed Loop - Sabatier, the Bosch maximum available impulse is significantly less than for Open Loop systems (233,000 lb_f-sec versus 500,000 lb_f-sec). It does supply enough impulse, however, to eliminate propellant resupply during the years 1995 through 1999 under the 2-sigma atmosphere.

Maximum impulse is generated by electrolyzing the 5.9 lbm/day excess water effluent, combining the resulting O_2 and H_2 with the 0.3 lbm/day excess H_2 effluent and then combusting/expanding the mixture in thrusters operating at a mixture ratio of 5.9:1. Minimum impulse is generated by using the excess water and H_2 in 960°R inlet temperature steam/H_2 thrusters.

For the nominal atmospheric conditions the Bosch effluents can meet all but three years of the 90-day impulse requirements between 1992 and 2003. During some of the middle years there is more than a sufficient amount of impulse available using a 960°R inlet temperature. Again this could be eliminated by the previously mentioned techniques.

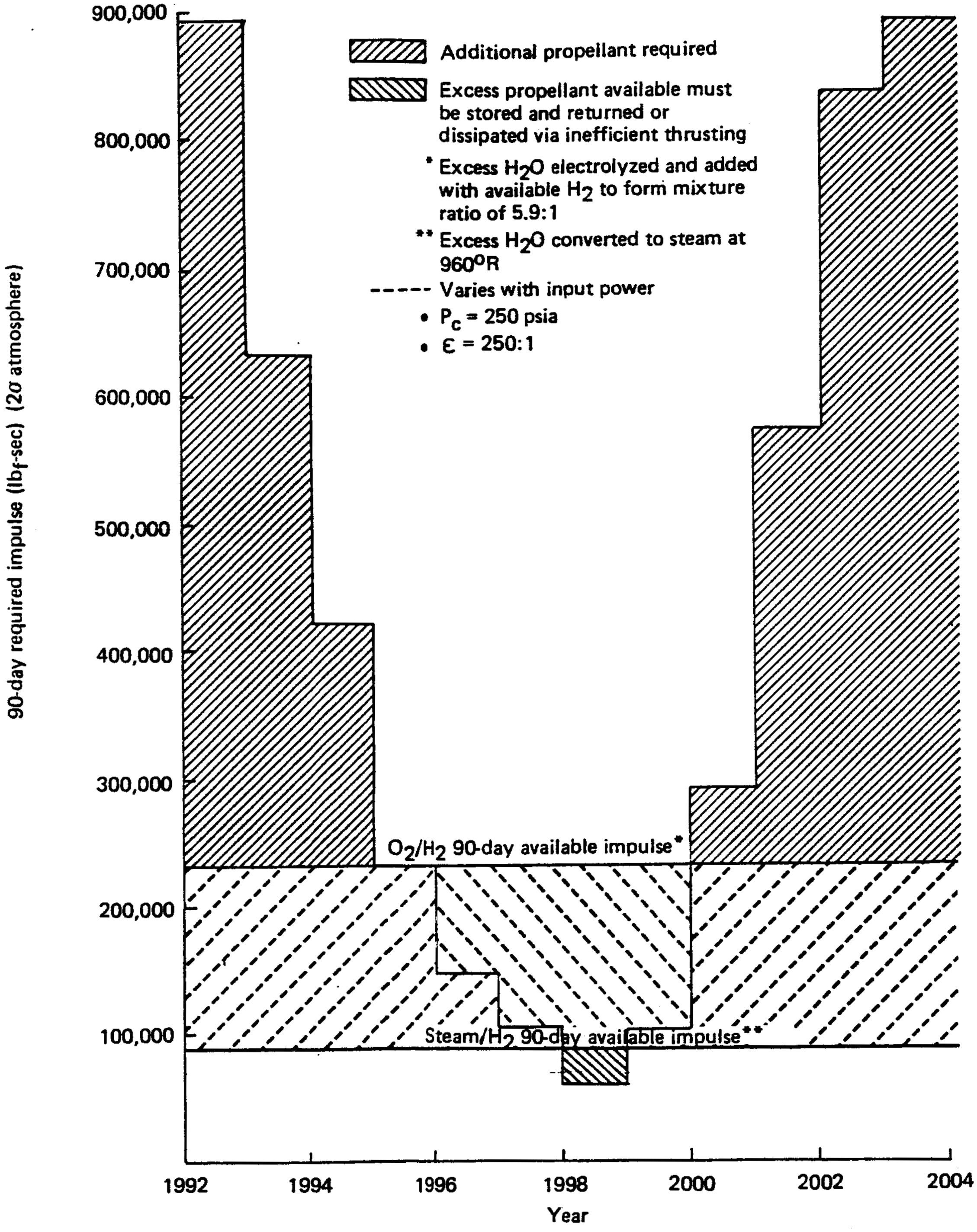


Figure 3-11. 90-Day Impulse Capability of BOSCH Effluents

3.3 Enhanced Total Impulse

In each of the four basic systems just discussed, no modification to the system material balance was made to improve propulsive performance. Of these four systems none could meet the 2-sigma impulse requirement during the initial and latter years of space station 10-year missions. However, all could meet or nearly meet the nominal impulse requirements. Hence, only during a peak period in which a 2-sigma atmosphere was experienced, would a system with significant enhanced impulse capability be required. In the system which is now discuss, a modification to the material balance is made for improved propulsive performance. This modification to the Closed Loop - Sabatier system involves no change in hardware concepts and only an increase in the water electrolysis unit sizing. In the modified Closed Loop Sabatier system, water in excess of that required for crew O_2 is electrolyzed to provide the additional H_2 needed to reduce all the CO_2 to CH_4, and to provide the O_2 for an O_2/CH_4 combustion jet.

Figure 3-12 shows the material balance of an ECLS system using Sabatier CO_2 reduction. This system requires 5.8 lbm/day of resupply water or 522 lbm every 90 days. For every 6.4 lbm/day of CH_4 generated, 10.4 lbm/day of O_2 is also generated. This corresponds to a mixture ratio of 1.625:1 and a total mass of 1512 lbm of O_2 and CH_4 generated every 90-days. At a chamber pressure of 250 psia and an expansion ratio of 250:1 a specific impulse of 341 lb_f-sec/lbm is attainable or a total impulse of 515,600 lb_f-sec every 90-days. Figure 3-13 illustrates this enhanced impulse capability. At mixture ratios less that 1.625:1 the CO_2 is no longer completely broken down. As the mixture ratio drops, more CO_2 is available until such a time when combustion is no longer possible. During these situations as long as the gases are heated to at lease 760°R then warm gas thrusters or resistojets can be used.

For mixture ratios above 1.625:1 excess H_2 is generated and hence the combustible mixture becomes $O_2/CH_4/H_2$. In order to meet the maximum 2-sigma impulse requirement of 894,000 lb_f-sec, 1256 lb_m of water needs to be electrolyzed every 90-days or 13.95 lbm/day. Figure 3-14 shows the material balance of such a system. In this system 17.65 lbm/day of O_2 are generated versus 6.4 lbm/day of CH_4 and 0.9 lbm/day of H_2. This correlates to a mixture ratio of O_2 to CH_4/H_2 of 1.72:1 or a specific impulse of 399 lb_f-sec/lbm. The effluent generated is 2241 lbm every 90-days. Figure 3-13 illustrates this maximum impulse capability.

To achieve impulses between 515,600 lb_f-sec and 894,000 lb_f-sec it is simply a matter of electrolyzing additional water. The mixture ratio will change and so will the amount

3.3 Continued

of generated effluent. The maximum power requirements of such a system is approximately 4kW to electrolyze the additional water. This much power solely for propulsion is excessive, however it only occurs during periods in which extra power may be available. During the initial years, all experiments may not be up and running until approximately eight resupply periods into the station life. During the latter years, more efficient solar dynamic collectors may be available instead of solar arrays.

This type of technique of modifying the ECLS system to generate additional effluent for higher impulse, though complicated, seems a credible concept and deserves further consideration and analysis.

3.4 Propulsion Systems Summary

Space Station propulsion system 90-day impulse requirements have been defined for a 2-sigma and nominal atmosphere. The first is used to design and size the propulsion system while second is used to estimate the expected propellant consumption and resupply schedule. For whichever propulsion systems is baselined for the station, in this case hydrazine, any of the four ECLS systems considered can generate sufficient quantities of effluent to satisfy nearly all of the nominal atmospheric 90 day impulse requirements. The next stage in this study is to try and determine which ECLS system, if any, benefits the most by reducing its fixed weight and volume and logistic weight and volume. This next section explains, in brief, the different methods of collecting and storing the effluents generated by the various ECLS systems whether they be used for propulsion or returned to earth.

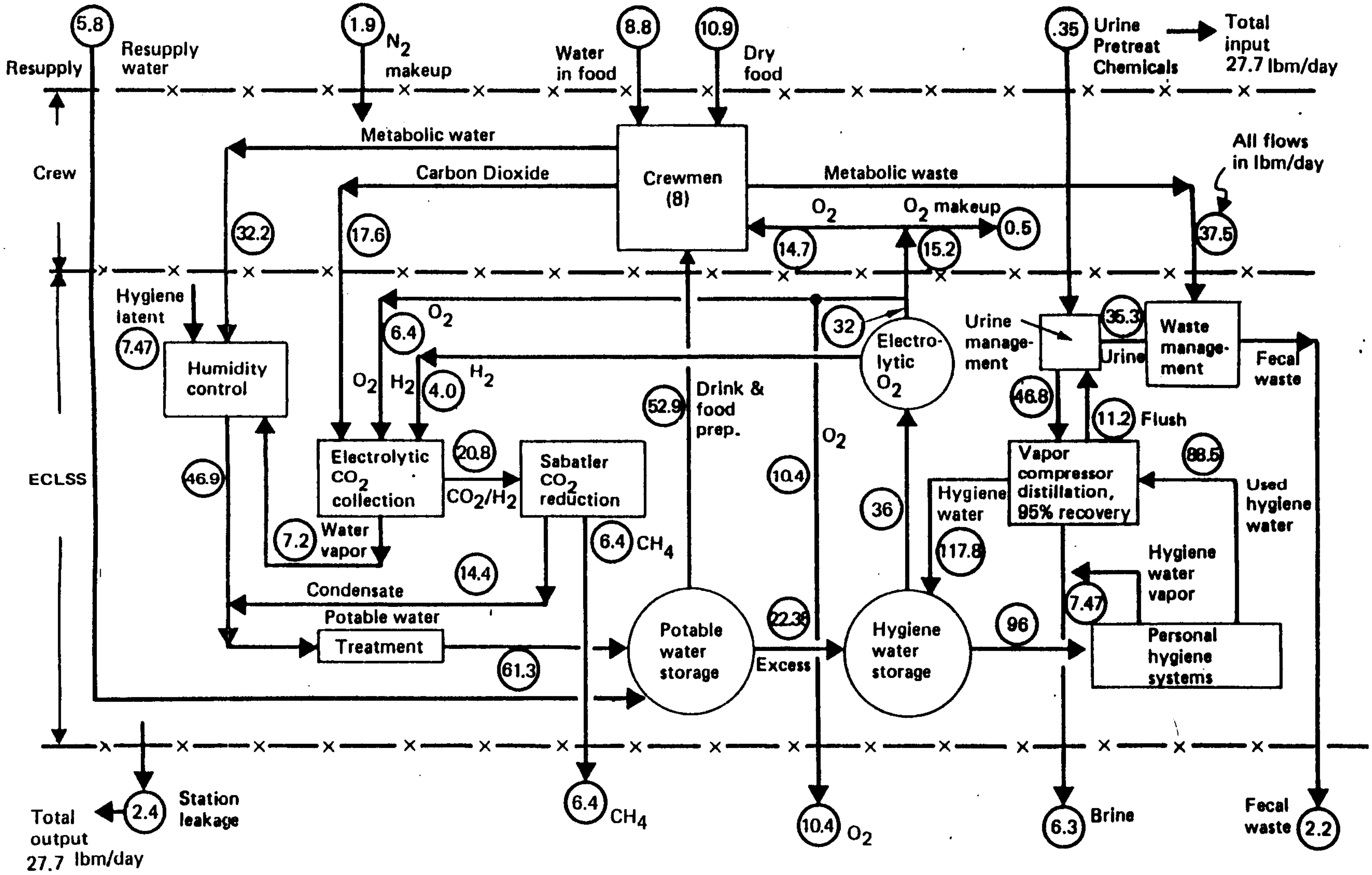


Figure 3-12. O_2/CH_4 Combustion Jet for Increased Impulse ECLSS Material Balance

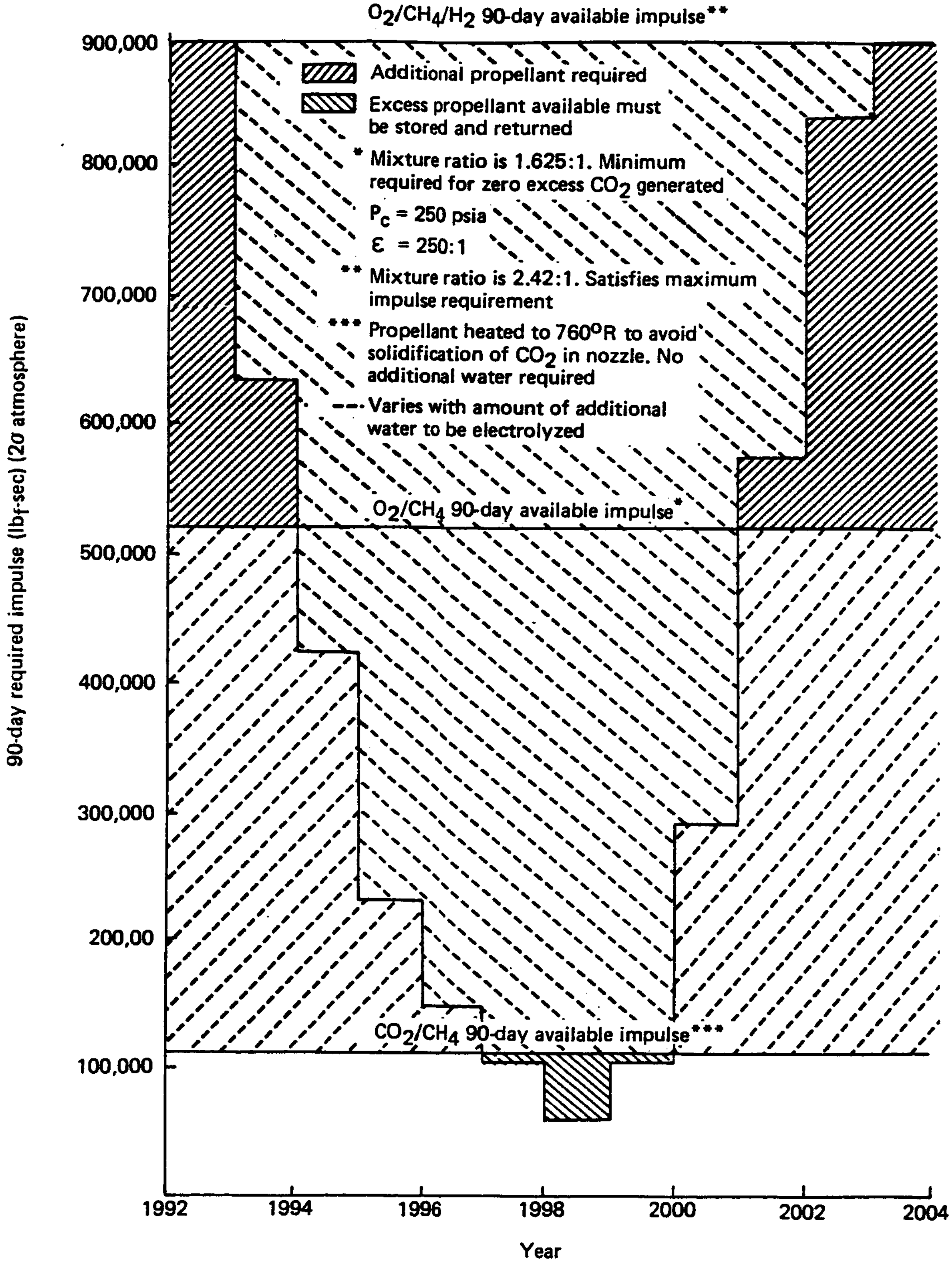


Figure 3-13. 90-Day Impulse Capability of a Sabatier System with Excess O_2 Generation for Enhanced Performance

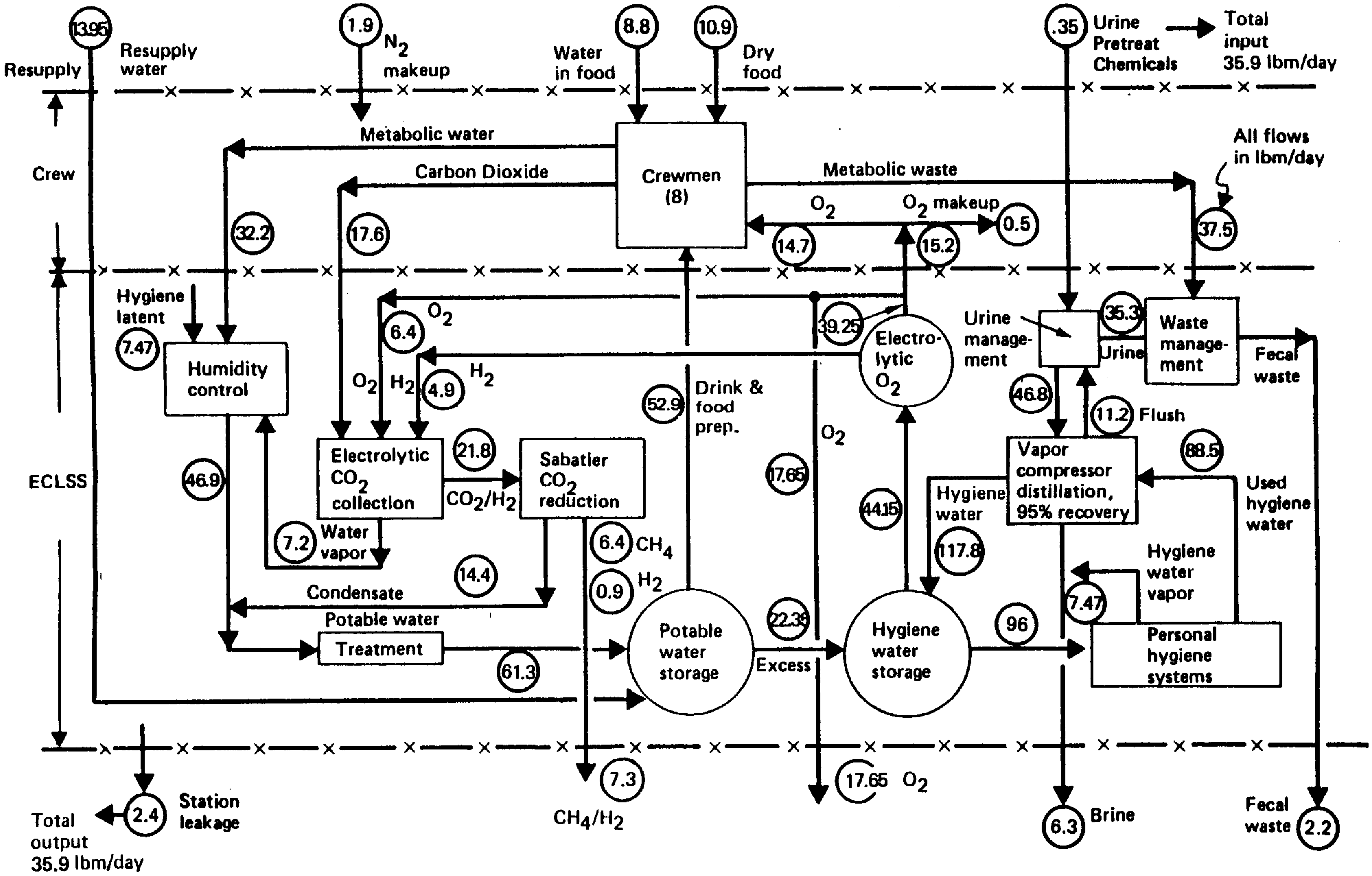


Figure 3-14. O_2/CH_4 Combustion Jet for Maximum Impulse ECLSS Material Balance

4.0 COLLECTION AND STORAGE

There are four options for the disposal of ECLSS gaseous effluents having a major impact on logistics: (l) vent them overboard (currently unacceptable), (2) collect, store and return them to earth at 90-day resupply periods, (3) collect and near continuously (on a daily basis or less) use effluents propulsively for drag makeup, and (4) collect, store and periodically use effluents propulsively for reboost.

For each of the above acceptable options, compression or compression and storage is required. Thus, before equipment can be sized, maximum compressor outlet pressure (equal to maximum tank pressure) must be selected. Selections of pressure were based on 1) the specific purpose of the effluent; 2) impact of pressure on compression power and tank weight/volume; and 3) engineering judgement. Thus for option 2, in which large quantities of gaseous effluents are compressed and stored for return to earth, a 3000 psia pressure was selected to provide for reasonable tank volumes and to achieve tank weight savings when highly non-ideal gases such as CO_2 are stored; for option 3, in which effluents are used on a daily basis or less in a 250 psia thruster, a 400 psia compressor outlet pressure was selected to account for line losses; and for option 4 in which gases are stored for only 10 days prior to use in a 250 psia thruster or gas generator, a 1000 psia pressure was selected to provide for reasonable tank volume weights.

For compression, a multistage compressor was used with intercooling between stages. Its characteristics and overall efficiency of 50% are based on a four-stage, flight-type, high pressure ratio, O_2 compressor designed by AirResearch. This design, though for somewhat larger flows than needed in this analysis, could be adapted to required flow requirements by returning proportional amounts of outlet flow to the compressor inlet.

The resulting tank volume and weights for ECLSS options are shown in tables 4-1 and 4-2 respectively. The tank weights are based on (1) the use of 2219 aluminum for O_2 storage, and 6 AL-4V titanium for the storage of all other gases, (2) spherical tanks, and (3) a factor of safety of 2.0 on the ultimate stress. At the bottom of table 4-1 is the respective flow rates, in lbm/day, of the various gas combinations from each of the ECLSS systems considered.

Alternatives to using metal tanks would be the use of composite tanks with aluminous or incone/liners and either a graphite or carbon overwrap. In addition to be lighter and cheaper to mass produce, they are also safer, since they do not explode at high pressures. This is important when storing high pressure gases such as oxygen and hydrogen.

Table 4-1 Storage and Accumulator Tank Volumes

PRESSURE (psia)	STORAGE AND ACCUMULATOR TANK VOLUMES, FT3																			
	SABATIER CO_2/CH_4	OPEN CO_2 LOOP (EDC) CO_2/H_2	OPEN CO_2 LOOP (SAWD)			BOSCH		BOSCH		Combustion Jet (Sabatier)		Combustion Jet (Sabatier)		Combustion Jet (EDC)		Combustion Jet (EDC)			Combustion Jet (Bosch)	
			CO_2	H_2	$H_2O_{(\ell)}$	$H_2O_{(\ell)}$	H_2	H_2	O_2	O_2	CH_4	O_2	CH_4/H_2	O_2	H_2	O_2	H_2	CO_2	O_2	H_2
14.7*	-	-	-	-	6.79	8.53	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1000**	22.4	90.6	14.9	75.7	-	-	11.9	38.2	12.2	24.1	27.4	41.0	63.2	44.6	171	31.2	142	14.9	51.1	109
3000***	24.4	213	27.9	185	-	-	29.2	-	-	-	-	-	-	-	-	-	-	-	-	-
Flow Rate (lbm/day)	11.0	19.5	17.6	1.90	4.70	5.90	0.30	0.96	5.24	10.4	6.4	17.65	7.30	19.2	4.30	13.4	3.58	17.6		

Table 4-2 Storage and Accumulator Tank Weights

PRESSURE (psia)	STORAGE AND ACCUMULATOR TANK WEIGHTS,**** lbm																			
	SABATIER CO_2/CH_4	OPEN CO_2 LOOP (EDC) CO_2/H_2	OPEN CO_2 LOOP (SAWD)			BOSCH		BOSCH		Combustion Jet (Sabatier)		Combustion Jet (Sabatier)		Combustion Jet (EDC)		Combustion Jet (EDC)			Combustion Jet (Bosch)	
			CO_2	H_2	$H_2O_{(\ell)}$	$H_2O_{(\ell)}$	H_2	H_2	O_2	O_2	CH_4	O_2	CH_4/H_2	O_2	H_2	O_2	H_2	CO_2	O_2	H_2
14.7*	-	-	-	-	15.3	17.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1000**	139.4	564	93.1	471	-	-	74.3	238	129	254	171	434	393	472	1064	330	886	93.1	540	680
3000***	455	3975	519	3453	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* 90-day storage and return of water only

** 10-day storage for use in propulsion only, 33% contingency added

*** 90-day storage and returjn of ECLS effluent not used for propulsion

**** All tanks containing O_2 use 2219 Alum, all other tanks use 6AL-4V Titanium

5.0 LOGISTICS

There are nineteen ECLS propulsion concepts that are described and analyzed in this section. Tables 5-1 a, b, and c summarize the fixed weight and volume, power and its equivalent weight, and logistics weight and volume up/down of these eighteen options for 1992 90-day impulse requirements. Table 5.1a summarizes the propulsion systems, table 5-1c summarizes the ECLS systems and table 5-1c summarizes the combination of the propulsion and ECLS systems. The fixed weight and volume, power and its equivalent weight have been discussed in previous sections. This section will deal primarily with logistics and the input it plays in trying to choose the best systems.

Logistics is a key factor in the evaluation and selection of an ECLSS and/or propulsion system due to shuttle constraints, difficulties/penalties associated with transferring equipments and fluids to/from the Shuttle, and transportation costs. In this study, only logistic weight and volume requirements for each of the eighteen options were defined so that future analyses regarding Shuttle constraints, equipment/fluid transfer and cost could be made.

For all options, the propulsion logistics weight up consist of the propellant (hydrazine or water), tanks, and thrusters. The thrusters are assumed to be replaced with the propulsion modules. The weight down consists of the emptied propellant tanks and the thrusters. The volume up and down consists of either four hydrazine modules (figure 5-1) or the water tank(s).

Also for all options, the ECLS logistics weight up consists of resupply water, water tank, and effluent storage tank(s) when the effluent is to be returned to earth. The logistics weight down consists of the water tank, effluent storage tank(s) and effluent when the effluent is not used for propulsion. The logistics volume up and down includes the water tank(s) and effluent storage tank(s) when the effluent is not used for propulsion.

To simplify the following discussion regarding logistics, alpha-numeric designations for options instead of the system combination name will be used. These are given in the first column of Tables 5-la, b, and c.

Table 5-1a ECLS - Propulsion System Comparisons (Propulsion)

SYSTEM				PROPULSION [1]								
ECLS	Options	Propulsion		Equipment		Power		Fixed & Equiv. Wt., lbm	Logistics			
		Thruster	Propellant	Fixed weight, lbm	Volume, ft³	Power required, kW	Power & Thermal Equiv. Wt, lbm		Weight up, lbm	Weight down, lbm	Volume up, ft³	Volume down, ft³
Open CO_2 Loop (EDC)	1A	CAT*	N_2H_4*	526	292	0	0	526	4,590	526	292	292
	1B	RES**	N_2H_4*	442	257	.62	366	808	3,524	442	257	257
	1C	CAT	$N_2H_4/CO_2/H_2$	② 992	② 342	.17	121	1,113	3,350	427	251	251
	1D	RES	$N_2H_4/CO_2/H_2$	③ 283	③ 182	.83	505	788	1,670	282	182	182
	1E	COMB***	O_2/H_2**	② 1,967	② 253	4.24	1,175	3,142	2,189	242	31.3	31.3
	1F	COMB	$O_2/H_2/CO_2$	② 1,901	③ 240	3.56	1,009	2,910	1,877	237	26.3	26.3
Open CO_2 loop (SAWD)	2A	CAT	$N_2H_4/CO_2/H_2$	② 992	② 342	.17	121	1,113	3,350	427	251	251
	2B	RES	$N_2H_4/CO_2/H_2$	③ 283	③ 182	.83	505	788	1,670	282	182	182
	2C	COMB	$O_2/H_2/CO_2$	② 1,901	② 240	3.56	1,009	2,910	1,870	230	19.6	19.6
SABATIER CO_2 Reduction	3A	CAT	N_2H_4*	526	292	0	0	526	4,590	526	292	292
	3B	RES	N_2H_4*	442	257	.62	366	808	3,524	442	257	257
	3C	CAT	$N_2H_4/CO_2/CH_4$	② 624	② 298	.05	35.9	660	4.071	485	276	276
	3D	RES	$N_2H_4/CO_2/CH_4$	③ 387	③ 233	.61	364	751	2,862	387	233	233
	3E	C + C****	$N_2H_4/CO_2/CH_4$	② 998	② 259	2.31	663	1,661	2,775	533	208	208
	3F	COMB	$O_2/CH_4/H_2$	② 1,164	② 185	3.96	1,147	2,311	1,487	231	20.2	20.2
BOSCH CO_2 Reduction	4A	CAT	N_2H_4/H_2	② 595	② 302	.02	14.2	609	4,550	521	290	290
	4B	RES	N_2H_4/H_2	③ 435	③ 254	.65	385	820	3,462	435	254	254
	4C	RES	$N_2H_4/Steam/H_2$	③ 393	③ 257	.74	437	830	2.954	393	236	236
	4D	COMB	O_2/H_2	② 664	② 193	2.83	787	2,451	1,925	259	26.8	26.8

* Catalytic Thruster (CAT)+
** Resistojet (RES)
*** Combustion Jet (COMB)+
**** Catalytic Thruster and Combustion Jet (C + C)+ + 10-day thrusting interval

[1]
- Fixed weight and volume = Propellant tanks + effluent tanks + thrusters + O_2 unit (when applicable)
- Power = Resistojet + compressor + O_2 unit (when applicable)
- Equivalent weight = Resistojet + compressor + O_2 unit
- Logistics weight up = Propellant + tanks + thrusters
- Logistics weight down = Propellant tanks + thrusters
- Logistics volume up and down = Hydrazine module or water tanks
- Hydrazine systems consist of four modules:
  - 12 thrusters per module { 6 - 25 lb_f thrusters, 6 resistojets (< 1 lb_f)
  - 4 propellant tanks per module
- Combustion systems consist of:
  - 12 thrusters per module { 6 - 25 lb_f thrusters, 6 resistojets (< 1 lb_f)
  - 4 propellant tanks per module

FOOTNOTES:

① Effluent stored at 3000 psia for 90 days

② Propellant stored at 1000 psia for 10 days

③ Propellant compressed to 400 psia, continuous thrusting, no storage tanks

④ CO_2 storage only, H_2 redistributed to propulsion

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Table 5-1b ECLS - Propulsion System Comparisons (ECLSS)

SYSTEM				ECLS [2]								
		Propulsion		Equipment		Power			Logistics			
ECLS	Options	Thruster	Propellant	Fixed weight, lbm	Volume, ft³	Power required, kW	Power & Thermal Equiv. Wt, lbm	Fixed & Equiv. Wt., lbm	Weight up, lbm	Weight down, lbm	Volume up, ft³	Volume down, ft³
Open CO_2 Loop (EDC)	1A	CAT*	N_2H_4*	① 7,227	237	4.76	1,734	8,971	① 7,546	① 8,536	① 225	① 225
	1B	RES**	N_2H_4*	① 7,227	237	4.76	1.734	8,971	① 7,546	① 8,536	① 225	① 225
	1C	CAT	$N_2H_4/CO_2/H_2$	484	23.6	4.38	1.469	1,953	788	22.7	12.3	12.3
	1D	RES	$N_2H_4/CO_2/H_2$	484	23.6	4.38	1.469	1,953	788	22.7	12.3	12.3
	1E	COMB***	O_2/H_2**	①④ 1,003	51.5	4.38	1,469	2,472	①④ 1,307	①④ 2,126	①④ 40.2	①④ 40.2
	1F	COMB	$O_2/H_2/CO_2$	484	23.6	4.38	1,469	1,953	788	22.7	12.3	12.3
Open CO_2 loop (SAWD)	2A	CAT	$N_2H_4/CO_2/H_2$	458	42.5	5.25	1.863	2,321	1,234	469	25.9	25.9
	2B	RES	$N_2H_4/CO_2/H_2$	458	42.5	5.25	1,863	2,321	1,234	469	25.9	25.9
	2C	COMB	$O_2/H_2/CO_2$	442	35.7	5.25	1,863	2,305	1,218	30.4	19.1	19.1
SABATIER CO_2 Reduction	3A	CAT	N_2H_4*	① 1,093	56.2	4.49	1,762	2,855	① 455	① 1,455	① 1,455	① 1,455
	3B	RES	N_2H_4*	① 1,093	56.2	4.49	1.762	2,855	① 455	① 1,455	① 1,455	① 1,455
	3C	CAT	$N_2H_4/CO_2/CH_4$	638	31.8	4.38	1,686	2,324	0	0	0	0
	3D	RES	$N_2H_4/CO_2/CH_4$	638	31.8	4.38	1,686	2,324	0	0	0	0
	3E	C + C****	$N_2H_4/CO_2/CH_4$	638	31.8	4.38	1,686	2,324	0	0	0	0
	3F	COMB	$O_2/CH_4/H_2$	638	31.8	4.38	1,686	2,324	0	0	0	0
BOSCH CO_2 Reduction	4A	CAT	N_2H_4/H_2	1,475	147	4.51	1,977	3,463	378	1,341	53.5	53.5
	4B	RES	N_2H_4/H_2	1,475	147	4.51	1,977	3,463	378	1,341	53.5	53.5
	4C	RES	N_2H_4/Steam/H_2	1,457	138	4.51	1,977	3,434	360	792	45.0	45.0
	4D	COMB	O_2/H_2	1,457	138	4.51	1.977	3,434	360	792	45.0	45.0

* Catalytic Thruster (CAT)⁺
** Resistojet (RES)
*** Combustion Jet (COMB)⁺
**** Catalytic Thruster and Combustion Jet (C + C)⁺ + 10 -day thrusting interval

[2]
- Fixed weight and volume = O_2 unit + EDC (or SAWD) + SABATIER (or BOSCH) (when applicable) + storage tanks + water resupply tanks
- Power = O_2 unit + EDC (or SAWD) + SABATIER (or BOSCH) + compressor (when returning effluent to earth every 90 days)
- Equivalent weight = EDC (or SAWD) + SABATIER (or BOSCH) + compressor + thermal cooling
- Logistics weight up = Resupply water + water tank + storage tanks (when used to return effluent)
- Logistics weight down = Water tank + storage tank(s) + e ffluent (when not used for propulsion)
- Logistics volume up and down = Water tank + storage tank(s)

FOOTNOTES:

① Effluent stored at 3000 psia for 90 days

② Propellant stored at 1000 psia for 10 days

③ Propellant compressed to 400 psia, continuous thrusting, no storage tanks

④ CO_2 storage only, H_2 redistributed to propulsion

Table 5-1c ECLS - Propulsion System Comparisons (Total)

SYSTEM				TOTAL						
ECLS	Options	Propulsion		Equipment volume, ft^3	Power, kW	Fixed & Equiv. Wt., lbm	Logistics			
		Thruster	Propellant				Weight up, lbm	Weight down, lbm	Volume up, ft^3	Volume down, ft^3
Open CO_2 Loop (EDC)	1A	CAT*	N_2H_4*	529	4.76	9,497	12,140	9,062	517	517
	1B	RES**	N_2H_4*	494	5.38	9,779	11,070	8,978	482	482
	1C	CAT	$N_2H_4/CO_2/H_2$	366	4.55	3,066	4,138	450	263	263
	1D	RES	$N_2H_4/CO_2/H_2$	206	5.21	2,741	2,458	305	194	194
	1E	COMB***	O_2/H_2**	305	8.62	5,614	3,496	2,368	71.5	71.5
	1F	COMB	$O_2/H_2/CO_2$	264	7.94	4,863	2,665	260	38.6	38.6
Open CO_2 loop (SAWD)	2A	CAT	$N_2H_4/CO_2/H_2$	385	5.42	3,434	5,671	896	277	277
	2B	RES	$N_2H_4/CO_2/H_2$	225	6.08	3,109	2,904	751	208	208
	2C	COMB	$O_2/H_2/CO_2$	276	8.81	5,215	3,088	260	38.7	38.7
SABATIER CO_2 Reduction	3A	CAT	N_2H_4*	348	4.49	3,381	5,045	1,971	316	316
	3B	RES	N_2H_4*	313	5.11	3,663	3,979	1,887	281	281
	3C	CAT	$N_2H_4/CO_2/CH_4$	330	4.43	2,984	4,071	485	276	276
	3D	RES	$N_2H_4/CO_2/CH_4$	265	4.99	3,075	2,862	387	233	233
	3E	C + C****	$N_2H_4/CO_2/CH_4$	291	6.69	3,985	2,775	533	208	208
	3F	COMB	$O_2/CH_4/H_2$	217	8.34	4,635	1,487	231	20.2	20.2
BOSCH CO_2 Reduction	4A	CAT	N_2H_4/H_2	449	4.53	4,072	4,928	1,862	344	344
	4B	RES	N_2H_4/H_2	401	5.16	4,283	3,840	1,776	308	308
	4C	RES	N_2H_4/Steam/H_2	395	5.25	4,264	3,314	1,185	281	281
	4D	COMB	O_2/H_2	331	7.34	5,885	2,285	1,052	71.8	71.8

* Catalytic Thruster (CAT) +

** Resistojet (RES)

*** Combustion Jet (COMB) +

**** Catalytic Thruster and Combustion Jet (C + C) + + 10 -day thrusting interval

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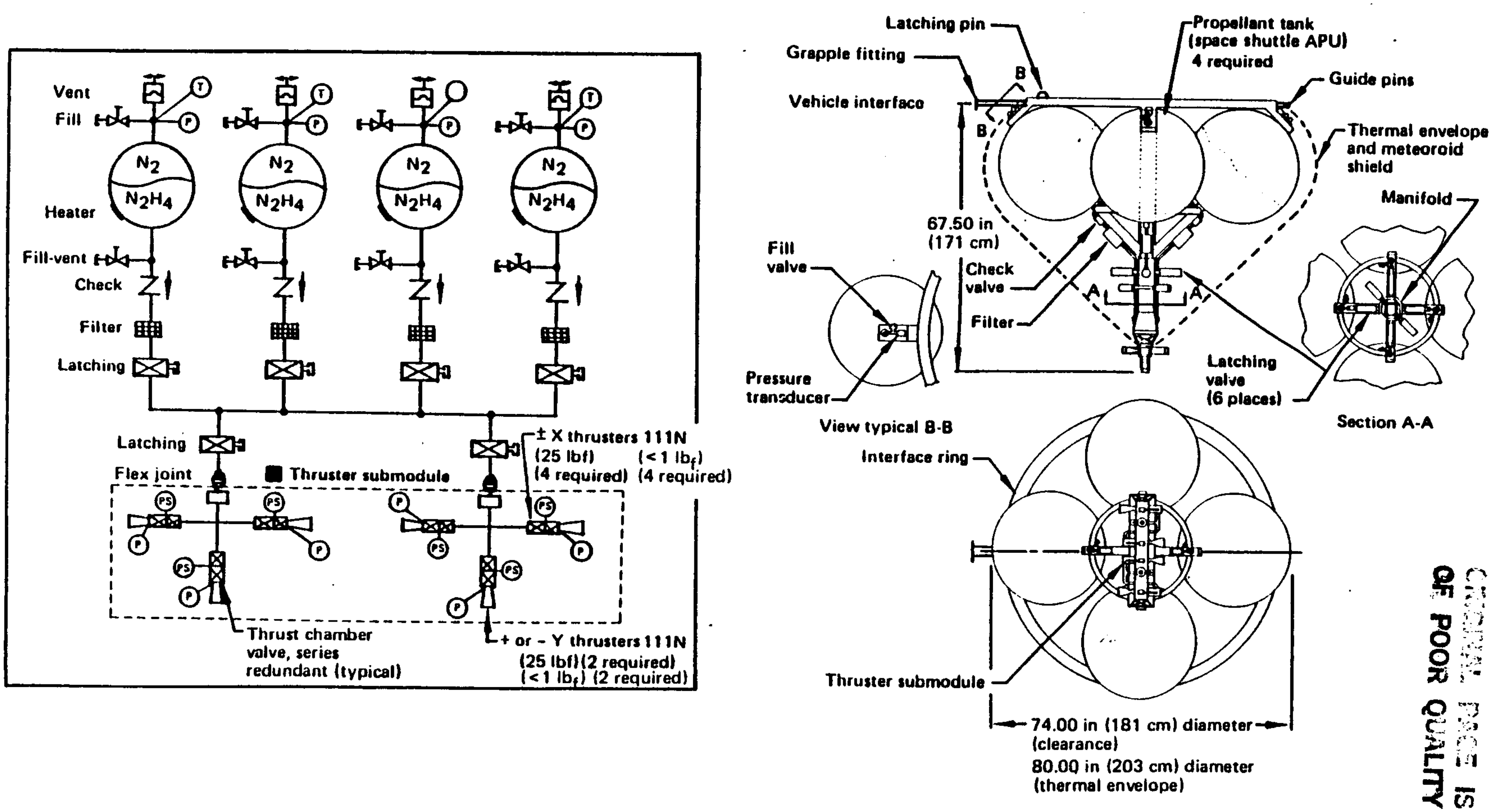
■ Propulsion Module Schematic

■ Propulsion Module Hardware Arrangement

Figure 5-1 Modular Propulsion System—Four Required for Station

In option 1A, the CO_2/H_2 effluent generated by the ECLS system is compressed to 3000 psia, stored for 90-days and then returned to earth, since there is zero commonality between the ECLS and propulsion systems. Because of this lack of commonality, the propulsion logistic weight requirements "up" are largely due to the amount of hydrazine resupply (see table 5-2) and the ECLS logistics weight "up" and "down" are largely due to the weight of a 90-day storage tank with (logistics "down") or without (logistics "up") 171 lbm of gaseous H_2 and 1584 lbm of CO_2. Corresponding volumes are also large. It should be reiterated that the propulsion propellant requirements in this study are only for reboost and do not include altitude control, collision avoidance, CMG desaturation, docking disturbances, or emergencies. Although, should these be included, they would require approximately 500,000 lb_f-sec of impulse. Half of this would be for altitude control and would need replenishing every 90-days. The remainder is contingency which is used infrequently (if at all).

It should be noted that in these cases (1A, 1B, 3A and 3B respectively), where no commonality exists between the ECLS and propulsion system and the effluent is returned to earth, where the ECLSS effluent and effluent storage tanks are charged to ECLSS logistics. For all other cases the effluent storage tanks are included in the propulsion system fixed weight and volume.

Option 1B is similar to 1A except that resistojets are used in place of the 25-lb_f catalytic thrusters (CAT) in 1A. More power is used (.62KW) but also considerably less logistics "up" is required per 90 days (1000 lbm). This results directly from the difference in specific impulse between an ACT and a CAT (290 sec vs. 220 sec).

In option 1C the ECLSS effluent of CO_2/H_2 is compressed to 1000 psia, stored for 10 days and then used propulsively in the 25 lb_f N_2H_4 catalytic thrusters. Since no combustion occurs between the CO_2/H_2 and N_2H_4 a weighted total impulse was used based on the total impulse of the available CO_2/H_2 and the total impulse of the N_2H_4 used to meet 90-day impulse requirements. This method was used for all options where the ECLSS effluent did not combust with the primary propellant. It is a simple method, providing sufficient accuracy for a scoping study such as this one. By using the CO_2/H_2 effluent, the logistics up/down weights per 90-days are dramatically reduced from those of option 1A or 1B.

For option 1C, the logistic "up" mass is reduced by over 6000 lbm and the logistic "down" mass by close to 9000 lbm. Similar dramatic changes occur in volume "up/down". The reason for this dramatic change is directly attributable to the change from the 90-day storage/return-to-earth in 1A and 1B to the 10-day storage with no return to earth of effluents in 1C.

Option 1D is similar to 1C except that it uses continuous resistojet (290 sec I_{sp}) thrusting rather than periodic catalytic (220 sec I_{sp}) thrusting. This increases the power required for thrusting, reduces the power required for compression (400 psia vs. 1000 psia), eliminates effluent storage tanks, and reduces propellant requirements. Consequently the power is higher (.66KW), the fixed weight lower by 1000 lbm, the logistics "up" mass lower by 1600 lbm and the logistics "down" mass about the same. Volumes "up/down" are also lower by about 25%.

In Options 1E and 1F, a centralized O_2/H_2 propulsion system rather than a modular N_2H_4 system is used to meet 1992 impulse requirements. In 1E only O_2/H_2 is used whereas in 1F an $O_2/H_2/CO_2$ propellant is used. In both cases the propulsion system is tied to the ECLSS: i.e. by the use of O_2 and H_2 from the ECLSS Water Electrolysis Subsystem (WES) in 1E, and by the use of O_2 and H_2 from the WES in combination with CO_2 from the EDC in 1F. Of the two options, 1F is superior in all the categories of interest, i.e. fixed weight/volume, power, and logistic weight/volume both up and down. This results from the use of ECLSS CO_2 as a propellant during the thrusting periods at 10 day intervals. By so doing, the 90-day CO_2 storage/return-to-earth requirement and associated tankage in 1E is converted to a 10-day storage requirement and associated tankage.

For both cases fixed weight/volume and logistic weight/volume are considerably less than options 1A and 1B. They, however, do not exhibit the same across the board superiority when compared with 1C and 1D. In comparison with 1C and 1D, their fixed plus equivalent weights are considerably higher due to the weight penalty associated with greater WES power. Option 1E, furthermore, has a considerably greater logistic "down" mass than either 1C or 1D because of its 90-day CO_2 storage/return-to-earth requirement and a somewhat higher logistics "up" mass than 1D.

Options 2A through 2C are similar to options 1C, 1D and 1F respectively. The only difference being in the ECLS portion of the system combinations where a SAWD with its greater water useage, rather than an EDC CO_2 concentrator, is used. This results in somewhat greater logistics "up" weight (10 to 15%), about the same logistic "down" weight, about the same logistic up/down volumes, and slightly greater power (20%) than those for options 1C, 1D and 1F.

Options 3A and 3B are similar to 1A and 1B in that the effluent from the ECLSS is not used propulsively. They instead use a modular N_2H_4 system for propulsion with no tie-in to the ECLSS. They are different from 1A and 1B in that they use a Sabatier subsystem to reduce about 60% of the CO_2 to CH_4 and H_2O vapor. The effluent mixture of unreacted CO_2 and CH_4 is then, based upon the study groundrules for effluent not used in propulsion, compressed to 3000 psia, stored and returned to earth every 90-days. Because of this, logistic up-down weight and volume is considerably greater than it is for systems in which the CO_2, CO_2/H_2, or CO_2/CH_4, are used propulsively in combination with a primary propellant (N_2 H_4 or O_2/H_2). However, its logistics requirements and fixed plus equivalent weights are still very much less than those of 1A and 1B primarily because there is less effluent to store.

Option 3C as in 1C or 2A use the effluent from the ECLSS in the propulsion system, thereby reducing 90-day propellant resupply requirements and eliminating the need to store/return-to-earth ECLSS effluents every 90-days. As in 1C, the effluent is compressed to 1000 psia and stored for 10-days before being mixed with decomposed N_2H_4 and expelled propulsively.

The total impulse of the available CO_2/CH_4 is less than the total impulse of the available CO_2/H_2 in 1C or 2A, thus N_2H_4 resupply is greater (3934 lbm vs. 3238 lbm). However, since the ACT thrusters operate only when the ECLS air revitalization system (ARS) operates no storage tanks are required. Instead the CO_2/CH_4 effluent from the Sabatier subsystem is continuously compressed whenever the ARS is operating to 400 psia and routed to the ACT thrusters.

Option 3D has the same relationship to 3C, as 1D has to 1C, i.e. identical ECLSS and propulsion systems which primarily differ because of the types of thruster used. In 3D, as in 1D, they are very low thrust N_2H_4 augmented catalytic thrusters (ACT) operating whenever the ARS of the ECLSS is operating, whereas in 3C they are 25 lb_f N_2H_4 catalytic thrusters (CAT). Option 3D therefore does not require the storage tanks used in 1C or 3C for 10-day effluent storage. Because of this, and because the ACT has considerably greater specific impulse than CAT when it uses resistance heating to heat both the decomposed N_2H_4 and the ECLSS effluents (2460°R for $N_2H_4/CO_2/H_2$ and 1800°R for $N_2H_4/CO_2/CH_4$ as in 1D, 2B and 3D, the 90-day logistics "up" mass is about 1200 lbm less than 3C, the logistic "down" mass about 15% less, and the logistic up/down volume about 15% less.

Options 3E and 3F examined a different approach to supplying additional impulse for propulsion. In this approach the Closed Loop - Sabatier which normally does not require water resupply, does require water resupply every 90-days. This excess water, i.e. water not needed for crew O_2, is used to generate the O_2 oxidizer, and the H_2 needed to reduce all the CO_2 to a CH_4 fuel for either an O_2/CH_4 combustion jet (3E) or an $O_2/CH_4/H_2$ combustion jet (3F).

In Option 3E, 522 lbm of water are used every 90-days to reduce all the crew generated CO_2 to CH_4. The resulting propellants of O_2 and CH_4 are then separately stored at 1000 psia prior to their useage in a combustion jet at 10-day intervals. This results in a specific impulse of 340 seconds (O_2/CH_4 of 1.625:1) and a 90-day impulse of 516,000 lb_f-sec.

For the additional impulse of 378,000 lb_f-sec needed to meet 1992 impulse requirements either a separate N_2H_4 system was used (Option 3E) or an extension of the above described combustion jet system was used (Option 3F).

In 3F, O_2 and H_2 from the electrolysis of water in excess of that required to provide for the complete reduction of CO_2 is after storage at 1000 psia used in an $O_2/CH_4/H_2$ combustion jet at 10-day intervals. This results in a specific impulse of 390 seconds ($O_2/CH_4/H_2$ of 2.42:1).

Each of the options is superior to their counterparts, i.e. 3E of all N_2H_4 or N_2H_4 combination options provides for the lowest logistic penalties and 3F of all O_2/H_2 or O_2/H_2 combination options provides for the lowest logistic penalties. Both require considerably more power than the thirteen options not using water electrolysis for supplying propellants. They furthermore have somewhat greater fixed plus equivalent weights due to the combustion jet system and the weight penalty for water electrolysis power.

The final four options 4A, 4B, 4C and 4D in use a Closed Loop - Bosch ECLSS in conjunction with either a N_2H_4 propulsion system using either H_2 or steam/H_2 injection or an O_2/H_2 propulsion system (4D) using both the excess water and H_2. Approximately 0.3 lbm/day of H_2 and 4.8 lbm/day of H_2O are available from the Bosch for augmenting the primary propulsion systems used in these options.

In Option 4A, the excess H_2 from the Bosch is stored at 1000 psia between the 10-day firing intervals, then used along with the primary N_2H_4 propellant in catalytic thrusters (CAT). Option 4B also only uses the excess H_2 from the Bosch to augment the primary N_2H_4 propulsion system. However, in 4B, as for all other cases using a combination propellant system with augmented catalytic thrusters (ACT), no storage of H_2 is required (thrusting is continuous when ARS operates), the specific impulse of the propellants is greater than for CAT, and the power requirement is greater than for CAT. As a consequence, logistic requirements are less for 4B vs. 4A but fixed weight plus equivalent weight for power and thermal cooling is greater.

Because Options 4A and 4B only make propulsive use of the small amount of H_2 available (excess H_2O is returned to earth), their N_2H_4 resupply requirements are nearly the same as 1A, 1B, 3A, and 3B. Overall, options 4A and 4B are comparable to options 3A and 3B logistically and in the use of power.

In Option 4C, the excess H_2 and water from the Bosch are used as propellants in augmented catalytic thrusters. Thus again as in 4B no storage of augmenting propellants is required. By using the H_2O and H_2 for augmenting primary N_2H_4 propulsion, a reduction in resupplied N_2H_4 of about 500 lbm from that needed in option 4B is realized. As a consequence of this propellant resupply and the elimination of water storage/return-to-earth, all logistic penalties are lower for 4C vs. 4B.

Option 4D utilizes the excess water and H_2 from the BOSCH to augment an O_2/H_2 water electrolysis propulsion system. In this system the excess water is electrolyzed with water resupplied from the ground for propulsion and then added with the excess H_2. This combination yields a mixture ratio of 7.2:1 and generates a specific impulse of approximately 402 lb_f-sec/lbm. During the 1992 2-sigma impulse year 1666 lbm of water are required for resupply and 2.83 kW of power for electrolysis and compression of the gases.

This option has the second lowest logistics requirements of all the options considered. Only option 3F is lower. However, option 3F has a higher power requirement by approximately 1.1 kW.

Tables 5-2 and 5-3 provide an overview of hydrazine and/or water resupply for propulsion, and the maximum resupply interval for each of the 19 options just discussed over the years from 1992 through 2002.

Table 5-2 Hydrazine and/or Water for 90-Day Impulse Requirements, + lbm

SYSTEM				YEAR										
ECLS	Options	Propulsion												
		Thruster	Propellant	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Open CO_2 Loop (EDC)	1A	CAT	N_2H_4*	4,060	2,860	1,870	1,060	673	459	282	459	1,340	2,610	3,820
	1B	RES	N_2H_4*	3,080	2,170	1,420	803	510	348	214	348	1,020	1,980	2,900
	1C	CAT	N_2H_4* CO_2/H_2	2,920	1,720	732	0	0	0	0	0	200	1,470	2,680
	1D	RES	N_2H_4* CO_2/H_2	1,390	478	0	0	0	0	0	0	0	288	1,200
	1E	COMB	O_2/H_2**	1,950	1,330	825	422	220	112	25	112	558	1,200	1,820
	1F	COMB	O_2/H_2-CO_2**	1,640	1,030	523	0	0	0	0	0	0	898	1,510
SABATIER CO_2 Reduction	3A	CAT	N_2H_4*	4,060	2,860	1,870	1,060	673	459	282	459	1,340	2,610	3,820
	3B	RES	N_2H_4*	3,080	2,170	1,420	803	510	348	214	348	1,020	1,980	2,900
	3C	CAT	N_2H_4* CO_2/CH_4	3,590	2,390	1,400	582	195	0	0	0	864	2,140	3,340
	3D	RES	N_2H_4* CO_2/CH_4	2,480	1,530	754	114	0	0	0	0	336	1,340	2,280
	3E	C + C	N_2H_4* O_2/CH_4	2,240***	1,040***	0	0	0	0	0	0	0	792***	2,000***
	3F	COMB	$O_2/CH_4/H_2$**	1,260	750	0	0	0	0	0	0	0	638	1,150
BOSCH CO_2 Reduction	4A	CAT	N_2H_4* H_2	4,030	2,830	1,840	1,010	638	425	247	425	1,310	2,580	3,780
	4B	RES	N_2H_4* H_2	3,030	2,120	1,370	748	454	292	158	292	961	1,930	2,840
	4C	RES	N_2H_4* Steam/H_2	2,540	1,630	879	262	0	0	0	0	476	1,440	2,360
	4D	COMB	O_2/H_2	1,666	998	447	0	0	0	0	0	367	859	1,529

\+ Based on a 20 atmosphere model, 270 nmi altitude, 8- to 12-man station
* Hydrazine
** Water
*** Includes 522 lbm of water

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Table 5-3 Maximum Resupply Intervals +

SYSTEM				YEAR										
ECLS	Options	Propulsion												
		Thruster	Propellant	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Open CO_2 Loop (EDC)	1A	CAT	N_2H_4*	1	.70	.46	.26	.17	.11	.07	.11	.33	.64	.94
	1B	RES	N_2H_4*	.76	.53	.35	.20	.13	.09	.05	.09	.25	.49	.71
	1C	CAT	N_2H_4* CO_2/H_2	.72	.42	.18	0	0	0	0	0	.05	.36	.66
	1D	RES	N_2H_4* CO_2/H_2	.34	.12	0	0	0	0	0	0	0	.07	.30
	1E	COMB	O_2/H_2**	.48	.33	.20	.10	.05	.03	.01	.03	.14	.30	.45
	1F	COMB	O_2/H_2-CO_2**	.40	.25	.13	0	0	0	0	0	0	.22	.37
SABATIER CO_2 Reduction	3A	CAT	N_2H_4*	1	.70	.46	.26	.17	.11	.07	.11	.33	.64	.94
	3B	RES	N_2H_4*	.76	.53	.35	.20	.13	.09	.05	.09	.25	.49	.71
	3C	CAT	N_2H_4* CO_2/CH_4	.88	.59	.34	.14	.05	0	0	0	.21	.53	.82
	3D	RES	N_2H_4* CO_2/CH_4	.61	.38	.19	.03	0	0	0	0	.08	.33	.56
	3E	C + C	N_2H_4* O_2/CH_4	.55	.26	0	0	0	0	0	0	0	.20	.49
	3F	COMB	$O_2/CH_4/H_2$**	.31	.18	0	0	0	0	0	0	0	.16	.28
BOSCH CO_2 Reduction	4A	CAT	N_2H_4* H_2	.99	.70	.45	.25	.16	.10	.06	.10	.32	.64	.93
	4B	RES	N_2H_4* H_2	.75	.52	.34	.18	.11	.07	.04	.07	.24	.48	.70
	4C	RES	N_2H_4* Steam/H_2	.63	.40	.22	.06	0	0	0	0	.12	.35	.58
	4D	COMB	O_2/H_2	.41	.25	.11	0	0	0	0	0	.09	.21	.38

\+ With respect to the baseline 90-day resupply system for 1992

* Requires hydrazine resupply only

** Requires water resupply only

*** Requires hydrazine and water resupply

From Table 5-2 it can be seen that these propellant resupply requirements range from a maximum of 4060 lbm every 90-days to zero for periods from 3 to 7 years. It should be further noted that Options 3E and 3F do not have to use, as indicated in Table 5-3, a $N_2H_4/CO_2/CH_4$ ACT system in the low impulse years. They could, by the use of no more than about 500 lbm of water every 90 days and inefficient thrusting, eliminate the need for the above ACT system.

Table 5-3 presents another way of looking at propulsion logistic "up" characteristics; namely the maximum resupply interval. The shown resupply intervals for N_2H_4 systems and for O_2/H_2 systems are with respect to the 90-day resupply requirement of option 1A, which is the baseline for this study. For systems 3E and 3F, the maximum resupply interval, if an ACT system was not used, as discussed above, would be about 340 days for each year from 1994 through 2000.

Table 5-4 shows the total power requirements (as defined on Tables 5-la and b) for the years 1992 through 2002. This summarizes the power requirements for the propulsion system and major components of the ECLS atmospheric revitalization subsystem. During the lower impulse years, high performance propulsion systems are not required, hence the power requirements decrease. Option 3F requires the highest power requirements during the high impulse years. This is a result of electrolyzing additional water to reduce the CO_2 to CH_4 and condensate. During the low impulse years option 4D requries the highest amount of power. This is a result of the Bosch generating less excess effluent, hence water still needs electrolyzing during low impulse years, unlike option 3F.

Option 3A, which is a non-integrated propulsion-ECLS system, has the lowest power requirements. Option lA, which is also a non-integrated system, requires that the large amounts of CO_2 and H_2 be compressed compared to the lesser amount of CO_2 and CH_4 in Option 3A.

Table 5-4 Total Power Requirements + + + (kW)

SYSTEM				YEAR										
ECLS	Options	Propulsion												
		Thruster	Propellant	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Open CO_2 Loop (EDC)	1A	CAT	N_2H_4*	4.76	4.76	4.76	4.76	4.76	4.76	4.76	4.76	4.76	4.76	4.76
	1B	RES	N_2H_4*	5.38	5.27	5.18	5.15	5.06	5.03	4.96	5.03	5.15	5.25	5.34
	1C	CAT	N_2H_4* CO_2/H_2	4.55	4.55	4.55	+	+	+	+	+	4.55	4.55	4.55
	1D	RES	N_2H_4* CO_2/H_2	5.21	5.23	4.75	4.56	4.63	4.67	4.70	4.67	4.62	5.13	5.22
	1E	COMB	O_2/H_2**	8.62	7.23	6.16	5.34	4.91	4.69	4.50	4.69	5.63	6.98	8.28
	1F	COMB	O_2/H_2-CO_2**	7.94	6.63	5.51	+	+	+	+	+		6.32	7.62
SABATIER CO_2 Reduction	3A	CAT	N_2H_4*	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49	4.49
	3B	RES	N_2H_4*	5.11	5.00	4.91	4.88	4.79	4.76	4.69	4.76	4.88	498	5.07
	3C	CAT	N_2H_4* CO_2/CH_4	4.43	4.43	4.43	4.43	4.43	+ +	+ +	+ +	4.43	4.43	4.43
	3D	RES	N_2H_4* CO_2/CH_4	4.99	4.98	4.94	4.75	4.54	4.45	4.43	4.45	4.82	4.91	4.99
	3E	C + C	N_2H_4* O_2/CH_4	6.69	6.69	+ +	+ +	+ +	+ +	+ +	+ +	4.82	6.69	6.69
	3F	COMB	$O_2/CH_4/H_2$**	8.34	8.09	+ +	+ +	+ +	+ +	+ +	+ +	4.82	7.02	8.10
BOSCH CO_2 Reduction	4A	CAT	N_2H_4* H_2	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53	4.53
	4B	RES	N_2H_4* H_2	5.16	5.05	4.97	4.93	4.84	4.80	4.72	4.80	4.93	5.03	5.13
	4C	RES	N_2H_4* Steam/H_2	5.25	5.15	5.09	4.98	4.51	4.51	4.51	4.51	5.02	5.12	5.24
	4D	COMB	O_2/H_2	7.34	6.48	5.77	5.20	5.20	5.20	5.20	5.20	5.67	6.30	7.17

\+ Uses RES - $N_2H_4/CO_2/H_2$ system
\+ \+ Uses RES - $N_2/H_4/CO_2/CH_4$ system
\+ \+ \+ See Tables 5-1a and b for definition of power requirements

6.0 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The primary objective of this NASA/LERC sponsored study was to determine the benefits that exist by utilizing the effluents generated by the Space Station Environmental Control and Life Support (ECLS) system for use in the propulsion system. In order to accomplish this study, the effort was divided into four tasks. Task one included defining four different ECLS systems and their levels of closure, plus determining their material balance and amount of effluent generated by each. Task two included determining the propulsion requirements for the years 1992 through 2002 and then evaluating the amount of impulse supplied by the various effluents to reduce the basic propulsion requirements. Task three included defining various collection and storing techniques and determining tank weights and volumes for the different ECLS effluents and propulsion gases. Finally, task four included the comparison of the various ECLS propulsion system options on the basis of logistics, fixed weights and volumes, and power requirements. The results of these four tasks are summarized in the following sections. An additional section is included to discuss recommendations for future work in areas where additional or new work should be performed.

6.1 ECLSS Definitions and Requirements

Four primary ECLS systems were considered in this study. They were:

1) Open CO_2 loop using EDC
2) Open CO_2 loop using SAWD
3) Sabatier CO_2 reduction using EDC
4) Bosch CO_2 reduction using EDC.

Mass balances were performed on each of the four systems. In addition, the Sabatier system was modified to provide additional impulse for the 2-sigma, high impulse years. Modifications were made in the form of electrolyzing additional water in order to further reduce the CO_2 to CH_4 and condensate.

The open CO_2 loop using SAWD generated the largest amount of usable effluent (1755 lb_m/90-days) of the unmodified ECLS systems, while the Bosch CO_2 reduction ECLS system generated the least amount of useable effluent (558 lb_m/90-days). In terms of system weight the ECLS system using Bosch is the heaviest at 3085 lb_{ms} and the open CO_2 loop ECLS system using EDC is the lightest at 1930 lb_m. It is noted that these weights are only for the major components of the systems.

6.2 Propulsion Definition and Requirements

Propulsion system requirements for the study were defined as only the reboost requirements and do not include attitude control, docking disturbances, desaturation, or emergency contingencies. Two atmospheric models were used in sizing the propulsion system and determining expected resupply requirements. They were a 2-sigma and a nominal atmospheric model. The 2-sigma was used to size the propulsion system while the nominal atmospheric model was used to determine expected propellant consumption over the life of the station.

Available impulse capabilities were determined for the various generated effluents. These impulse capabilities were compared against the required impulse for the 2-sigma and nominal atmospheric models over the expected 10-year life of the station. The Open CO_2 loop ECLS system using EDC provided the greatest amount of impulse capability, while the Sabatier CO_2 reduction ECLS system using EDC provided the least. However, none of the unmodified systems provided enough impulse to satisfy the 2-sigma impulse requirements for all ten years. In the case of the nominal atmospheric model, the open CO_2 loop ECLS systems using EDC and SAWD satisfied the impulse requirements for all ten years (compare figure 3-4 with figures 3-8 and 3-9). In most years there was more than enough available impulse and hence some method of inefficient thrusting or flying the station at a lower altitude could be used to balance the excess effluent against the requirements.

The Sabatier and Bosch CO_2 reduction systems meet all, but a few, of the 90-day impulse requirements for the nominal atmospheric model (compare figure 3-4 with figure 3-10 and 3-11). In those years when additional impulse capability will be required many different options exist to make up the difference. In the case of the Sabatier system, two options are available. The first is to resupply hydrazine and run the CO_2/CH_4 effluent into a chamber to combine with the decomposed N_2H_4 after it has run through a catalyst bed. The mixture can then be expelled through a typical DeLavel nozzle or through a resistojet. The latter case reduces the amount of N_2H_4 to be resupplied, but increases, the overall system power consumption.

The second option is to resupply water and electrolyze it in the Sabatier ECLS system. The additional hydrogen allows for further reduction of CO_2 and enables the excess O_2 to be combined with the CH_4 and remaining CO_2. Depending on the amount of additional impulse required and hence additional water, all of the CO_2 can be reduced to condensate and CH_4, thus enabling an O_2/CH_4 combustion jet. Based on an eight man crew this condition occurs after an additional 522 lbm of water have been electrolyzed.

In the case of the Bosch CO_2 reduction system there are four options that exist. Of these four, only two make a significant impact in reducing propulsion logistic requirements. The first is to run the excess water and hydrogen in a resistojet to generate an impulse in the range of 90,000 to 160,000 lb_f-sec. The major disadvantage to this is the required purity of the water in order to avoid throat blockage with residue. The second option is to electrolyze the excess water and combine it with the excess H_2 to form a mixture ratio of 5.5:1. This technique supplies additional impulse of 233,000 lb-sec every 90 days.

6.3 Collection and Storage Techniques

Three techniques are used in collecting and storing generated ECLS effluents. The first is to collect the gases, compress them to 3000 psia and return them to earth every 90 days. The second technique is to collect and compress the gasses to 1000 psia for ten days and then expel the gases through an engine thus generating impulse capability for reboost. The third technique is to compress the gases continuously or near continuously on a per orbit basis, to 400 psia. The gases can then be heated and ejected through a resistojet in order to offset the drag force.

6.4 ECLS-Propulsion Options Considered

There were nineteen different ECLS-propulsion options considered in this study. Though others exist, these nineteen were assessed to be the most practical. Options 3F and 4D were determined to have the most significant impact on reducing logistic requirements for both the ECLS and propulsion systems..

Option 3F is a Sabatier CO_2 Reduction ECLS system combined with a combustion jet propulsion system. In order to meet the 1992 2-sigma atmospheric requirement, extra water is resupplied and electrolyzed to reduce the CO_2 to CH_4 and water condensate. The impulse requirement forced the final gas mixture to be $O_2/CH_4/H_2$.

The excess hydrogen is a result of all the CO_2 being completely reduced before sufficient impulse capability is generated. Though this system has the lowest logistics requirement of the options considered, it has other questionable attributes. One example is the by-products generated by combustion of 0_2 and CH_4. Approximately 8% solid carbon is formed from this chemical reaction.

Option 4D used a Bosch CO_2 reduction ECLS system in conjunction with an $0_2/H_2$ combustion jet. In order to meet the 1992 2-sigma impulse requirement, additional water (1666 lb_m) has to be resupplied. This water is electrolyzed and combined with the excess hydrogen and electrolyzed water from the Bosch ECLS system. As the impulse requirement drops, less water is required for resupply until the excess water and hydrogen satisfies all requirements.

All of the options considered, excluding the baseline system, reduce the logistics requirement of both the ECLS and propulsion systems. Regardless of which ECLS system is eventually used on the station, an appropriate propulsion system can be integrated effectively. It can be seen from Table 5-1C that some propulsion systems work better with some ECLS systems than with others. For example, in the Bosch ECLS system, options 4A and use a hydrazine propulsion system in conjunction with hydrogen. Unfortunately, there is an insignificant amount of H_2 to augment N_2H_4 very well and thus there is little reduction in the overall logistics of the system. Option C uses hydrazine in conjunction with steam and hydrogen. Though there is more mass, steam does not effectively augment hydrazine. Option 4D, on the other hand, uses $0_2/H_2$ combustion, and hence can utilize the excess hydrogen and water more efficiently.

6.5 Recommendations for Further Work

It was not the purpose of this study to recommend one system combination over another. Rather, it is to suggest alternatives depending on which ECLS system is chosen. Factors which were not considered, but play a significant role in eventually choosing an ECLS-propulsion system combination include the cost of developing either system, maintenance cost to keep it operating, and assembly cost to bring the system up and put it together. However, none of these costs (or delta costs) are as significant as the life cycle resupply cost which can run into the billions if dealing with large quantities of fluids.

The one system which, based on data presented in this study, shows the most potential independent of the atmospheric model, is the Bosch ECLS - O_2/H_2 combustion jet propulsion system. Studies which should be conducted to confirm the viability of this type of system include:

1) Test bed analysis of an integrated system.
2) Development of a space qualified, long life compressor.
3) Development of an O_2/H_2 thruster which can operate over a wide mixture ratio.
4) Compatibility testing of storage tanks for high pressure oxygen and hydrogen.
5) Testing of a static feed water electrolysis unit at various pressures (i.e., 150 to 3000 psia)

Additional studies include testing multifuel resistojets (i.e., $CO_2/CH_4/N_2H_4$) to determine impulse capability and contamination and testing of an O_2/CH_4 and $O_2/CH_4/H_2$ combustion jet. More general studies include integrating not only the ECLS and propulsion systems, but the material laboratory, shuttle, regenerative fuel cell, co-orbiting platforms and electrophoresis experiments as well.

APPENDIX A

ECLSS MASS FLOW, WEIGHT, AND VOLUME SIZING

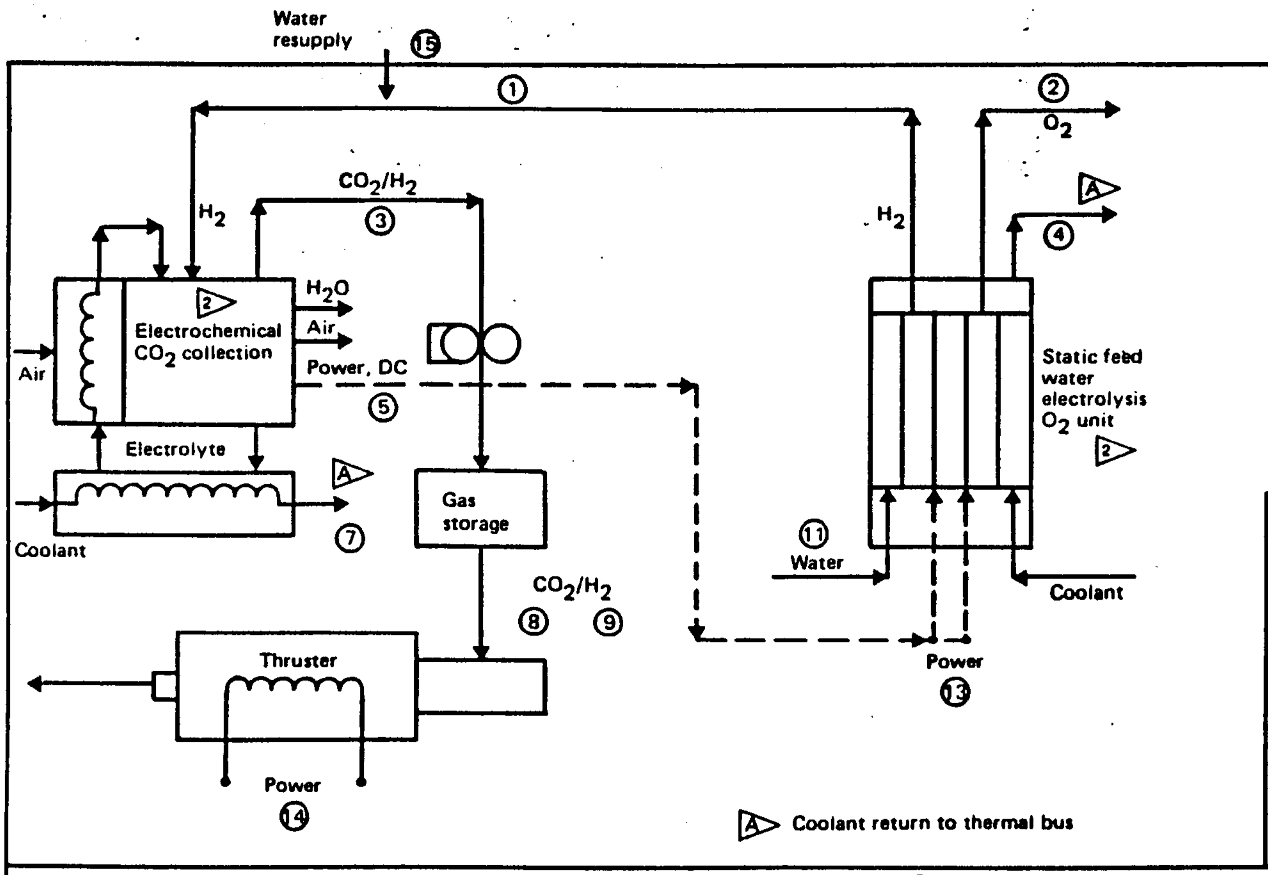
As mentioned in Section 2.0, only the major components of the ECLS system's atmospheric revitalization subsystem are considered in this study. These major components, which vary with each of the four ECLS systems considered are shown in Figures A-1 through A-4. The schematics on each of the figures illustrates inputs and outputs of each unit operation, as well as their mass flow rates, in lb_m/day, thermal (heat rejection) loads, and power requirements. Station numbers indicate entrance and exit points. The table in the upper right corner of each figure summarizes the fixed weight and volume and resupply requirements of the major ECLS components. Storage requirements (not shown) are addressed in Section 4.0 and their effects on the ECLS system shown in Table 5-1b.

Table A-1 shows the electrical and thermal equivalent weight penalties for both continuous and light side operations. The EDC and O_2 units both operate during the light side of the orbit while requiring regulated VDC. The Sabatier unit also operates on the light side only and requires both liquid and air heat removal. The Bosch has light side operation only and uses AC/DC power. Both the compressor power and resistojet power are based on continuous operation where the former uses regulated VAC and the latter regulated VDC.

Table A-2 summarizes the weight, volume, and expendable penalties for each ECLS system considered and how they compare to the baseline system.

The fixed weight, volume, power, and heat rejection estimates for the EDC and SAWD CO_2 collection subsystems are as published by Life Systems, Inc. (Ref. 5). The Bosch and Sabatier CO_2 reduction subsystems parameters were obtained from Hamilton Standard Technology option data sheets (Ref. 6). Equivalent weight penalties and heat rejection were provided by Life Systems (Ref. 7).

Figure A-1 shows a working schematic of the major components for the Open CO_2 loop systems using EDC. It should be noted that this system, as well as the other three, are partially to completely closed. Hence, choosing a staring point for the station numbers is somewhat arbitrary.



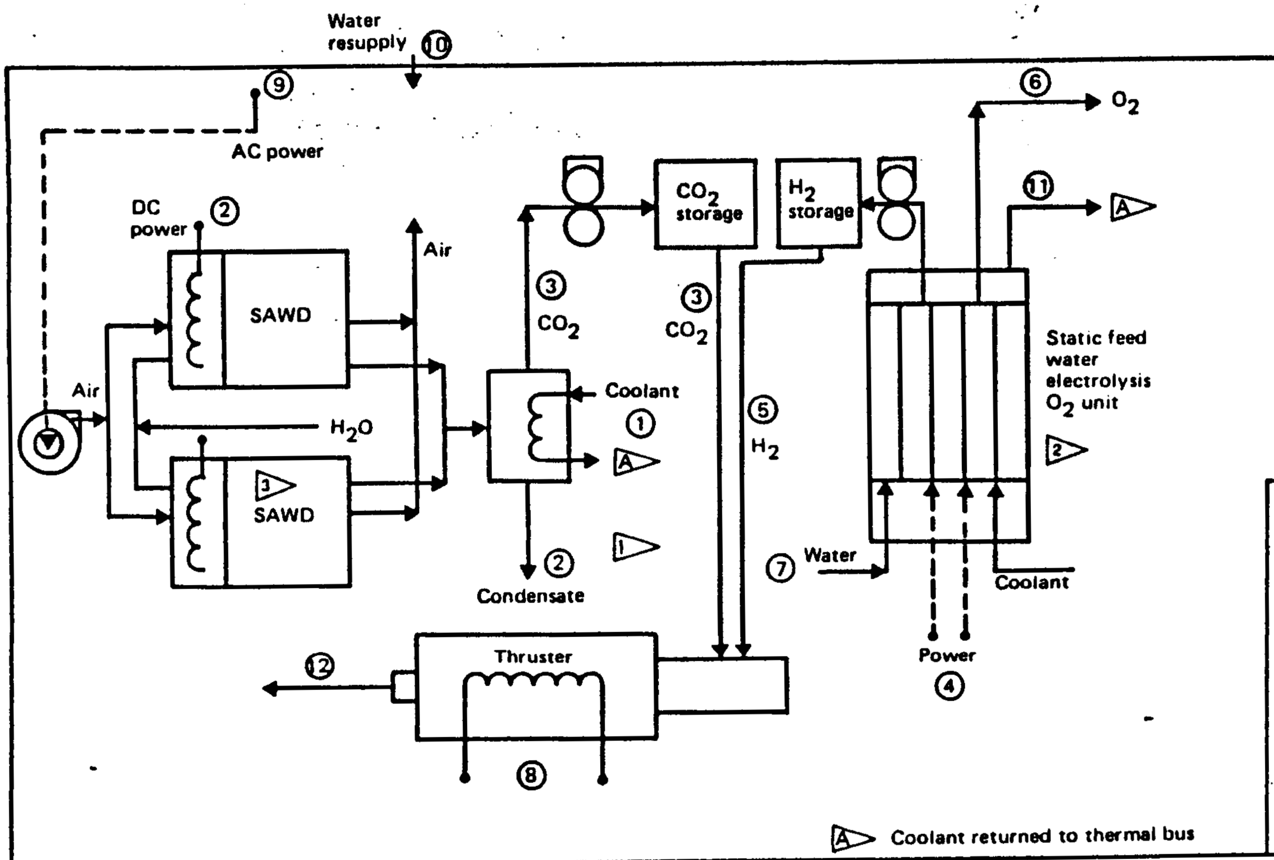
Weight and volume penalties		
Subsystem	Fixed weight, lbs	Volume ft^3
O_2 (SFSP)	265	6.4
CO_2 (EDC)	196	5.0
Storage	▷6	▷6
Equivalent weight, power	1,210	
Equivalent weight, thermal	259	
Fixed totals	1930	11.4
Resupply, lbs ▷3	841	13.5

Notes: System sized for eight crewmen

▷1 Maximum = Light side operation only (60 minutes)
Normal = Continuous (24 hour) operation
▷2 Light side operation
▷3 90-day resupply cycle, 10% of net added for tankage
▷4 Power generated by EDC
▷5 Function of desired I_{sp} when using resistojets
▷6 Storage tanks addressed in section 4.0

	Station																
Parameter	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮	⑯	Total
Flow rate, lbs/day																	
Maximum ▷1	4.5	36	32.5	4,711			22,800	29.3	3.2		40.5						
Normal	2.7	21.6	19.5	2,827			22,800	17.6	1.9		24.3				8.5		
Thermal, BTU/hr (heat rejection) Maximum				3,276			1,520										
Power, watts					(225) ▷4								4,608	▷5			4,383
Duty cycle, hrs/day	14.4	14.4	14.4	14.4	14.4		14.4						14.4				
Equivalent weight power, lbs					(35)								1,245				1,210
Thermal, kW				.96			.45										1.41
Equivalent weight thermal, lbs				177			82										259
90-day resupply, lbs															765		765

Figure A-1 Electrochemical Depolarized CO_2 Collection No CO_2 Reduction (Baseline) System



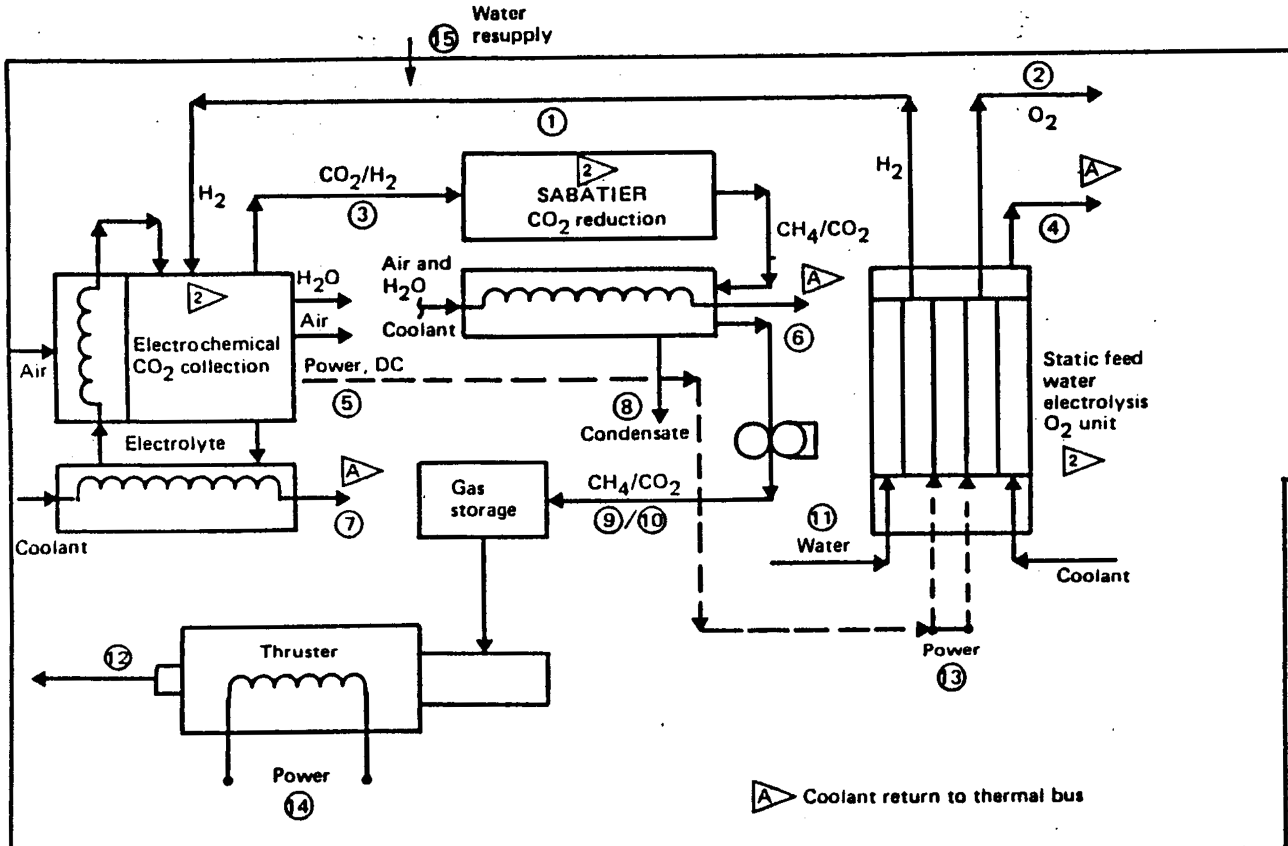
Weight and volume penalties		
Subsystem	Fixed weight, lbs	Volume ft^3
O_2 (SFSP)	214	6.0
CO_2 (SAWD)	198	10.6
Storage	▷8	▷8
Equipment weight, power	1,459	
Equipment weight, thermal	404	
Fixed totals	2,275	16.6
Resupply, lbs ▷4	1,307	20.9

Notes: System sized for eight crewmen

▷1 Maximum = Light side operation only (60 minutes)
Normal = Continuous (24 hour) operation
▷2 Light side operation
▷3 Light side desorption 26 min, sorption 74 min
▷4 90-day resupply cycle, 10% of net-added for tankage
▷5 Function of desired I_{sp} when using resistojets
▷6 VDC heaters
▷7 836 lbs/kW power penalty
▷8 Storage tanks addressed in section 4.0

	Station																
Parameter	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮	⑯	Total
Flow rate, lbs/day																	
Maximum ▷1	48,000	123	29		3.2	25.3	28.5				6,000	32.2					
Normal	28,670	32	17.6		1.9	15.2	17.1			13.2	6,000	19.5					
Thermal, BTU/hr (heat rejection) — Maximum	4,870										2,607						
Power, watts		1,427 ▷6		3694				▷5	125 ▷7								5,246
Duty cycle, hrs/day		6.24		14.4	14.4	14.4	14.4				14.4						
Equivalent weight power, lbs		357		997					105								1,459
Thermal, kW	1.43										.76						2.19
Equivalent weight thermal, lbs	263										141						404
90-day resupply, lbs										1,188							1,188

Figure A-2 SAWD CO_2 Collection No CO_2 Reduction System



.Weight and volume penalties		
Subsystem	Fixed weight, lbs	Volume ft³
O_2 (SFSP)	265	6.4
CO_2 (EDC)	196	5.0
SABATIER	192	20.5
Storage	▷5	▷5
Equivalent weight, power	1,210	
Equivalent weight, thermal	476	
Fixed totals	2,339	31.9
Resupply, lbs	0.0	0.0

Notes: System sized for eight crewmen

▷1 Maximum = Light side operation only (60 minutes)
Normal = Continuous (24 hour) operation

▷2 Light side operation

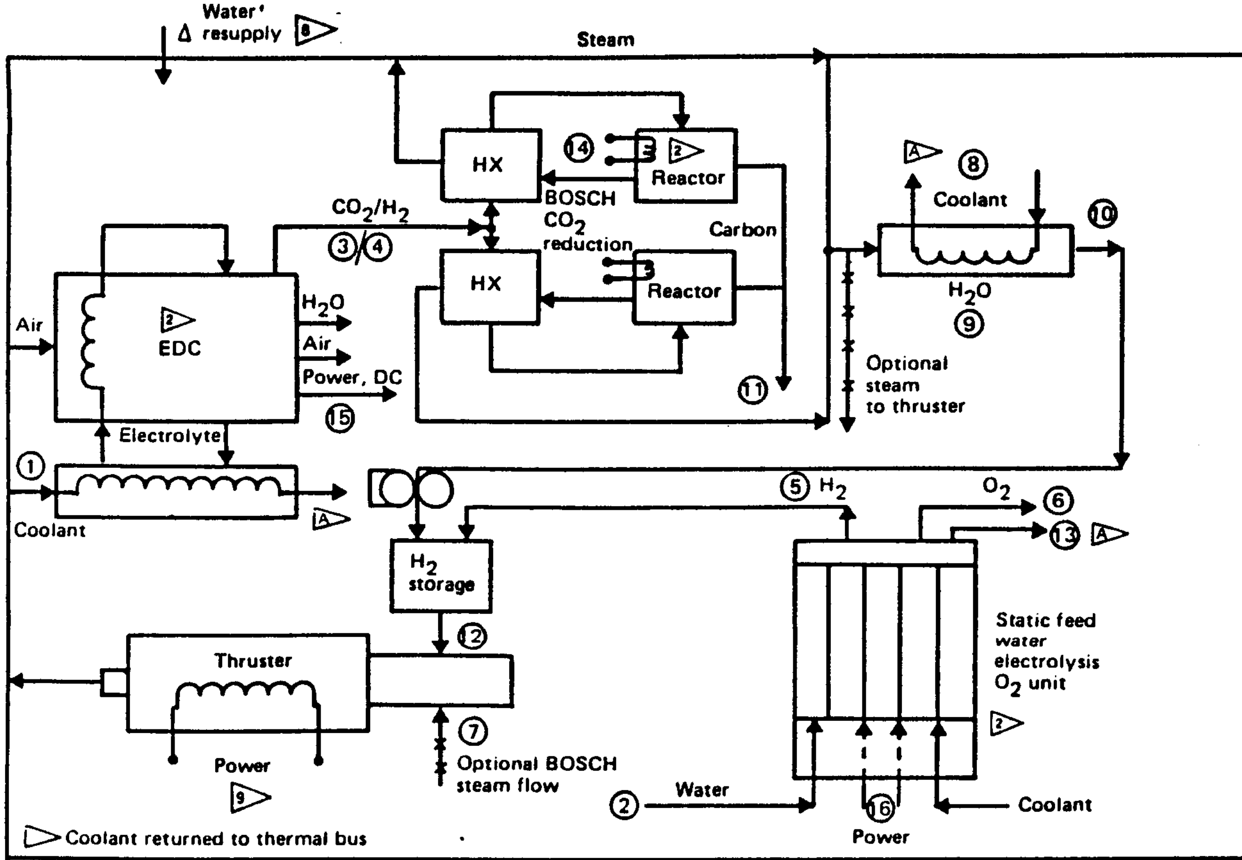
▷3 Power generated by EDC

▷4 Function of desired I_{sp} when using resistojets

▷5 Storage tanks addressed in section 4.0

	Station																
Parameter	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮	⑯	Total
Flow rate, lbs/day																	
Maximum ▷1	4.5	36	32.5	6,000		2,200	22,800	14.2	6.3	12	40.5				Zero		
Normal	2.7	21.6	19.5	6,000		2,200	22,800	8.5	3.8	7.2	24.3	11.0			Zero		
Thermal, BTU/hr (heat rejection) Maximum				3,276		2,033	1,520										
Power, watts					(225)▷3								4,608	▷4			4,383
Duty cycle, hrs/day	14.4	14.4	14.4	14.4	14.4	14.4	14.4		14.4	14.4	14.4		14.4				
Equivalent weight power, lbs					(35)								1,576	1,245			1,210
Thermal, kW				.96		.60	.45										2.01
Equivalent weight thermal, lbs				177		217	82										476
90-day resupply, lbs															Zero		Zero

Figure A-3 Electrochemical Depolarized CO_2 Collection SABATIER CO_2 Reduction System



▷ Coolant returned to thermal bus

Weight and volume penalties		
Subsystem	Fixed weight, lbs	Volume ft^3
O_2 (SFSP)	265	6.4
CO_2 (EDC)	196	5.0
BOSCH	1,011	127
Storage	▷10	▷10
Equivalent weight, power	1,245	
Equivalent weight, thermal	368	
Fixed totals	3085	138
Resupply, lbs ▷7	360	45

Notes: System sized for eight crewmen

▷1 Maximum = Light side operation only (60 minutes)
Normal = continuous (24 hour) operation
▷2 Light side operation
▷3 24 hour continuous operation
▷4 Power generated by EDC
▷5 BOSCH catalyst and canister, lbs/day
▷6 AC/DC power
▷7 90-day resupply cycle
▷8 Zero resupply
▷9 Function of desired I_{sp} when using resistojets
▷10 Storage tanks addressed in section 4.0

	Station																
Parameter	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬	⑭	⑮	⑯	Total
Flow rate, lbs/day																	
Maximum ▷1	22,800	40.5	29.3	3.2	4.5	36	9.8	4,800	24	0.5	8.0	5.0	6,000				
Normal	22,800	24.3	17.6	1.9	2.7	21.6	5.9	4,800	14.4	0.3	4.8	3.0	6,000				
Thermal, BTU/hr (heat rejection) — Maximum	1,520								590				3,276				
Power, watts														▷6 195/130	▷4 (225)	4,608	4,513
Duty cycle, hrs/day	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4			14.4	14.4	14.4	
Equivalent weight power, lbs														68/35	(35)	1,245	1,245
Thermal, kW	.45												.96				1.41
Equivalent weight thermal, lbs	82								109				177				368
90-day resupply, lbs	4 ▷5															360	360

Figure A-4 Electrochemical Depolarized CO_2 Collection BOSCH CO_2 Reduction System

Table A-2 ECLS Subsystem Parameters

Subsystem	Ref	Weight, lbm	Volume, ft^3	Power, watts [2]	Thermal, watts [2]
Electrolytic O2	3	*Figure A-5*	*Figure A-5*	$\frac{O_2 \text{ lbm/day}}{31.5} \cdot 4038$	$\frac{O_2 \text{ lbm/day}}{31.5} \cdot 835$
EDC	5	196 [1]	5.0 [1]	[3]	2.24(lbm CO_2/day)^2 + 18.57(lbm CO_2/day - 8.8)
SAWD	8	1.1 (62 + 14.7•N)	1.1 (4.2 + .68•N)	(DC) (260 + 125.8•N)/3.413 + (AC) 15.63•N	(260 + 125.8•N)/3.413
BOSCH	6	572.5 + 24.95 lbm CO_2/day	51.0 + 4.33 lbm CO_2/day	81.0 + 13.97 lbm CO_2/day	330 + 51.25 lbm CO_2/day (air) 39.27 • lbm CO_2/day (water)
SABATIER	9, 10	122 + 3.96 lbm CO_2/day	15.95 + 0.26 lbm CO_2/day	29.7 + 0.24 lbm CO_2/day	27 + 18.78 lbm CO_2/day (air) 9.8 • lbm CO_2/day (water)

Notes: N = Number of crewmen

[1] 2 four men units, each can process CO_2 at an 8 man continuous rate (17.6 lbm CO_2/day)

[2] Continuous 24 hour rates (100% duty cycle)

[3] Power delivered varies with efficiency of unit at various processing rates, i.e.

lbm CO_2/day	Watts	Cell DC volt	Cell amps
8.8	119	0.5	238
14.7	156	0.35	445
17.6	135	0.25	540

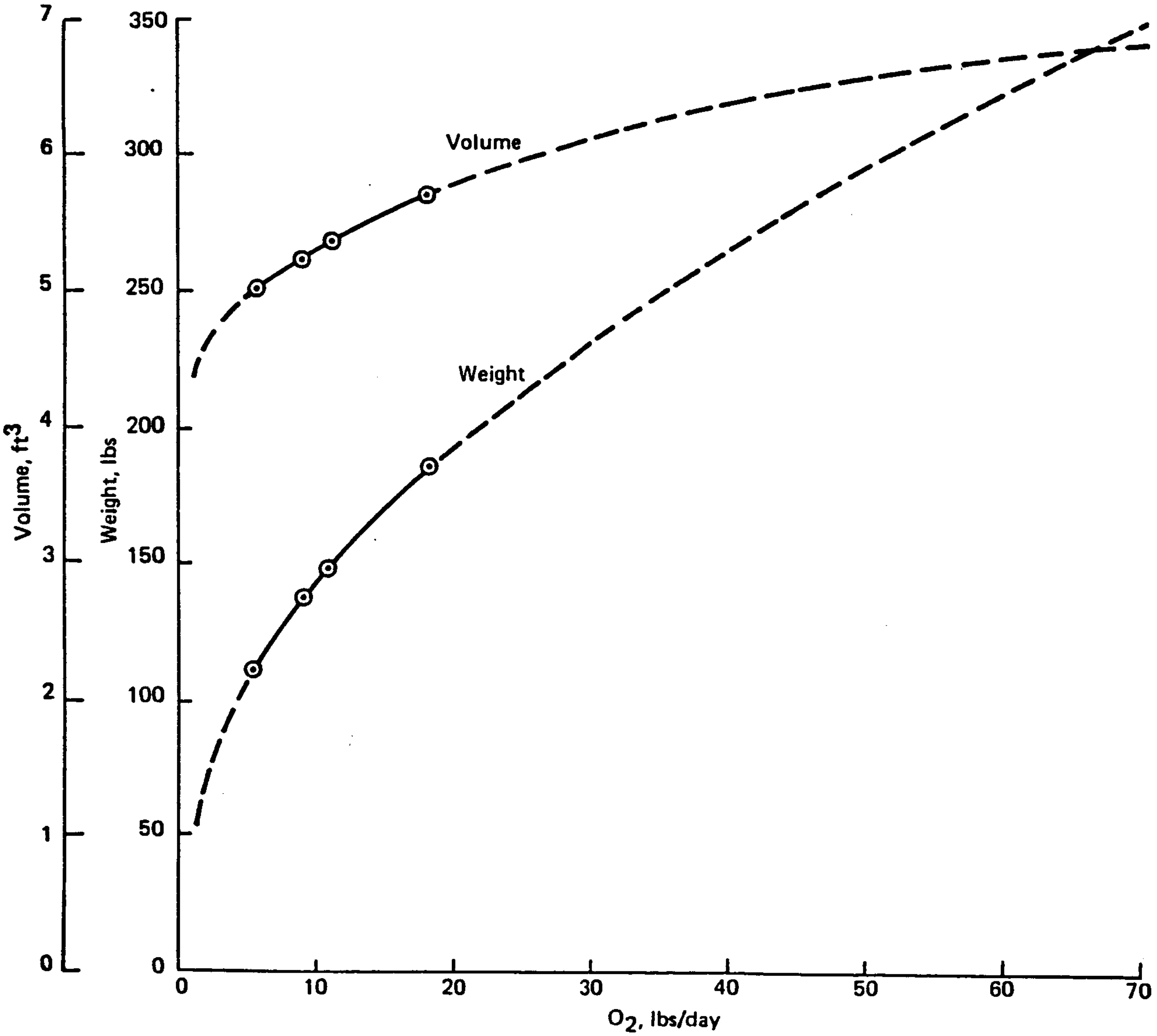


Figure A-5 *Electrolytic Oxygen System Weight and Volume as a Function of Oxygen Generation Rate for Continuous Operation*

As discussed previously, the hydrogen and part of the oxygen generated from water electrolysis combine in the EDC unit to form water vapor. The CO_2 collected by the EDC unit mixes with remaining H_2 and are sent to storage tanks. The air which enters the EDC unit is recirculated and the water vapor is used partly for crew drink and food preparation (potable water) and for electrolysis or personal hygiene (hygiene water). The coolant which is used for both the EDC unit and the electrolysis unit is returned to the thermal bus. This schematic shows the generated effluent being used for propulsion. If a continuous or near continuous thrusting sequence is used then the thruster shown in the schematic would be a resistojet. Less frequent thrusting sequences (i.e., 10 days) would require warm gas or combustion thrusters.

Figure A-2 shows a working schematic of the Open CO_2 loop system using SAWD. THis system requires less water for electrolysis than the EDC system since the SAWD unit does not require 0_2 and H_2. However, the SAWD unit requires more power to operate the blowers and move the air and water through the system. Coolant in this system is used in the 0_2 unit and the SAWD unit and then returned to the thermal bus. The CO_2 and H_2 are stored in separate storage tanks for 10 days at 1000 psia. The AC blower for SAWD unit results in a 836 lb_m/KW penalty.

Figure A-3 illustrates a Sabatier CO_2 reduction working schematic. This requires coolant for the 0_2 unit, EDC unit, and Sabatier unit. This system operates the same as the Open CO_2 loop system using EDC, except that the CO_2 and H_2 are sent into the Sabatier unit to be reduced to water condensate and a CO_2/CH_2 mixture, which is then sent to storage. The condensate combines with the water generated by the EDC unit to contribute to the available potable water for drink and food preparation and electrolysis.

The Bosch CO_2 reduction system working schematic is shown in Figure A-4. In this system, the CO_2 and H_2 generated from the EDC unit are heated through a heat exchanger with steam and then separated into condensate (14.4 lb_m/day), carbon, and hydrogen.

The steam used by the Bosch unit is closed looped. The excess water generated by the Bosch system can be used both for the ECLS and propulsion system, since an excess of 5.9 lb_m/day of hygiene water is generated. Coolant is required for the Bosch unit, as well as the 0_2 and EDC units which when after it has been used is sent back to the thermal bus.

1. Report No.
NASA CR 175093

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Space Station Propulsion - ECLSS Interaction Study

5. Report Date
April 1986

6. Performing Organization Code
506-49-22

7. Author(s)
Scott M. Brennan

8. Performing Organization Report No.
D483-10060-1

9. Performing Organization Name and Address
Boeing Aerospace Company
P.O. Box 3999
Seattle, Washington 98124

10. Work Unit No.

11. Contract or Grant No.
NAS 3-23353

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Washington, D.C. 20546

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code
506-64-12

15. Supplementary Notes
Final Report

Lewis Project Manager - R. M. Donovan, Power System Engineering Division,
NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

The benefits of the utilization of the effluents of the Space Station Environmental Control and Life Support (ECLS) system are examined. Various ECLSS-propulsion system interaction options are evaluated and compared on the basis of weight, volume and power requirements. Annual propulsive impulse to maintain station altitude during a complete solar cycle of eleven years and the effect on station resupply are considered.

17. Key Words (Suggested by Author(s))

18. Distribution Statement
General Release

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of pages

22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161