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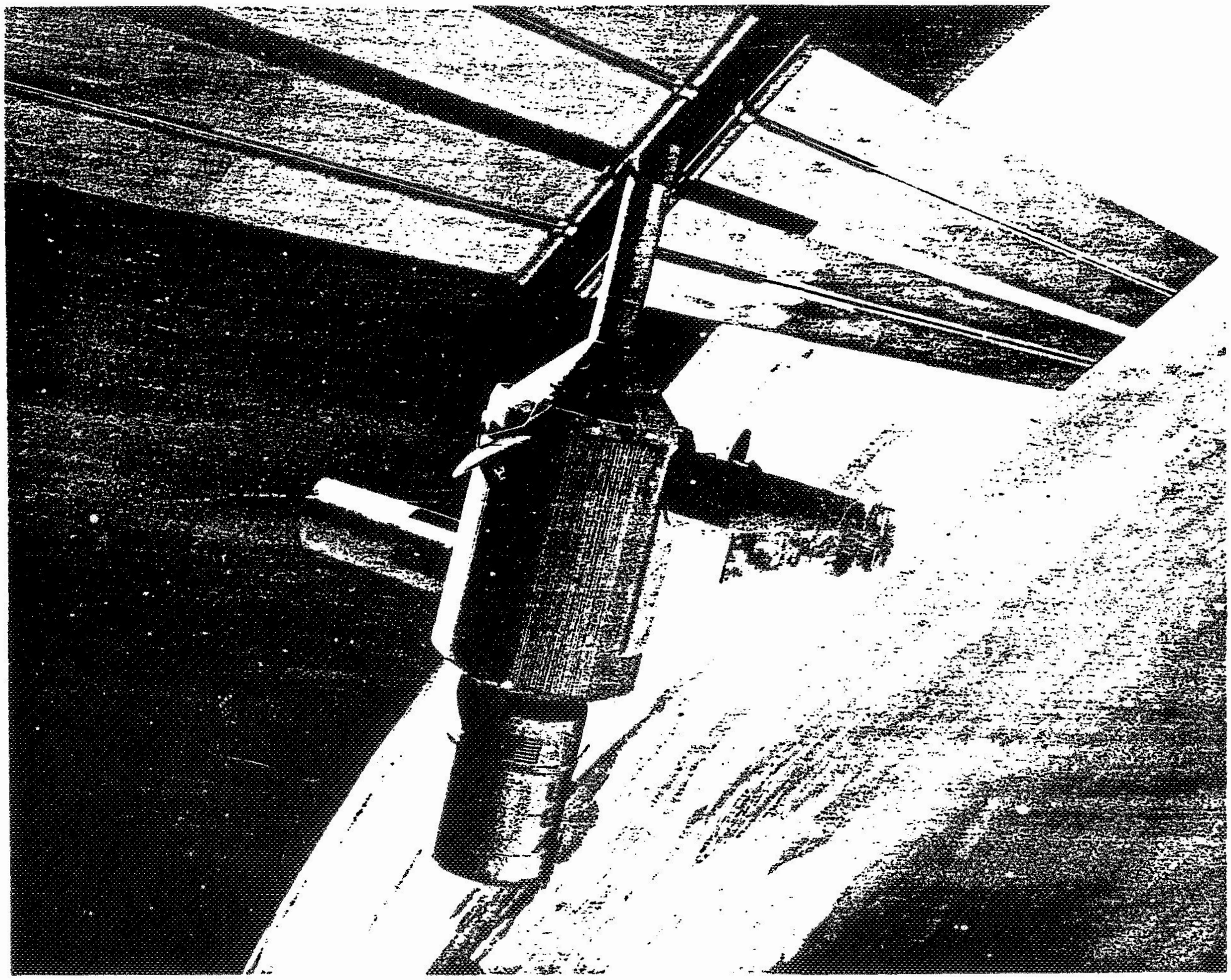
A STUDY OF
RESISTOJET SYSTEMS DIRECTED TO THE SPACE STATION/BASE



Prepared Under Contract NAS1-10170 by
Space Division, North American Rockwell
Downey, California 90241

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Approved by:

L. F. Duncan

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Program Manager
Space Division, North American Rockwell

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TECHNICAL REPORT INDEX/ABSTRACT

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AUTHOR(S) DUNCAN, L. F. * SCHAEDLE, G. C. * PROESCHEL, R. A.	

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ABSTRACT

A BIOWASTE RESISTOJET SUBSYSTEM STUDY IS BEING CONDUCTED BY THE SPACE DIVISION OF NORTH AMERICAN ROCKWELL, UNDER CONTRACT NAS1-10170, TO ASSIST THE LANGLEY RESEARCH CENTER IN THE INITIATION OF AN INTEGRATED ENVIRONMENTAL CONTROL/LIFE SUPPORT-RESISTOJET-CMG DEMONSTRATION PROGRAM.

THE OBJECTIVE OF THIS STUDY IS TO PROVIDE INFORMATION REQUIRED BY THE LANGLEY RESEARCH CENTER TO ENSURE THAT THE PLANNED DEVELOPMENT AND DEMONSTRATION OF A PROTOTYPE BIOWASTE RESISTOJET SUBSYSTEM IS CONDUCTED IN A MANNER SO AS TO BE REALISTIC, CONSIDERING SPACE STATION/BASE OPERATION CONDITIONS AND REQUIREMENTS. THE STUDY IS BASED ON THE CHARACTERISTICS OF THE SOLAR ARRAY POWERED SPACE STATION AND THE SPACE BASE DEFINED UNDER NASA CONTRACT NAS9-9953, SPACE STATION PROGRAM PHASE B DEFINITION STUDY. INFORMATION FROM THE SPACE STATION PHASE B STUDY IS UTILIZED AS IT BECOMES AVAILABLE.

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FOREWORD

This final report is submitted by North American Rockwell, through its Space Division, Downey, California, to the National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, as required by Contract No. NAS1-10170, A Study of Resistojet Systems Directed to the Space Station/Base. The work was conducted under the technical direction of Mr. Earl VanLandingham, of the Space Technology Division of the Langley Research Center.

This report is also identified as North American Rockwell Space Division document SD 70-549.

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I. INTRODUCTION

The objective of this study is to provide information required to assure that the planned development and demonstration of a prototype biowaste subsystem is conducted in a manner that reflects space station and base operational conditions and requirements. The study is based on the characteristics of the solar-array-powered Space Station and the Space Base defined under NASA Contract NAS9-9953, Space Station Program Phase B Definition Study.

The resistojet system studied herein utilizes biowaste gases that are residual to a Sabatier-type oxygen regeneration system. Metabolically produced carbon dioxide is adsorbed from the cabin atmosphere by a molecular sieve. The carbon dioxide is combined with hydrogen in a Sabatier reactor to form, ideally, water and waste methane gas. The water is electrolyzed to provide oxygen for crew consumption and some of the hydrogen required by the Sabatier reactor. The additional hydrogen required for reduction of all the carbon dioxide is provided by boiloff from the cryogenic hydrogen on the Space Station or from ammonia dissociation, which is used in the Space Base to produce nitrogen for cabin leakage makeup. The waste methane is used as the propellant in a resistojet to provide control moment gyroscope (CMG) desaturation and orbit-keeping functions. The resistojet may also use other excess or waste fluids such as water that may be available from the environment control and life support subsystem (ECLSS). In conjunction with the resistojet system, a gaseous oxygen/hydrogen (cryogenically stored) medium thrust system is used for attitude maneuvers.

Studies concerning the use of resistojets for Space Station low-thrust functions have shown that this approach offers considerable promise. The operation of the resistojets using gases residual to the ECLSS result in considerable savings in propellant resupply weight. Development of the resistojet thrusters is proceeding well; however, essentially no work has been directed toward development of the complete system required to use biowaste gases. In the proposed development program, the resistojet system would use ECLSS waste fluids to simulate a duty cycle dictated by CMG desaturation impulse requirements and drag makeup requirements of a hypothetical space station or base in a particular orbit and orientation. Subsequently, the measured performance of the thruster system would be integrated into the CMG computer program to verify that delivered performance, response, and system reliability were adequate to meet the desaturation and orbit-keeping requirements.

For system demonstration, the major preparatory effort involves the design and fabrication of the system to collect, condition, and feed the biowaste gases to the resistojet thrusters. Toward this goal, this study concentrated on questions regarding probable duty cycles, thrust levels, and biowaste availability.

II. SUMMARY

The study of resistojet systems directed to the Space Station/Base covers three basic areas: space station subsystem design, space base subsystem design, and technology requirements. The space station and space base sections of this report are each ordered similarly. First, the vehicle configuration, flight mode, and reaction control subsystem (RCS) requirements relative to biowaste resistojets are discussed. Second, that portion of the environmental control and life support subsystem (ECLSS) which might have an interface with the biowaste resistojet is described, and the waste fluids that might be available as propellants are identified. Finally, the resistojet operational modes, duty cycles, etc., to use these waste fluids to meet the impulse requirements are defined. The space station subsystems are defined in much more detail than for the space base.

SPACE STATION

The space station used as the baseline design for this study is the 12-man, solar-array-powered space station defined by North American Rockwell (NR) under Contract NAS9-9953, Space Station Program Phase B Definition. Other space stations are being considered under the Phase B Definition Study (e.g., nuclear reactor powered, radioisotope powered, and modular buildup stations). These designs are not considered within the scope of this study, although the possible impact of changes in the medium-thrust RCS is discussed briefly.

The space station RCS functional requirements that can be fulfilled by low-thrust resistojets are orbit maintenance to counteract atmospheric drag, and desaturation of the control moment gyros as nonperiodic torques build up resulting from aerodynamic and gravity gradient forces. Both of these functions are a function of altitude and solar sunspot activity. These requirements are summarized in Table 2-1.

The most reliable source of waste fluids from the ECLSS is the gas effluent from the Sabatier reactor. The reactor combines metabolically produced carbon dioxide with hydrogen to produce water which is subsequently electrolyzed to produce oxygen for metabolic consumption. In addition to the water, waste gases consisting mostly of methane and unreacted carbon dioxide are also produced. Hydrogen is available from the medium-thrust RCS hydrogen storage tanks to supplement the hydrogen from water electrolysis

Table 2.1. Summary of Space Station Orbit Maintenance and CMG Desaturation Impulse Requirements (X-POP)

Orbit Altitude, Date	Impulse Requirement - lb sec/day			
	Orbit Maintenance		CMG Desaturation*	
	Nominal Atmosphere	2σ Atmosphere	Nominal Atmosphere	2σ Atmosphere
200 nm,				
1 Jan. 1975 (min)	1100	3300	470	860
1 Oct. 1978 (max)	8300	21500	1700	4000
240 nm,				
1 Jan. 1975 (min)	190	780	310	410
1 Oct. 1978 (max)	2300	8400	670	1770
300 nm,				
1 Jan. 1975 (min)	21	105	260	280
1 Oct. 1978 (max)	430	2500	335	700

*Assumes 16-foot moment arm

so that most of the carbon dioxide is reacted and only methane is produced as waste gas. The baseline waste gases used for preliminary design are listed in Table 2-2.

The quantities in Table 2-2 assume a 100-percent CO_2 conversion efficiency with 5-percent excess H_2 over stoichiometric requirements, and no gases other than CO_2 desorbed from the molecular sieve subassembly. The H_2O results from assuming saturated conditions in the Sabatier condenser-separator at 70 F, 15 psia, and 100-percent gas-liquid separation. A more detailed definition of the effluent composition and variations in the composition is given in the following section and in Appendix A.

Additional sources of waste fluids are the ECLSS water management assembly, waste management assembly, and experiments. The water management assembly defined in the Space Station Phase B preliminary design has a perfect water balance. However, because of system variations and some conservatism in certain assumptions, there might, in fact, be some excess water. The factors and possible quantities of water are summarized in Table 2-3.

Table 2-2. Baseline Waste Gases

CH_4	9.82 lb/day
H_2	0.25 lb/day
H_2O	0.33 lb/day

There also is waste water that is either vented to vacuum or stored in the vapor compression subassembly for periodic return to earth by the logistics shuttle vehicle. These quantities are also summarized in Table 2-3. Recovery of this water for use in the resistojet would require the design and development of hardware not presently planned for space station design. There may be some waste experiment water that cannot be recovered by the ECLSS water management assembly because of unusual contamination products. However, the waste experiment water composition is not defined at this time and no estimate of the quantities or suitability of the water for resistojet use is possible.

Table 2-3. Possible Sources of Excess Water

Source of Variation	Nominal Value Used	Anticipated Variation	Change in Water Balance
Variations in water balance			
Vapor compression still efficiency	97.5%	97.5 to 98.5	0 to 2 lb/day H_2O
Cabin leakage	20 lb day	?	$-0.27 \frac{\text{lb/day } H_2O}{\text{lb/day leakage}}$
Crew metabolic water production	0.78 lb/man-day	0.66 to 0.95	-1.4 to 2.0 lb/day H_2O
Water in wet food	60% water in wet pack; 1.6 lb/man-day	60 to 85%	+11.5 lb/day H_2O at 75%
Waste water (not presently recovered)			
Fecal water		3.0 lb/day	
Water in trash		2.4 lb/day	
Water in solids dryer (vapor compression loss)		5.3 lb/day	
Contaminated experiment water		?	

Fluids used by the experiments also were investigated in the study. However, the experiments are not defined in sufficient depth at this time to establish whether any of these fluids could be recovered for use in a resistojet system.

The resistojet concept employs the addition of energy to a gas by electric resistive heating, and the subsequent expansion of the gas through a converging-diverging nozzle to produce thrust. For a given gas composition, the theoretical specific impulse varies as the square root of the gas temperature. The gas temperature of a particular composition may be limited by undesirable products resulting from gas decomposition at high temperature, gas-thruster material compatibility and/or electric power available for heating.

The biowaste gases containing methane are limited to 1700 to 2000 R due to the formation of carbon which coats the heater elements and breaks down the electric resistance, clogs the thrust chamber throat, and results in loss of performance. Carbon particles in the plume also may be detrimental to external spacecraft and experiment surfaces. For this study, a temperature limit of 2000 R was used for all gas mixtures containing methane. Gas mixtures containing water vapors and/or carbon dioxide are limited to approximately 2700 R because of thruster material compatibility with the oxidizing environment. The total impulse available from the biowaste gases and water vapor (assuming 10 lb/day water vapor availability) is shown in Figure 2-1.

Also illustrated in Figure 2-1 is the orbit maintenance requirement for the space station "design to" altitude of 240 nm for the predicted nominal and 2 σ sunspot atmospheres. The CMG desaturation function can be done concurrently with the orbit maintenance function, so that the requirements shown in Figure 2-1 represent the total low-thrust impulse required. It can be seen that the biowaste gases alone produce sufficient impulse for the nominal atmosphere requirements and for all the 2 σ atmosphere requirements except for five of the 11 years of the solar cycle.

The resistojet has the flexibility of variable thrust and/or variable specific impulse by the control of inlet pressures and/or thrust chamber temperature, respectively. The various combinations of fixed and variable parameter operations are discussed. It is recommended that the development test have the capability of varying both pressure and temperature although the flight system will most likely have a fixed thruster inlet pressure with variable gas temperature to prolong thruster life during years with low-impulse requirements. Equations are derived that define the duty cycle of each thruster as a function of orbit maintenance and CMG desaturation requirements for fixed-thrust operation.

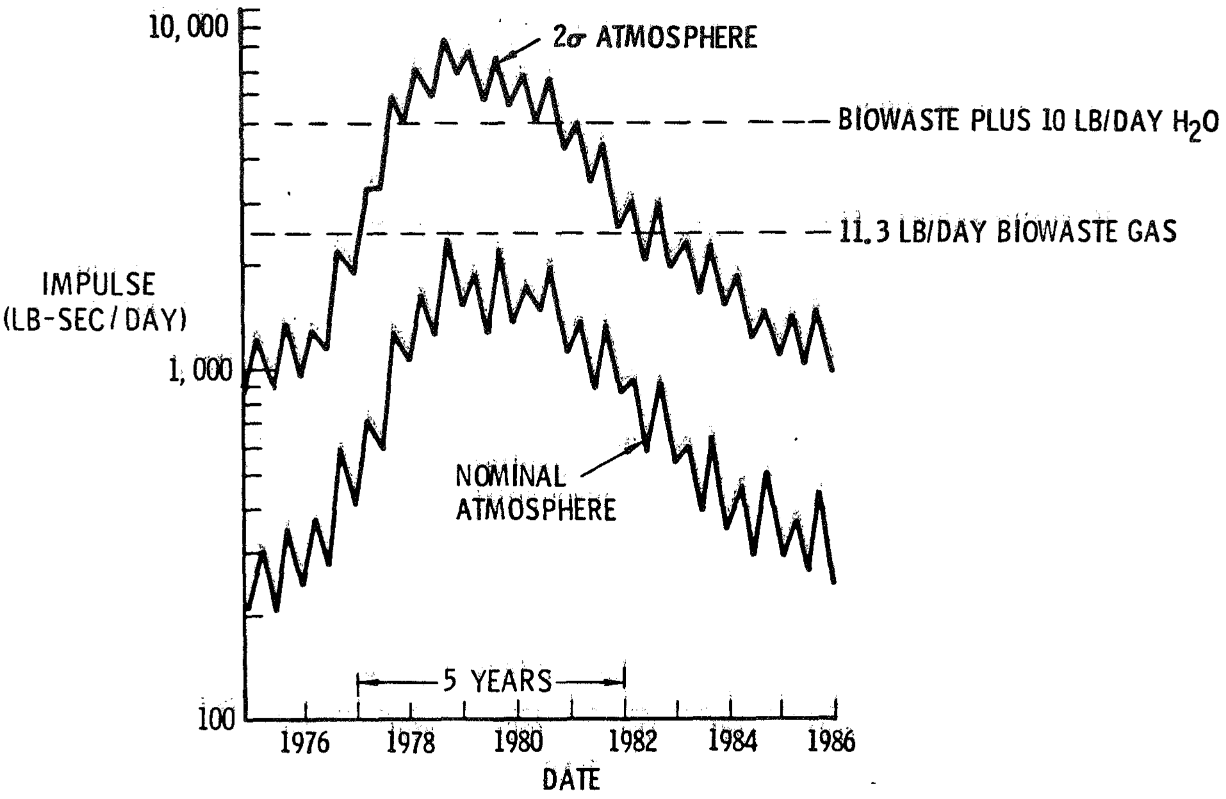


Figure 2-1. Orbit Maintenance Requirement and Resistojet Capability (240-Nautical-Mile Altitude)

The gases from the Sabatier condenser-separator contain water vapors which are saturated at 15 psia and 54 F. When these gases are compressed and stored in the accumulator at ambient temperature, condensation occurs. It is desirable, therefore, to remove sufficient water vapor from the biowaste gases to prevent condensation. Several concepts for the removal of the water vapor are presented. Another alternative is to use the gases continuously, with little or no compression, so that condensation does not occur. This requires both variable thrust and specific impulse capability. It is recommended that this mode of operation be tested in the development program.

SPACE BASE

The Space Station Program Phase B Definition Study, Contract NAS9-9953, includes as a portion of the study, the conceptual design (Phase A) of a space base as a centralized earth-orbital facility for the conduct of a multidisciplinary research development and operations program.

The space base, Figure 2-2, consists of an artificial-gravity section rotating about a zero-gravity section. One portion of the zero-gravity section is earth referenced and the other is inertially referenced.

The reaction control functional requirements, pertinent to the resistojet thrusters, are orbit maintenance to counteract aerodynamic drag and momentum vector control to maintain the spin axis perpendicular to the orbit plane, as the orbit plane regresses. Momentum vector control is a function of vehicle mass properties and orbit altitude only. These requirements are summarized in Table 2-4.

The space base ECLSS CO_2 management assembly is similar to the space station assembly. The major difference is that ammonia dissociation provides excess hydrogen for the Sabatier reactor and nitrogen for makeup of cabin leakage. There is more hydrogen produced in this manner than is required for the Sabatier reactor.

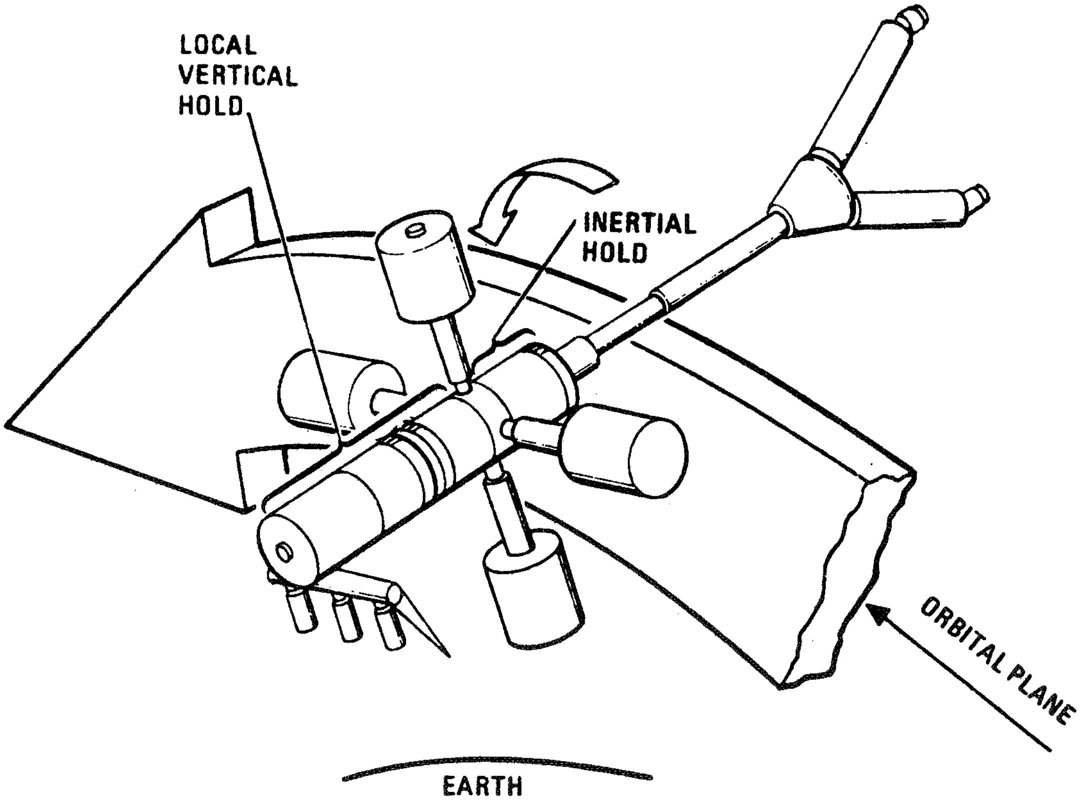


Figure 2-2. Space Base Flight Mode

Table 2-4. Space Base Orbit Maintenance and CMG Desaturation Impulse Requirements

Atmosphere Altitude	Orbit Maintenance (lb-sec/day)	Momentum Vector Control (lb-sec/day)
Nominal sunspot activity		
200 nm	15000	13200
240 nm	4500	12700
270 nm	1780	12300
+2 σ sunspot activity		
200 nm	40000	13200
240 nm	16500	12700
270 nm	8300	12300

The medium thrust O_2/H_2 thrusters obtain hydrogen and oxygen from water electrolysis at a mixture ratio of 8:1. It is desirable to operate the thrusters at a lower mixture ratio; therefore, the extra hydrogen not used by the Sabatier reactor is first provided to the medium-thrust subsystem as required to provide a mixture ratio of 3:1. Any remaining hydrogen is used by the resistojets.

There is some excess water (14.1 lb/day for the nominal base) available from the ECLSS water management assembly. This would be electrolyzed for O_2/H_2 propellant, as required. Any water remaining could be used in the resistojet.

It is shown that by the proper combination of thrust vectors to provide orbit maintenance and momentum vector control concurrently, most of the impulse requirements of Table 2-4 can be met with the biowaste resistojets and O_2/H_2 thrusters with a minimal amount of propellant resupply. However, at low altitudes (200 nm) and high atmospheric density, the RCS impulse capability is exceeded. For these conditions, it is recommended that ammonia be used as a supplemental propellant for the resistojets. Off-nominal crew sizes and the buildup and growth phase of the base were also studied. The system, as designed, meets all requirements.

The differences between the space station and space base resistojet systems which might require a delta development for the base are:

1. Up to 10-percent hydrogen in the base waste gases
2. Use of ammonia as a supplemental propellant for the base resistojet.

STATION BASE TECHNOLOGY REQUIREMENTS

Three specific areas requiring special development consideration were identified. They are removal of water vapor from the Sabatier effluent; additional thruster development for the use of hydrazine as a supplemental propellant (for the space station); and development of a unit to recover waste water from the solids dryer, fecal collection subassembly, and trash compactor.

III. SPACE STATION

The space station used as the baseline design for this study is the 12-man, solar-array-powered Space Station defined by NR under Contract NAS9-9953, "Space Station Program Phase B Definition." At the beginning of this study, Phase B preliminary design of the solar array space station was not complete. Therefore, some differences may exist between data used in the early phases of this study and the Phase B preliminary design documented in Reference 1. These differences are minor, however, and do not affect the biowaste resistojet study.

Contract No. NAS9-9953 also includes preliminary design of reactor-powered and radioisotope-powered space stations. These designs are not considered within the scope of this study.

The reaction control subsystem (RCS) selected for the solar-array-powered space station is an oxygen-hydrogen bipropellant medium-thrust-level system for all requirements. The propellants are stored as cryogenic liquids but are subsequently converted to the gaseous state for use in the engines. It was recommended that a low-thrust resistojet system be installed to utilize the ECLSS waste gases for orbit maintenance and CMG desaturation. This would be a development subsystem for use on the future space base (Phase A studies of the space base recommended a biowaste resistojet subsystem as part of the primary RCS). This development biowaste resistojet subsystem is not included in the Phase B preliminary design of the space station, however.

This study provides information to assure that the development and demonstration of a prototype biowaste resistojet subsystem would be conducted in a realistic manner, given solar array space station operational conditions and requirements.

SPACE STATION RCS REQUIREMENTS

The space station core module is a cylinder 33 feet in internal diameter. The wall thickness and meteoroid and thermal protection add approximately eight inches to the diameter. The module is approximately 50 feet in length, has four decks, and toroidal end bulkheads. It has an internal storage capacity of 180 days for a crew of 12. There are two separate pressurized compartments in series. Either compartment can be isolated in case it is damaged or rendered untenable. There are six docking ports, three for each pressurized volume. One end docking port is sufficiently strong to withstand thrust loads for use in orbital maneuvers and attitude control. There is a clear exterior surface area for a nominal-size ECS radiator of 2500 square feet. The core module structural arrangement is shown in Figure 3-1.

In addition to bulk storage space, both toroidal end bulkheads contain subsystem equipment and spares. Deck 1 contains two docking ports, access to an end docking port, recreation area, dining area, galley area, and medical facility. Decks 2 and 3, separated by a pressure bulkhead with an air lock, each contain six staterooms and a personal hygiene facility. In addition, Deck 2 contains the primary control center for the station. Deck 3 contains the intervolume air lock, a photo lab, and a maintenance and repair area. Deck 4 houses the experiments area, which includes an experiment maintenance and repair area, air lock laboratory, data reduction lab, and an experiment control center/station backup control center. There are also two docking ports and access to an end docking port on Deck 4. The station has no laundry facilities.

FLIGHT MODE

The following definition of the space station orbit altitude, inclination and orientation was obtained from Reference 2.

Many of the generic experiment disciplines produce mission operational requirements which result in specific space station design requirements. Guidelines and constraints for the NASA Space Station established a mission flight envelope which ranges in altitude from 200 to 300 nautical miles, at orbit inclinations from 28.5 to 55 degrees. The space station will also be capable of operating at an altitude of 200 nautical miles for polar (90-degree inclination) and sun-synchronous (97-degree inclination) orbits.

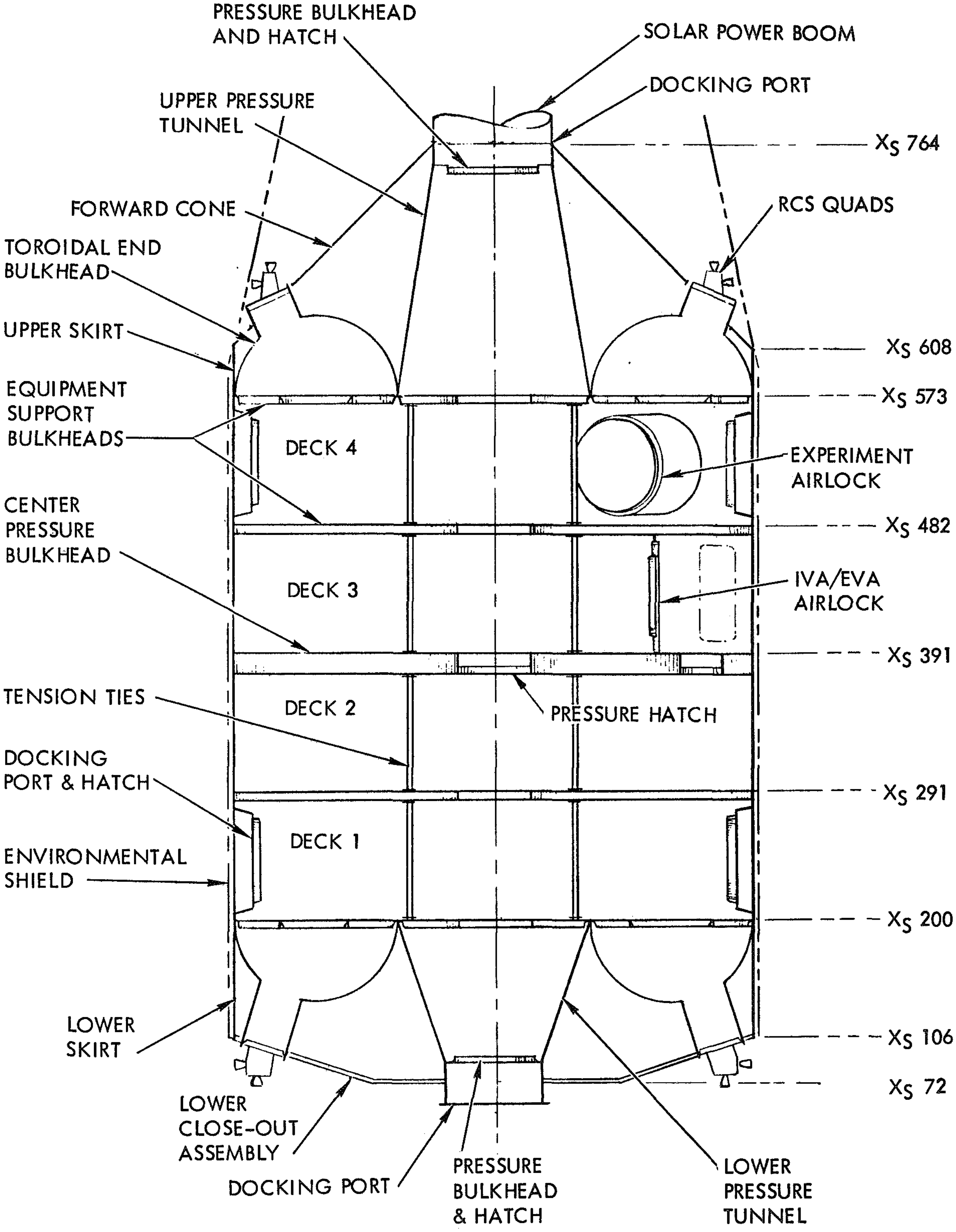


Figure 3-1. Core Module Structural Configuration

An evaluation of subsystem performance and logistic resupply requirements resulted in the space station subsystem design-to altitude of 240 nautical miles. This altitude would permit the space station to operate within all portions of the flight box, although operational resupply of consumables will be more frequent at lower altitudes and less frequent at higher altitudes.

A number of typical experiments that had either an altitude requirement or an inclination or pointing-direction requirement were investigated to determine the orbit which best satisfies the desired requirements. An inclination of 45 to 75 degrees satisfies the requirements of all experiments examined. A 55-degree orbit inclination was selected because a maximum of the earth's surface is covered (for earth surveys) within the established flight box. The experiment altitude requirement can be satisfied by altitudes between 200 and 270 nautical miles. An operate-to altitude of 270 nautical miles was selected to reduce orbit decay rates and subsequent resupply requirements for orbit makeup. It should be noted that early preliminary analyses of the shuttle vehicle performance indicated that the payload penalty was not excessive for flights to the high side of the altitude and inclination box. Further analyses with updated shuttle payload performance capabilities may show that lower altitudes may be more cost-effective over a ten-year period. Further, orbit makeup requirements are significantly affected by the power concept selected (e. g., the solar-array concept has much higher drag than has a nuclear reactor or radioisotope power configuration.

Because of the various experiment pointing requirements, those experiments attached to the space station established the operational requirement of maintaining any flight attitude. However, all experiment attitude requirements can be satisfied with a primary and secondary flight attitude mode. The primary flight attitude mode where the X-axis is perpendicular to the orbit plane (X-POP) is illustrated in Figure 3-2. A secondary flight attitude mode is required to provide an inertial platform capable of pointing experiments toward celestial bodies.

Although the two flight-attitude modes described above are required to meet all experiment pointing requirements, only the primary X-POP mode is studied in detail in the definition of a biowaste resistojet subsystem. The secondary flight mode is considered when an impact on the subsystem design exists (i. e., engine number and location).

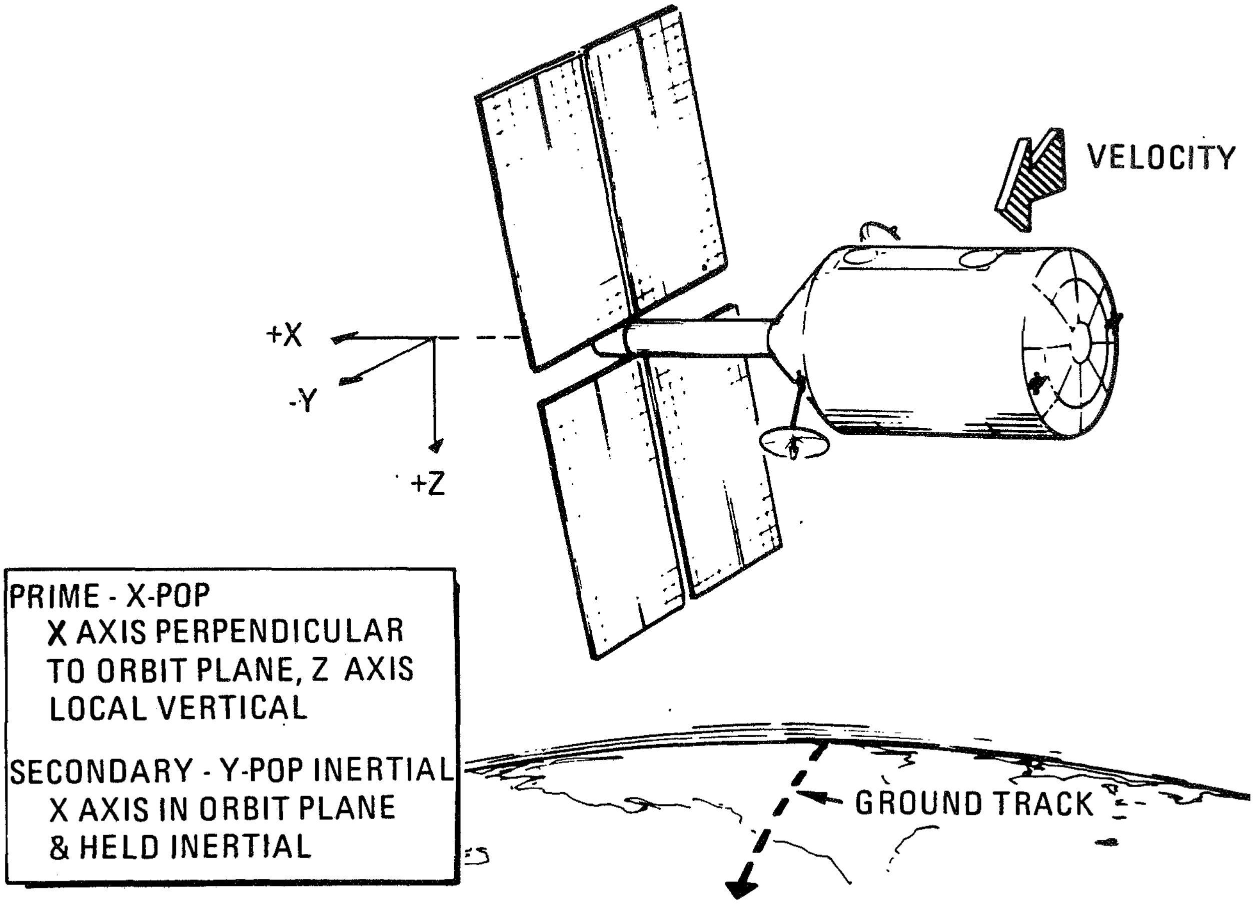


Figure 3-2. Primary Flight Attitude Mode

REACTION CONTROL FUNCTIONAL REQUIREMENTS

The space station RCS must provide thrust for four functions during zero-gravity operations: control-moment gyro (CMG) desaturation, attitude changes, orbit maintenance, and control of docking torques. In the artificial gravity assessment period, spin-up, despin, and momentum vector control are required.

Control of docking torques, spin-up, and despin require thrust levels larger than would be feasible for a resistojet (10 pounds or greater). Attitude changes could be made with low thrust if the small angular rates were acceptable. However, the impulse requirements for this function are arbitrary and small compared with orbit maintenance and CMG desaturation. This function is not considered further in this study.

During the artificial gravity assessment period, the solar arrays are fixed and the spin axis of the space station is oriented parallel to the sun line. The control required to maintain this orientation throughout the artificial gravity assessment is called momentum vector control. Since the space station/S-II artificial gravity configuration is rotating at 4 RPM, any single thruster is in the proper position for momentum vector control for approximately five seconds. The biowaste resistojet thrusters presently under development are not designed for economical operation for short pulses. Since the artificial gravity assessment will be done for only a short period and since the total momentum vector control impulse (49,600 lb-sec/day) is an order of magnitude greater than the impulse available from a biowaste resistojet with the waste fluids available, a special development for a pulsing resistojet design is not recommended and is not considered further.

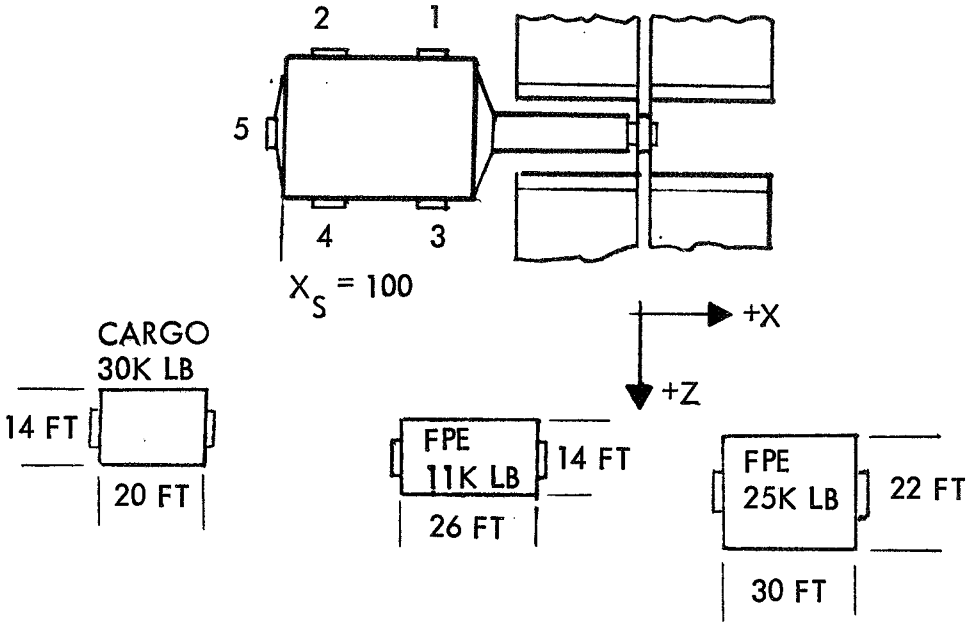
The major functions of the space station biowaste resistojet subsystem, therefore, are to provide impulse to offset the degradation of altitude caused by aerodynamic drag and to counteract nonperiodic gravity gradient and aerodynamic torques. The nonperiodic torques result in a continual increase in the CMG residual momentum, requiring a periodic desaturation of the CMG's by mass expulsion.

Vehicle Mass Properties

The space station mass properties used in the calculation of RCS impulse requirements for this study are based on vehicle characteristics before completion of the Space Station Phase B preliminary design. These are the same characteristics used to determine RCS requirements for the preliminary design of the space station RCS. Final mass properties resulting from the Phase B preliminary design were not sufficiently different to require an adjustment of the RCS requirements.

The impulse requirements for orbit maintenance and CMG desaturation are a function, to a large degree, of the number, size, and location of cargo and/or experiment modules attached to the space station. Numbering of the docking ports, modules, and combinations considered are shown on Figure 3-3. The corresponding mass properties are given in Table 3-1. Configuration H results in the largest RCS impulse requirements and is also most representative of the anticipated space station configuration throughout most of the ten-year life span.

There is the possibility that the advanced logistics shuttle (ALS) will be docked to the space station for five days in each 90-day period. This results in a significant increase in both orbit maintenance and CMG desaturation for these periods. Combined mass properties and docking mode used to estimate the impulse requirements are shown in Figure 3-4. These mass properties were estimated before the initiation of Contract NAS9-10960, "Space Shuttle System Program Definition (Phase B)," and do not reflect work done during that contract. Since the orbit maintenance and CMG



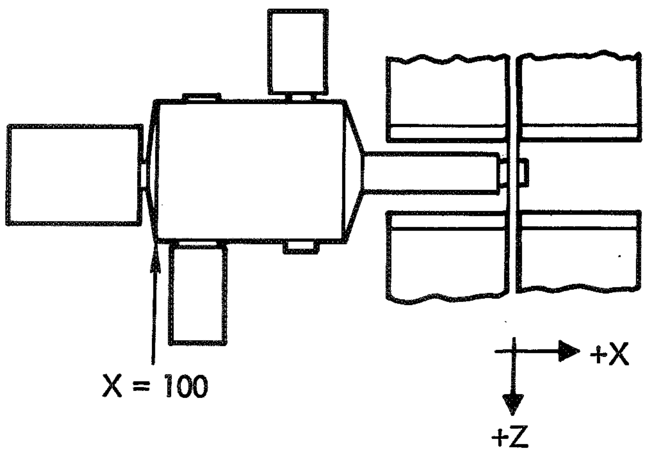
CONFIG	MODULE ATTACHED TO PORT NO.				
	1	2	3	4	5
A	-	-	-	-	-
B	CARGO	-	-	-	-
C	-	CARGO	-	-	-
D	CARGO	-	-	11K LB FPE	-
E	-	CARGO	-	11K LB FPE	-
F	CARGO	-	-	-	25K LB FPE
G	-	CARGO	-	-	25K LB FPE
H	CARGO	-	-	11K LB FPE	25K LB FPE
J	-	CARGO	-	11K LB FPE	25K LB FPE

Figure 3-3. Docked Module Combinations

Table 3-1. Inertia and Mass Properties

Configuration	Minimum Growth Weight (lb)	Center of Gravity			Moment of Inertia (10^6 slug ft^2)			Product of Inertia (10^6 slug ft^2)		
		$\overline{X}$	$\overline{Y}$	$\overline{Z}$	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
A	163300	433.5	0	0	1.09	2.62	2.22	0	0	0
B	193300	450.8	0	-53.1	1.77	3.38	2.32	0	-0.21	0
C	193300	404.7	0	-53.1	1.77	5.02	3.96	0	0.35	0
D	204300	439.9	0	-29.9	2.21	3.91	2.42	0	-0.40	0
E	204300	439.9	0	-29.9	2.21	5.52	4.25	0	0.20	0
F	218300	387.3	0	-47.0	1.83	4.95	3.87	0	-0.35	0
G	218300	346.5	0	-47.0	1.83	6.34	5.27	0	0.23	0
H	229300	380.6	0	-26.6	3.26	5.41	3.91	0	-0.48	0
J	229300	341.7	0	-26.6	2.26	6.80	5.52	0	0.13	0

CONFIGURATION H



	Maximum Area (sq ft)		Centroid of Planform		
	Cross Section	Planform	$\overline{X}$	$\overline{Y}$	$\overline{Z}$
A	855	1818	448.5	0	0
B	1135	2098	461.4	0	-45.6
C	1135	2098	421.7	0	-45.6
D	1499	2462	429.8	0	17.0
E	1499	2462	396.0	0	17.0
F	1135	2758	326.1	0	-34.7
G	1135	2758	295.9	0	-34.7
H	1499	3122	317.0	0	13.4
J	1499	3122	290.3	0	13.4

desaturation requirements with the ALS docked exceed the biowaste resistojet impulse capability under most attitude/atmosphere conditions, an update of the ALS properties was not considered pertinent to this study.

Orbit Maintenance/CMG Desaturation Impulse

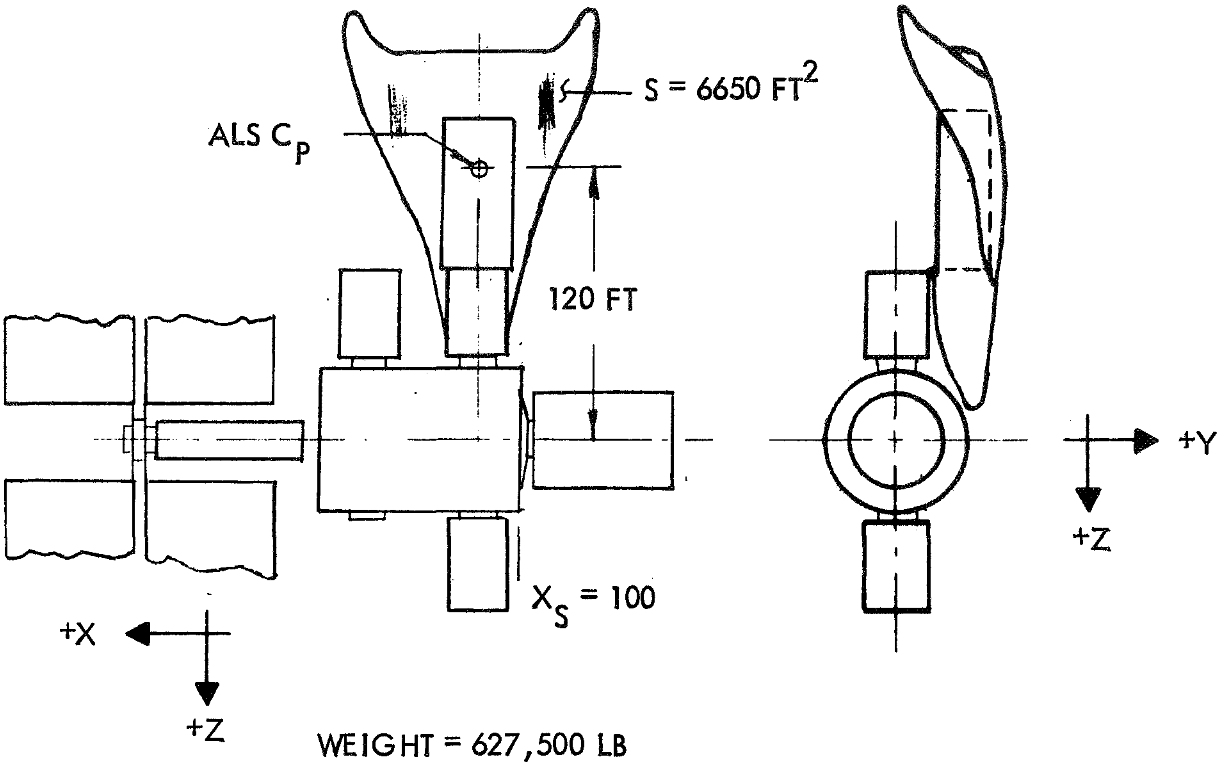
Orbit maintenance and CMG desaturation impulse requirements are functions of atmospheric density, altitude, flight orientation, and attached-module configuration.

Atmospheric density is a function of altitude and solar (sunspot) activity. The solar flux varies through a cycle lasting approximately 11 years. The atmospheric density models used in this study were obtained from Reference 3 for a predicted nominal and +2 sigma solar flux. A typical 11-year density profile for 250 nautical miles is shown in Figure 3-5.

The primary flight mode (X-POP) was used to determine the impulse requirements for station Configuration H. The gravity gradient torques about the Y-axis are larger for the secondary flight mode (Y-POP inertial) than for the primary mode, but are periodic. The CMG's have the capacity to accommodate this periodic torque. The solar arrays constitute the major cross-sectional area for drag and do not change with orientation. Therefore, the orbit-maintenance requirements for the secondary flight mode are less than those for the primary flight mode, so that the overall RCS impulse requirements for the secondary flight mode are less than those for the primary flight mode.

Orbit maintenance linear impulse requirements for station Configuration H in the primary flight mode are shown in Figures 3-6 and 3-7 for the predicted nominal and +2 sigma solar flux, respectively, as a function of altitude and the 11-year solar cycle from 1 January 1975 to 1 January 1986. The CMG desaturation angular impulse requirements are shown in Figures 3-8 and 3-9. Similar curves for the ALS docked configuration are given in Figures 3-10 through 3-13.

As stated earlier, the CMG desaturation requirement results from nonperiodic torques caused by gravity gradient and aerodynamic forces. In the X-POP primary flight mode (+Z-axis always colinear with the nadir), these torques are nonperiodic about the X-axis only. The gravity gradient torque results from misalignment of the attached modules on the docking ports (±0.5 degrees). Aerodynamic torque results if the center of pressure (centroid of planform) does not coincide with the center of gravity when projected into the plane perpendicular to the velocity vector. For the CMG desaturation requirements shown in Figures 3-8, 3-9, 3-12, and 3-13, the worst case is assumed where the gravity gradient and aerodynamic torques are additive. The gravity gradient torque alone is presented in Figures 3-14



WEIGHT = 627,500 LB

MOMENT OF INERTIA (I_{XX}) = 26.1×10^6 SLUG - FT^2

PRODUCT OF INERTIA (I_{YZ}) = 1.44×10^5 SLUG - FT^2

CENTER OF GRAVITY (INCHES)

$\bar{X} = 216$

$\bar{Y} = 136$

$\bar{Z} = 474$

Figure 3-4. Station/ALS Docked Mass Properties

and 3-15 for the station only and station/ALS docked configurations, respectively. The other extreme, where the gravity gradient counteracts the aerodynamic torque, can be calculated by subtracting twice the value obtained from Figures 3-14 or 3-15 from the corresponding value obtained from Figures 3-8, 3-9, 3-12, or 3-13, respectively. Note that a negative impulse value obtained in this manner indicates a reversal in the direction of the angular impulse required about the X-axis.

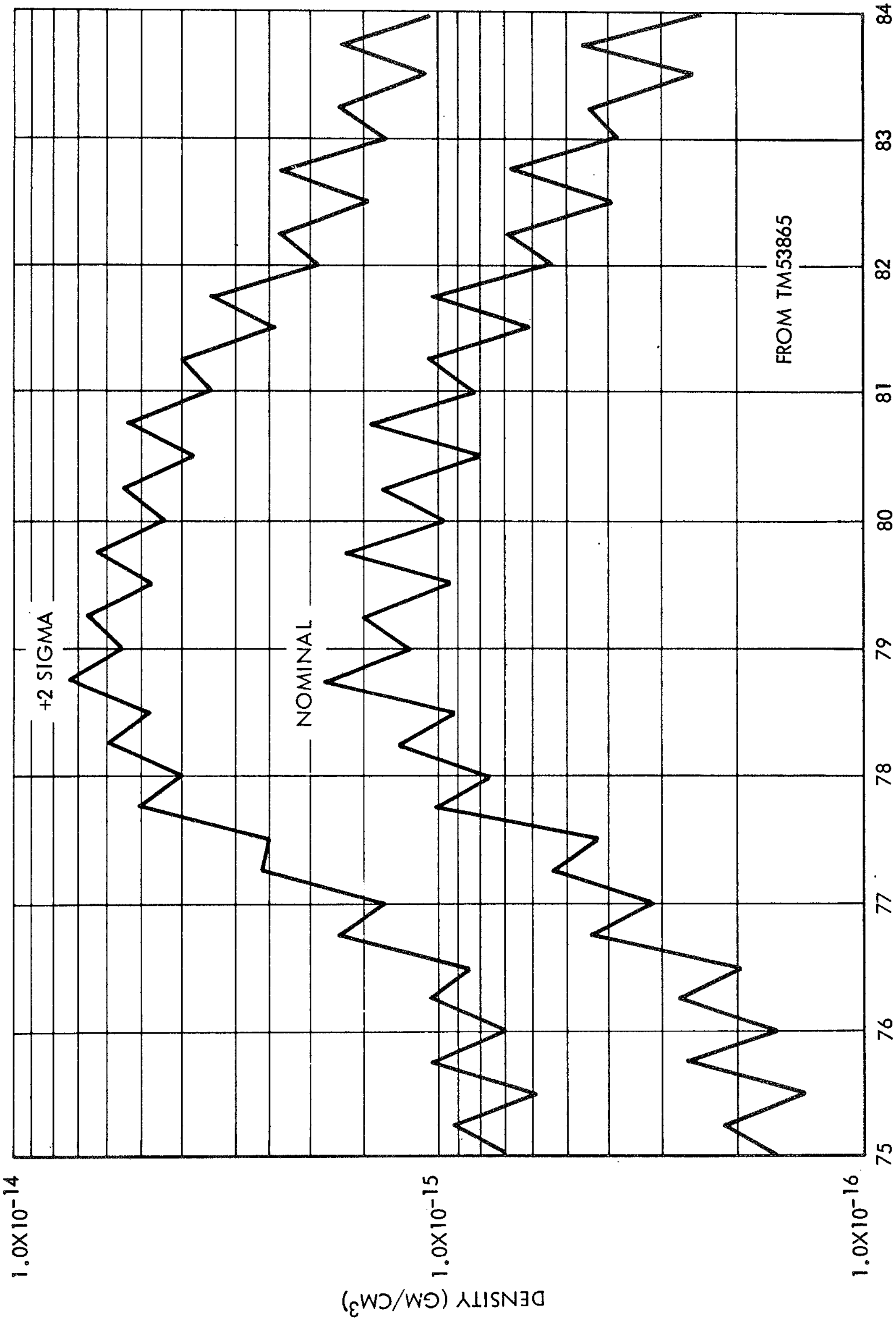


Figure 3-5. Density History for H = 250 Nautical Miles

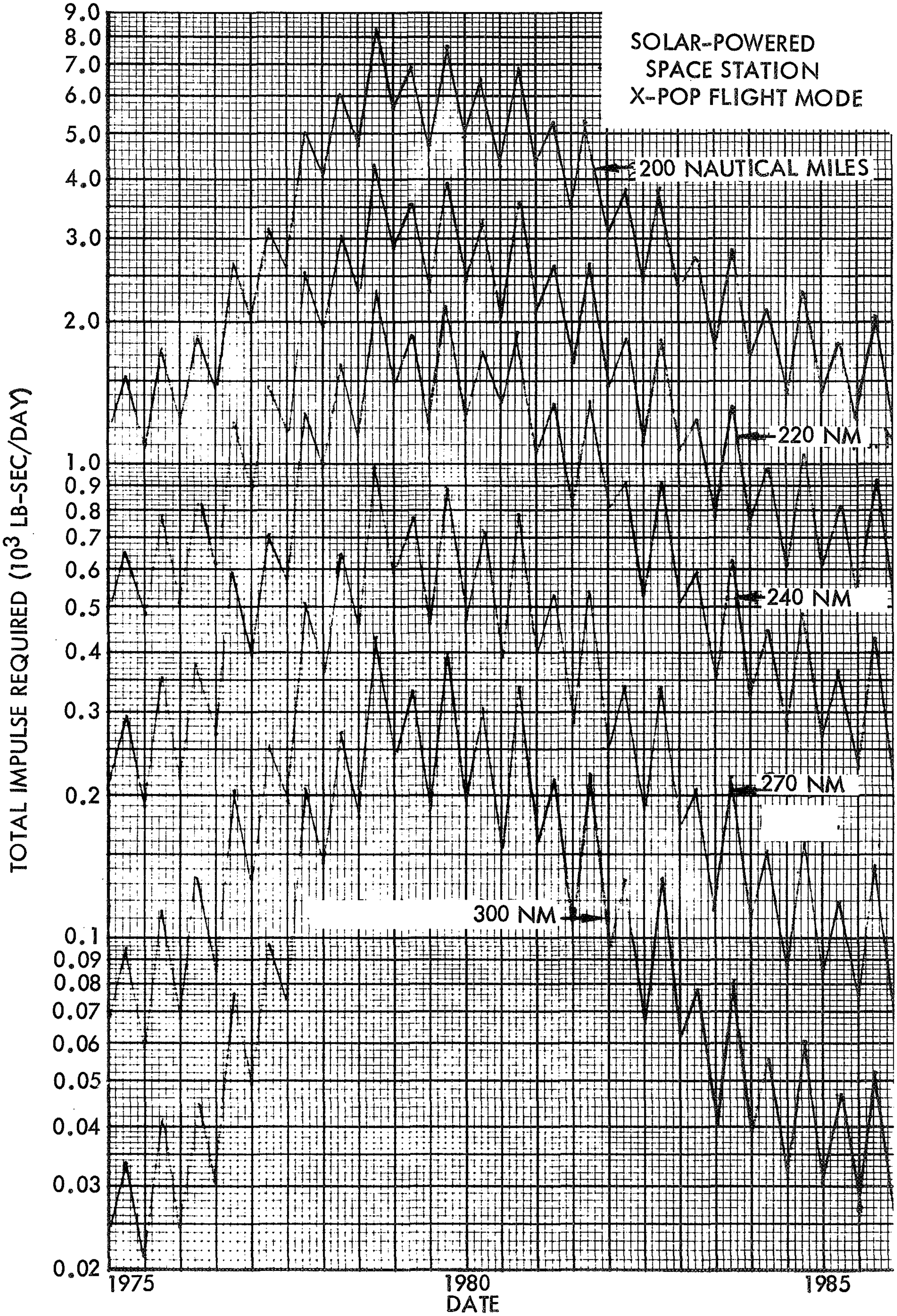


Figure 3-6. Orbit Maintenance Impulse, Nominal Atmosphere, Station Only

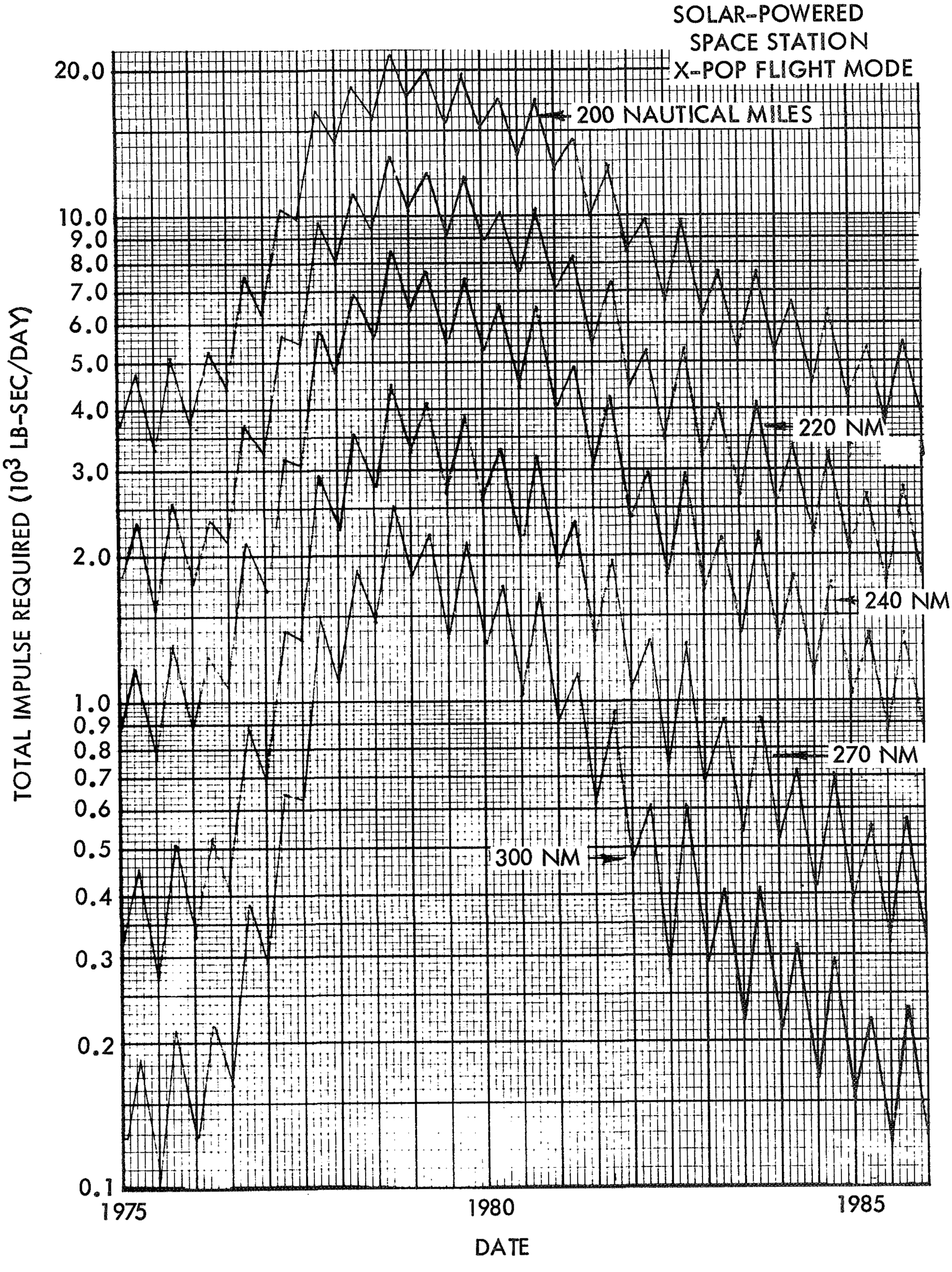


Figure 3-7. Orbit Maintenance Impulse, 2σ Atmosphere, Station Only

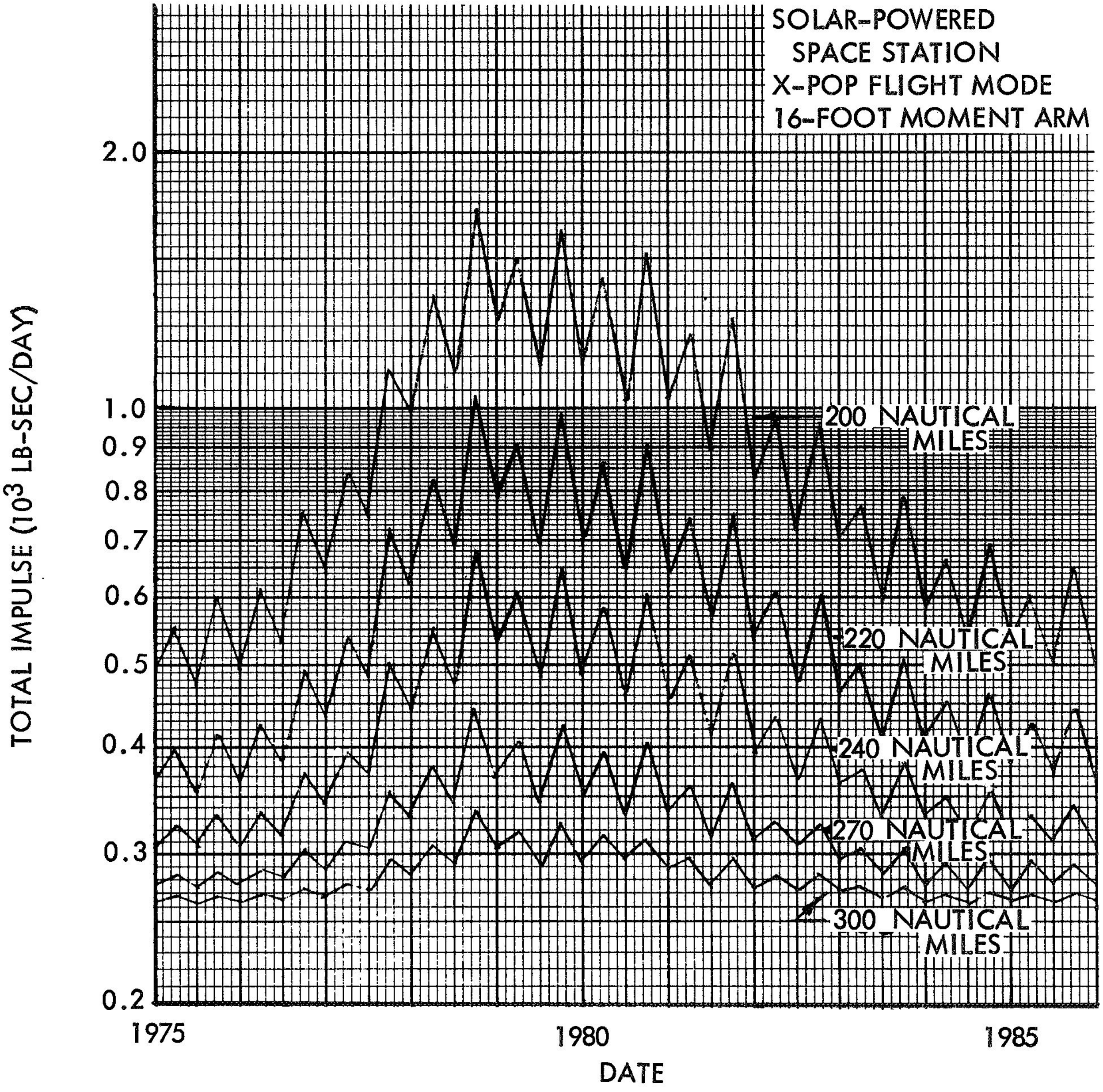


Figure 3-8. CMG Desaturation Impulse, Nominal Atmosphere, Station Only

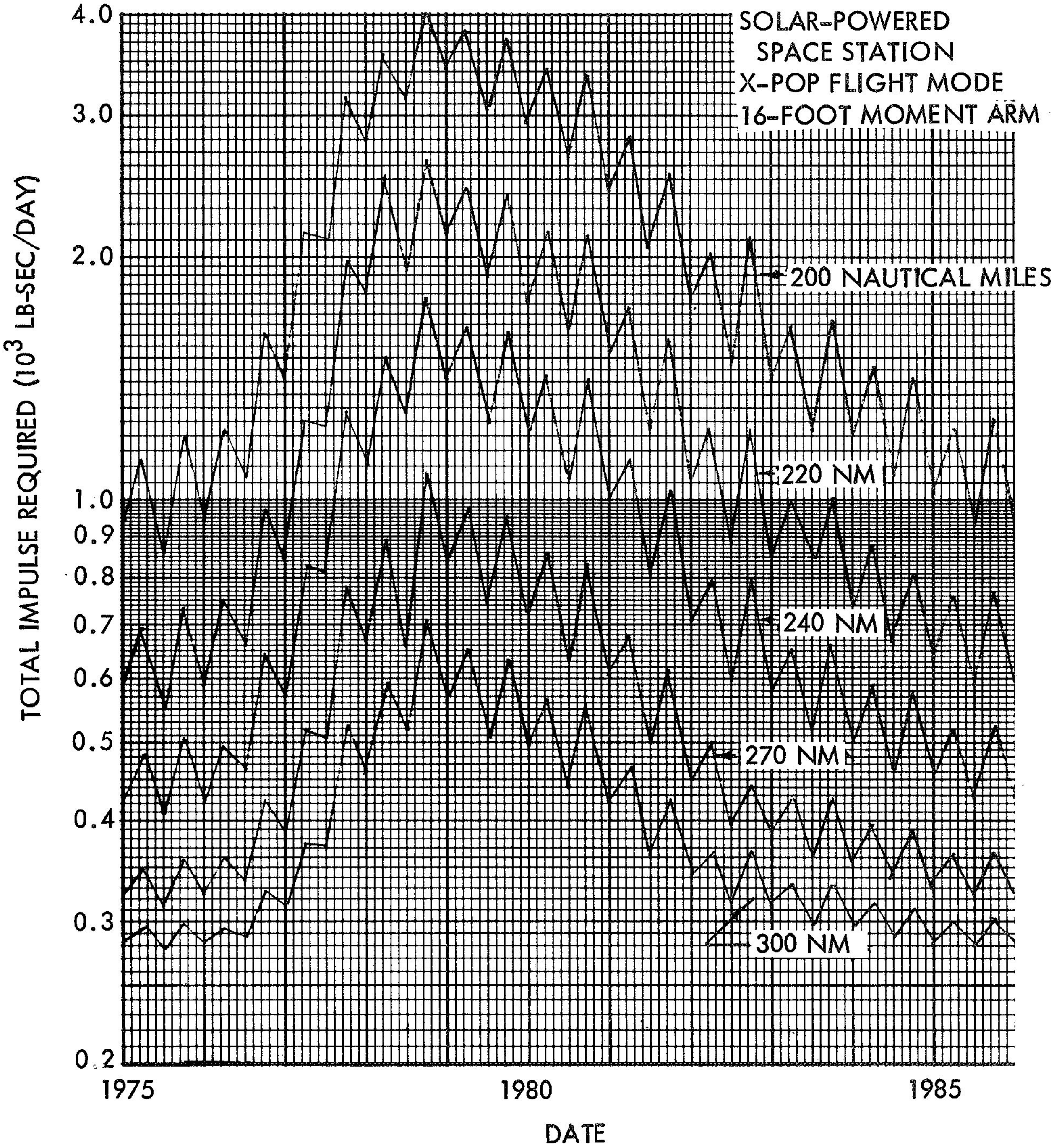


Figure 3-9. CMG Desaturation Impulse, 2σ Atmosphere, Station Only

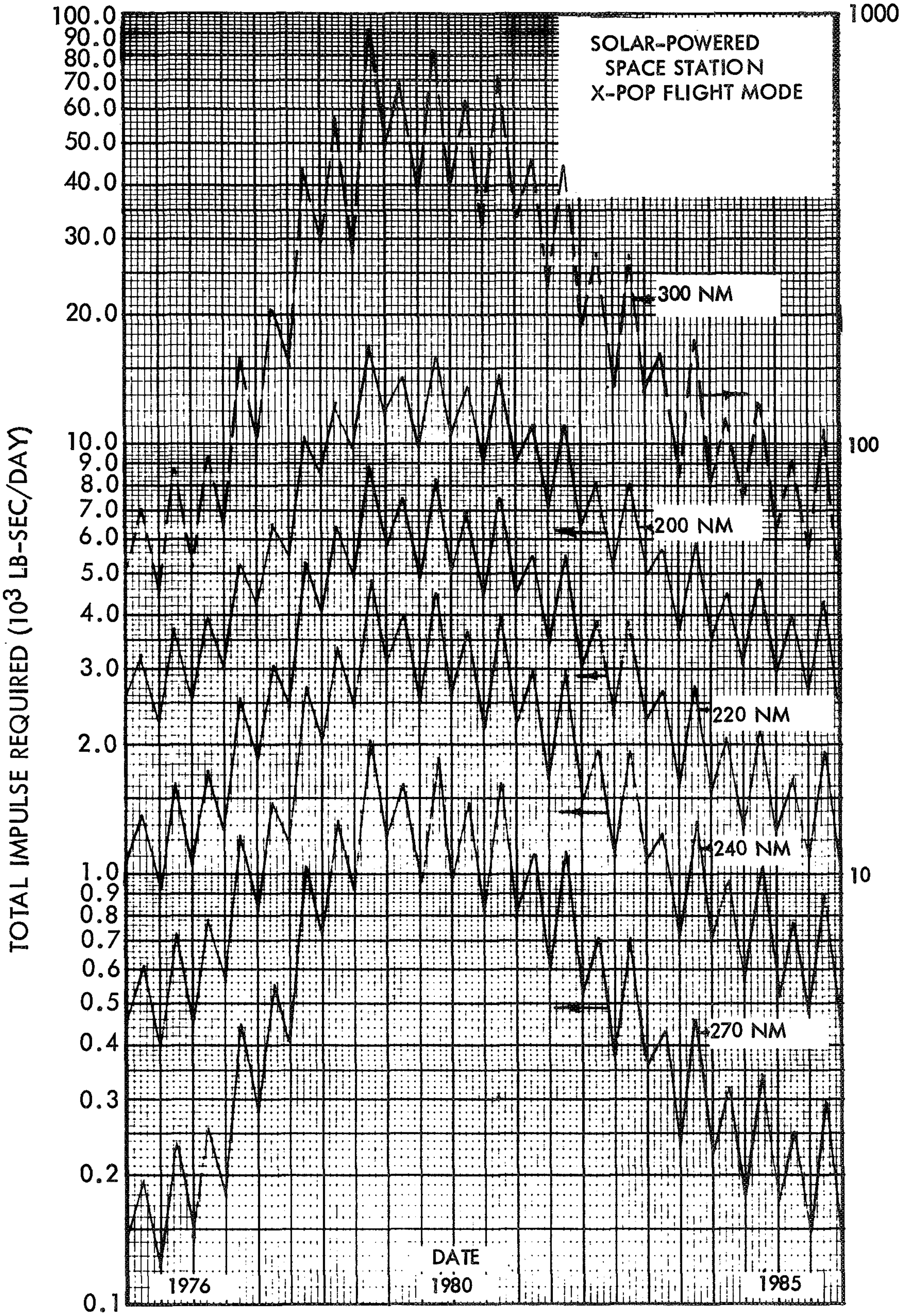


Figure 3-10. Orbit Maintenance Impulse, Nominal Atmosphere, With ALS

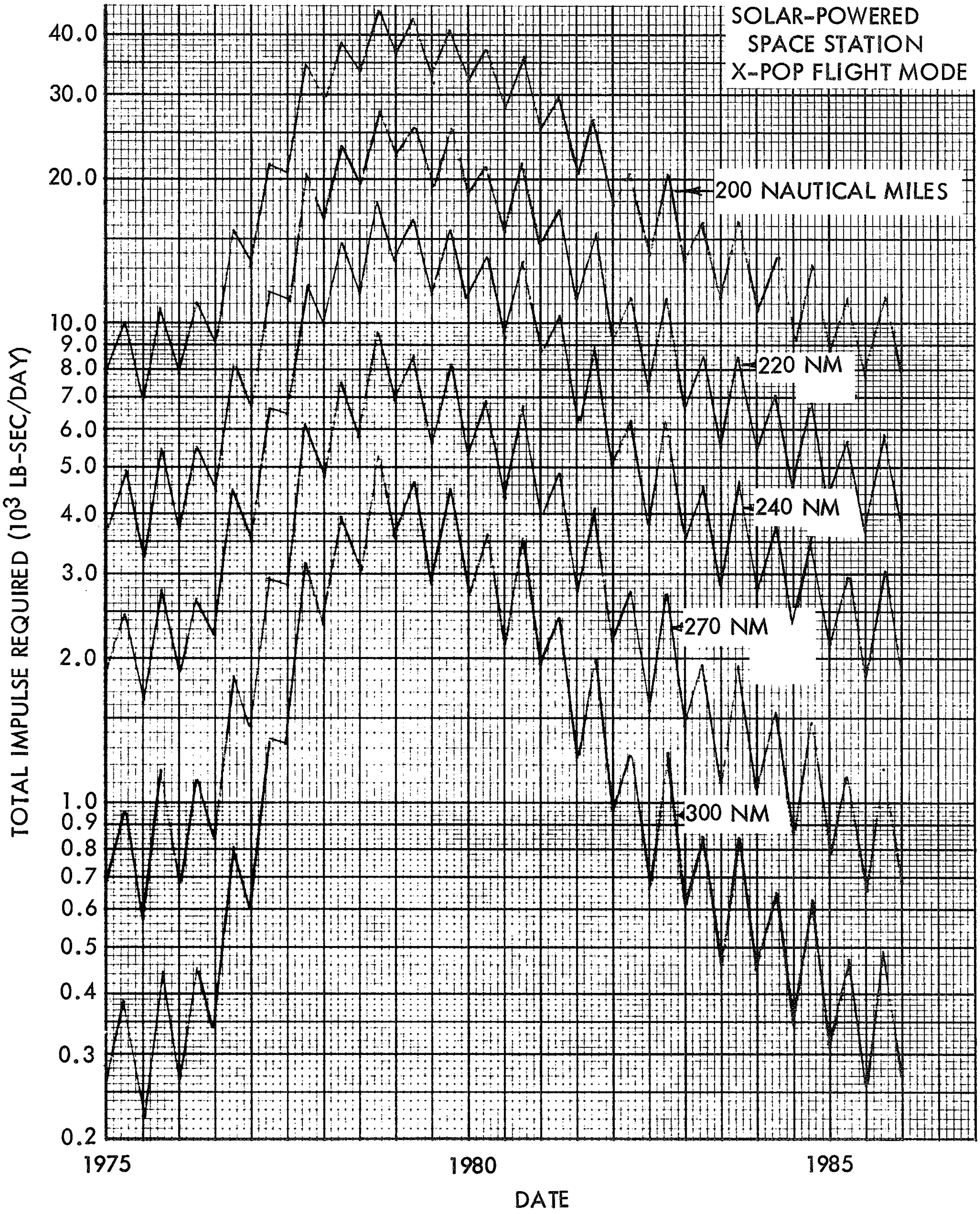


Figure 3-11. Orbit Maintenance Impulse, 2σ Atmosphere, With ALS

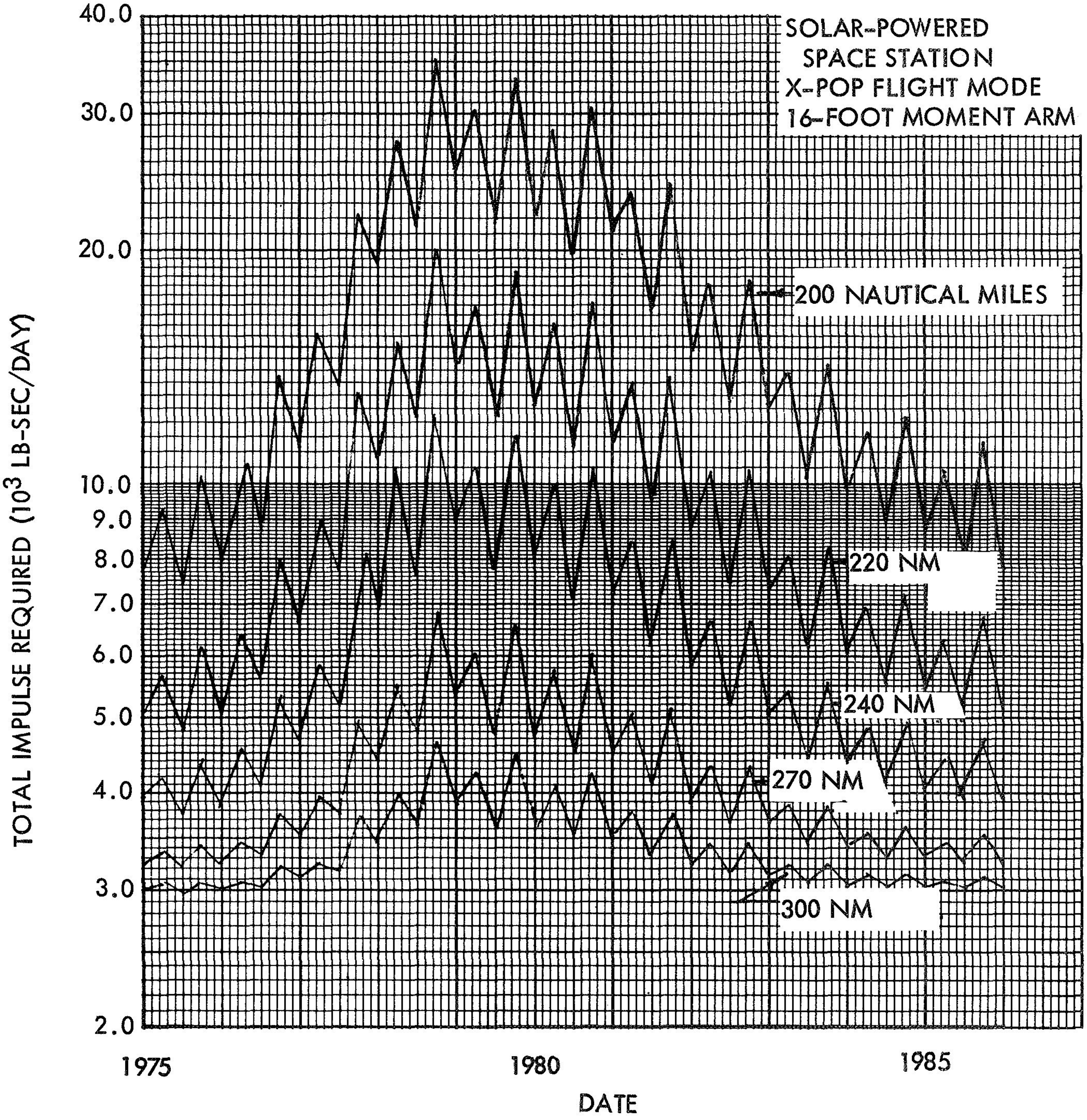


Figure 3-12. CMG Desaturation Impulse, Nominal Atmosphere, With ALS

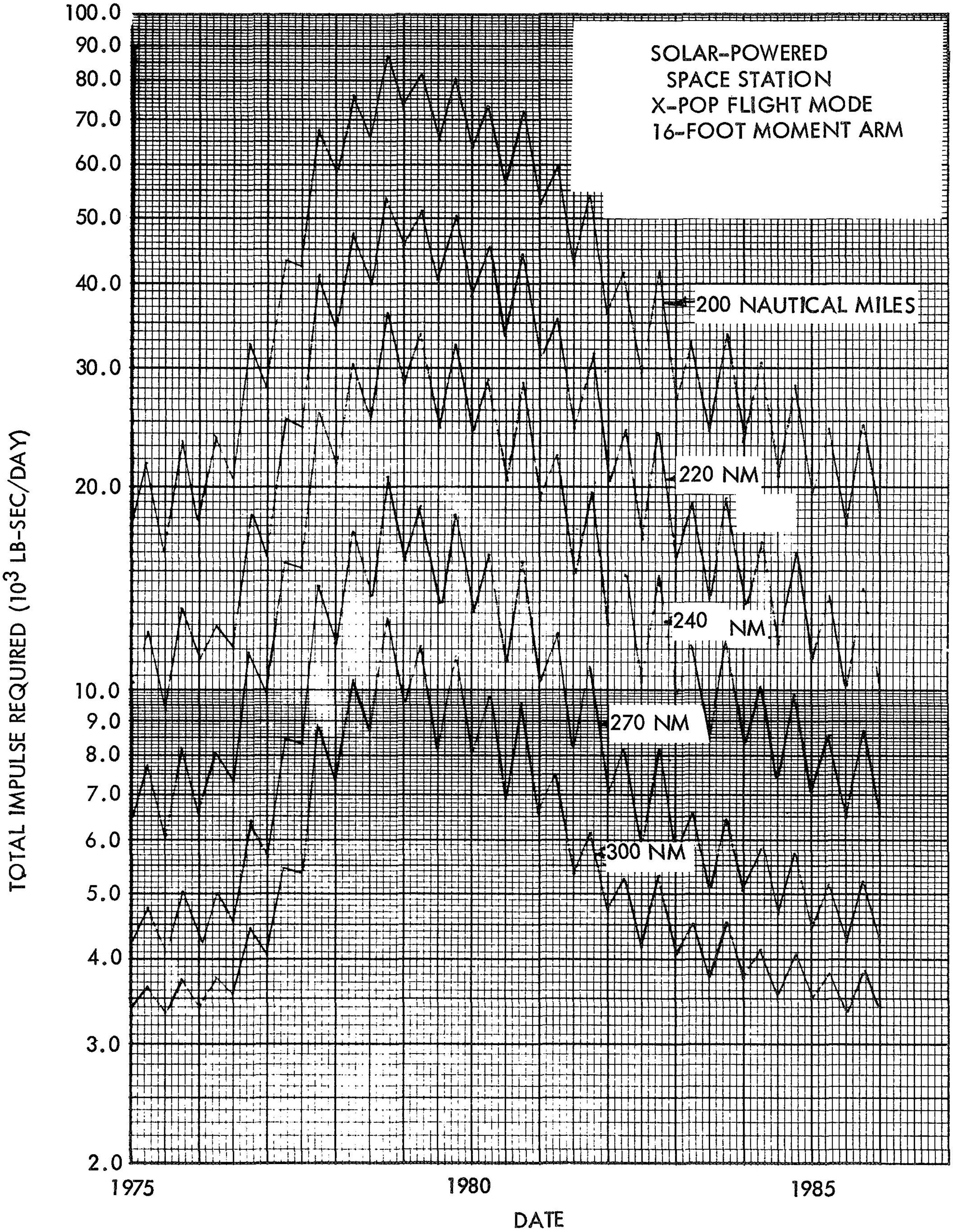


Figure 3-13. CMG Desaturation Impulse, 2σ Atmosphere, With ALS

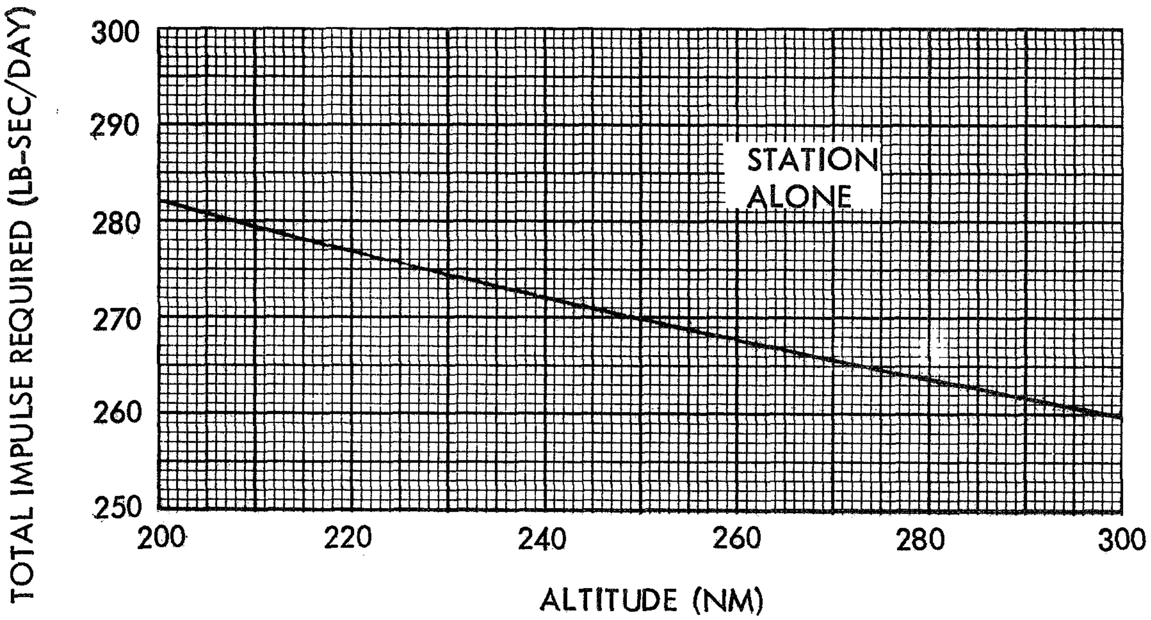


Figure 3-14. Gravity Gradient Impulse, Station Only

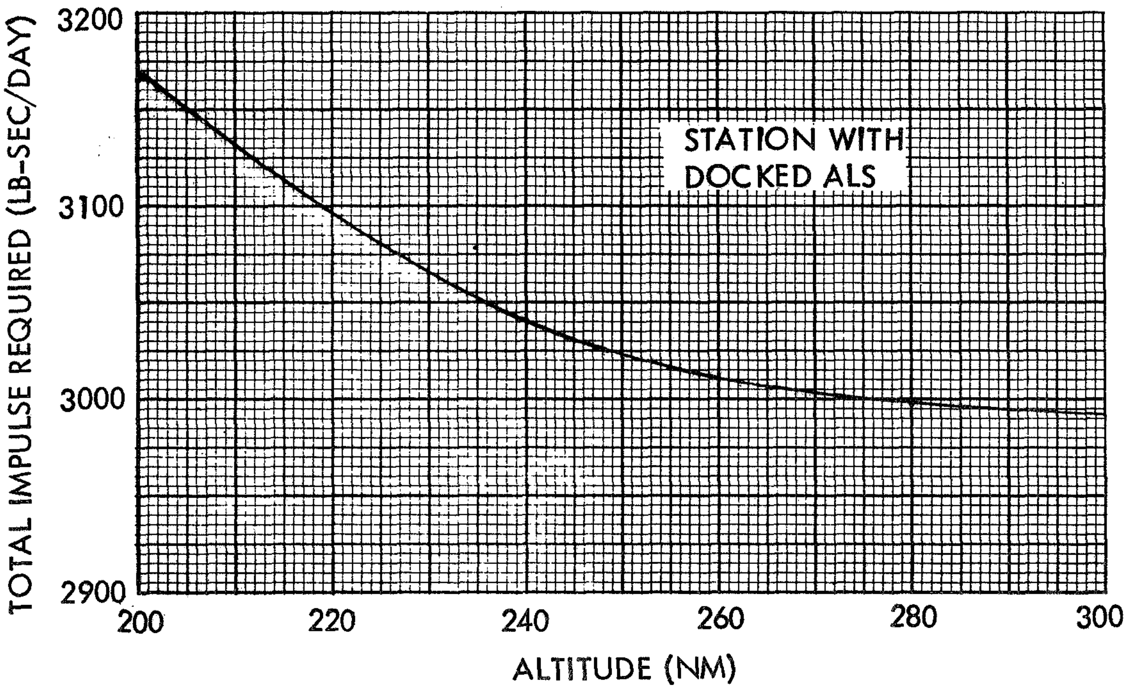


Figure 3-15. Gravity Gradient Impulse, With ALS

ECLSS OPERATION AND WASTE FLUIDS AVAILABILITY

The resistojet thruster can utilize a wide variety of vehicle waste fluids as propellant. The restrictions are governed by materials compatibility, external vehicle surface contamination due to condensation of a chemical species in the exhaust plume, and safety (explosive mixtures). The fluids must also be supplied to the thruster as a gas.

There are three possible sources of waste fluids suitable for propulsion use in the space station: (1) waste gases from the carbon dioxide management assembly, (2) excess water from the water management assembly, and (3) waste fluids from the experiments or ECLSS.

The following sections describe the subassemblies from which these fluids might be obtained and the quantities that might be anticipated.

CO_2 MANAGEMENT ASSEMBLY

The CO_2 management assembly consists of subassemblies for removal, CO_2 reduction, and water electrolysis.

The molecular sieve CO_2 removal subassembly, which consists of CO_2 absorber and desiccant beds operated on a regenerative cycle, provides for removal of CO_2 from the cabin atmosphere and for concentration of the CO_2 for oxygen reclamation. The collected CO_2 is transferred to the Sabatier reactor, where it is combined with hydrogen to form methane and water. The methane is returned for RCS (resistojet) utilization as a development test or vented overboard while the product water plus a sufficient amount of makeup water is electrolyzed to provide the metabolic and leakage oxygen requirements. The hydrogen resulting from electrolysis is returned to the Sabatier reactor and again is reacted. Sufficient additional hydrogen is provided to the Sabatier reactor from the RCS cryogenic H_2 storage tanks so that all the CO_2 can be reduced.

The CO_2 removal concept selected for the space station is being reevaluated. Control of the atmosphere CO_2 partial pressure to 3 millimeters of mercury rather than 5 millimeters of mercury has been imposed on station design and is being studied as a part of the Phase B options. This issue may not be resolved until January 1971. The concept used in this study and described below is based on the concept defined in Volume II of Reference 1.

Carbon Dioxide Removal

A functional block diagram of a four-bed molecular sieve is shown in Figure 3-16. Basic to the operation of this four-bed sorption system is an artificial zeolite (molecular sieve) sorbent material with a high affinity for CO_2. Two canisters of this material function alternatively, with one canister absorbing and the other desorbing. Because the sorbent has a preferential affinity for water vapor, an additional pair of desiccant canisters containing silica gel are used to absorb the moisture from the process stream before it enters the CO_2 removal beds.

Air drawn from the humidity control subassembly by the process flow fan passes through a liquid-cooled adsorbing desiccant bed, where the stream is dried to a dewpoint of approximately -85 F. The air continues through a liquid-cooled adsorbing molecular sieve canister, where CO_2 is removed by adsorption on zeolite. Effluent air returns to the cabin through the desorbing desiccant canister, where desorption of the contained water rehumidifies the air and regenerates the desiccant bed. Heat is supplied to the desorbing desiccant canister by resistance heaters embedded in the canister.

The remaining components of this subassembly are simultaneously engaged in recovering previously absorbed carbon dioxide. The canister that had been absorbing carbon dioxide from cabin air is isolated from the other canisters and is ready for desorption, which is a sequenced operation. In the first desorbing phase, atmospheric gas filling the void volume in the isolated, desorbing, zeolite canister is first returned to the concentrator inlet by the compressor. The accompanying reduction in canister pressure to approximately 1.0 psia causes partial desorption of air and carbon dioxide, which return with the void volume gas. This ullage and adsorbed air recycling is necessary for the delivery of CO_2 of high purity.

In the second phase of this recovery operation, the compressor discharge is diverted into the accumulator by a solenoid-operated valve. The compressor maintains reduced pressure in the desorbing zeolite canister and transfers the carbon dioxide to the accumulator as it is desorbed. This desorption process is accelerated by the transfer of heat to the zeolite bed from electric resistance heaters in the bed. Near the end of the cycle, the bed is precooled before adsorption. The operation is controlled by a timer that cycles the valves in a predetermined manner. An alternate operating mode is vacuum desorption, which is used to remove CO_2 from the atmosphere in case the CO_2 pump or Sabatier unit fails. This mode would be used in an emergency or during crew exchange periods, because both CO_2 and air are lost in the process.

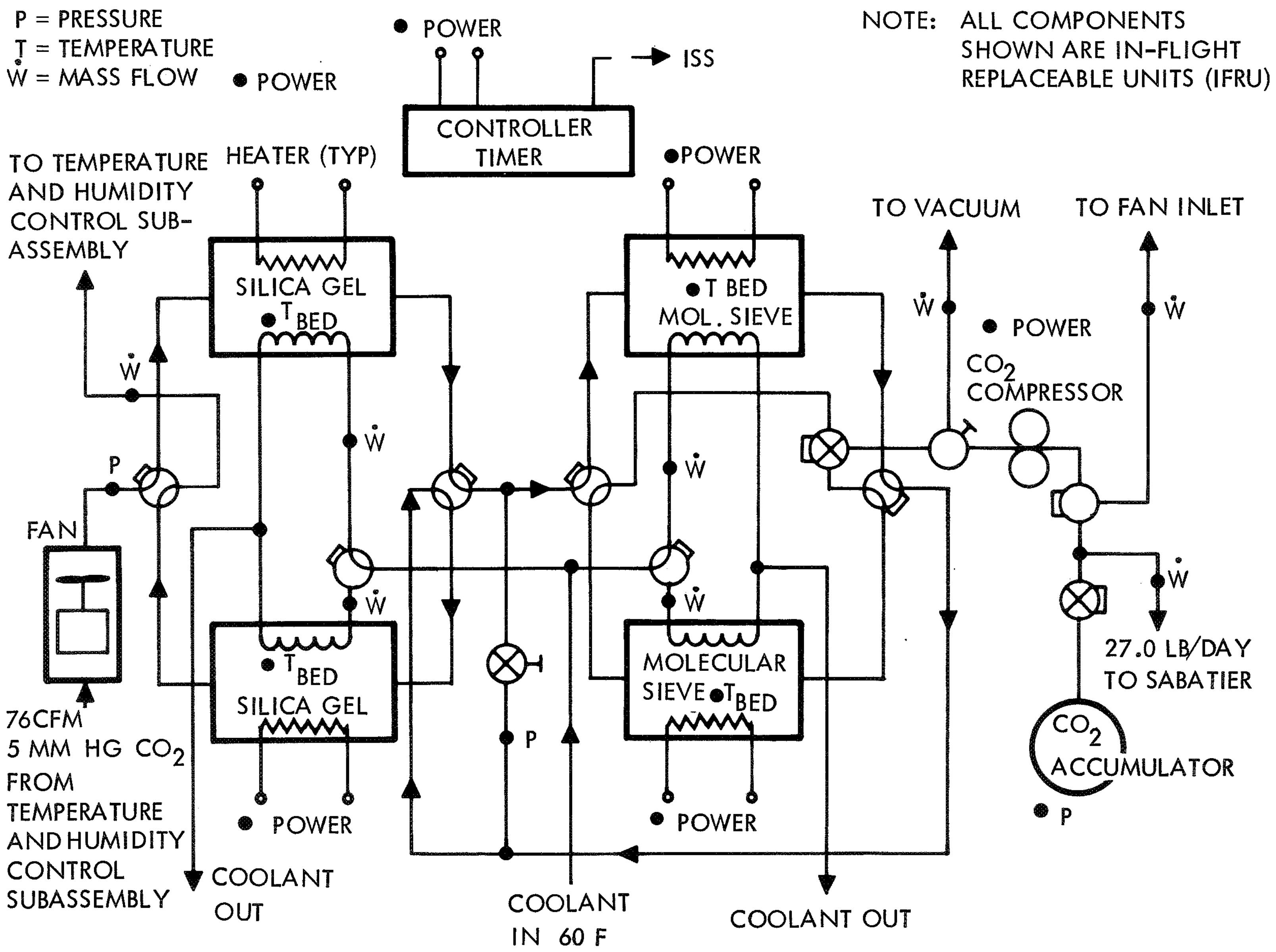


Figure 3-16. Molecular Sieve Subassembly

Operation of this unit is synchronized with the sun-side portion of the orbit by information subsystem (ISS) control to take advantage of the available power. The half-cycle times of the molecular sieve and silica gel beds are 68 and 34 minutes, respectively. The operation time extends approximately 10 minutes into the dark portion of the orbit, during which time the desorbing beds are precooled before going on line (during the rest of the dark period, coolant continues to circulate through the beds, but the fan and compressor are shut off).

During start-up, the silica gel beds must be dried by cycling them without allowing flow into the molecular sieve bed. This must be done to prevent the poisoning of the molecular sieve beds by the ambient moisture in the silica gel beds.

The primary CO_2 removal subassembly in the lower toroid normally removes CO_2 for the entire vehicle. Flow circulated by the temperature and humidity control subassembly assures that process flow reaches all decks. The redundant molecular sieve subassembly in the upper toroid is used in a water save-CO_2 dump mode during crew exchange or in a normal mode in the event of primary subassembly failure.

The primary performance characteristics for 12-man nominal operations are as follow:

Nominal CO_2 collection rate	1.75 pounds per hour on absorbing cycle
Nominal CO_2 collection rate	1.1 pounds per hour (daily average)
Inlet CO_2 partial pressure	5.0 mm Hg (cabin concentration)
Air flow rate	76 cfm
Desorption bed temperature	180 F
Desorption bed pressure	1.0 psia
Heat rejection	11,900 Btu's per hour
Coolant temperature	$\approx$60 F
Zeolite bed inlet dewpoint	-85 F
Accumulator capacity	3.1 pounds of CO_2 at 40 psia
Accumulator pressure	20 to 40 psia

The secondary performance characteristics are as follows:

> CO_2 removal rate with two units operating: 2.20 pounds per hour, average, with 24-man production rate and CO_2 partial pressure of 5.0 mm Hg at inlet
>
> CO_2 partial pressure increase from 5.0 mm Hg to 7.6 mm Hg in 12 hours with no molecular sieve operating

A significant interface of the molecular sieve subassembly is with the Sabatier subassembly for processing collected CO_2. Because the molecular sieve is cyclic in operation and the Sabatier is continuous in operation, a CO_2 accumulator is provided to afford a continuous supply of CO_2 to the Sabatier reactor.

Sabatier Carbon Dioxide Reduction

The Sabatier subassembly consists of a reactor, a condenser-separator, a condensate pump, and controls. Figure 3-17 is a block diagram of this subassembly. The Sabatier subassembly hydrogenates carbon dioxide and produces methane and water according to the following chemical reaction:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O + \text{heat} \qquad (3\text{-}1)$$

The hydrogen to support reaction comes from two sources (electrolysis and RCS storage) and is supplied in an amount five percent above that required by the previous equation, to ensure complete reaction of CO_2 and ultimate recovery of all oxygen available.

The normal operation of the Sabatier reactor is continuous, with CO_2 being supplied from molecular sieve subassembly accumulators and hydrogen being supplied from electrolysis or the RCS. The electrolysis unit, which operates during the light side of the orbit, supplies the required hydrogen during that period. Hydrogen is supplied from RCS stores during the dark side of orbit. For nominal orbits, the electrolysis unit H_2 production exceeds that required by the Sabatier unit for continuous operation. Therefore, a hydrogen accumulator is required to contain and utilize this excess hydrogen production. The mixture of hydrogen and carbon dioxide is controlled by a pressure regulator and orifices to maintain a constant preset ratio. The temperature profile along the reactor is maintained at 600 F at the inlet and at 400 F at the outlet, by control of the coolant. The reactor is started by start-up heaters, which bring the reactor to an operating temperature before the entrance of H_2 and CO_2. The water produced is directed to the wash water assembly. The gases (primarily methane) from

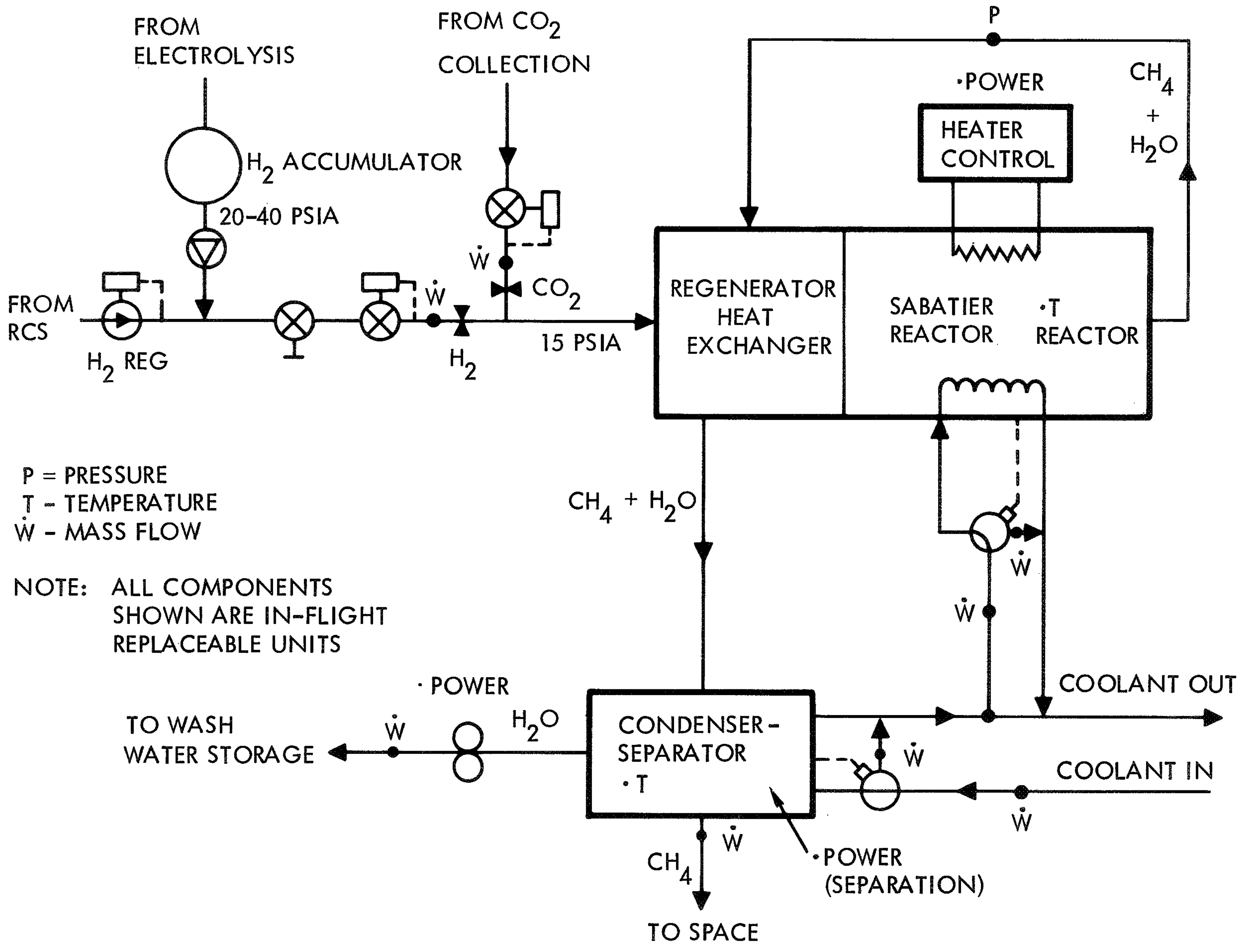


Figure 3-17. Sabatier CO_2 Reduction Schematic

the condenser-separator may be vented overboard or used for resistojet propellant.

The primary performance characteristics of the Sabatier subassembly for 12-man continuous operation are as follows:

Operating time	Continuous
CO_2 reduction	1.13 pounds per hour
H_2 flow	0.207 pound per hour
H_2 electrolysis	3.5 pounds per day (average); RCS H_2—1.7 pounds per day (average)
H_2 accumulator volume	4.0 cu ft
H_2 accumulator capability	0.054 pound at 40 psia
Waste CH_4	9.8 pounds per day (average)
Waste H_2	0.25 pound per day (average)
H_2O produced	22.1 lb/day
Heat rejection	Condenser: 300 Btu's per hour at 50 F Reactor: 210 Btu's per hour at 90 F

Water Electrolysis Subassembly

The electrolysis subassembly provides oxygen for crew metabolic consumption and leakage makeup and the major portion of hydrogen required for CO_2 reduction by water electrolysis. Figure 3-18 is a functional block diagram of the water electrolysis subassembly. Water from the potable water reclamation subassembly is fed to the electrolysis cells, which are stacked to form modules. Within each cell, feed water enters a compartment separated from the hydrogen cavity by a wicking material. This water is absorbed into the wick and transported to the other side of the wick. From the wick, the water evaporates into the product hydrogen stream, where it diffuses through the hydrogen stream to the electrolyte matrix. This water vapor is absorbed by the potassium hydroxide electrolyte and electrolyzed to form oxygen, which evolves at the anode, and hydrogen, which evolves at the cathode. Oxygen passes through a condenser-separator (condensed water is pumped back to the cells) to the cabin atmosphere. Hydrogen passes through a condenser-separator to the H_2 accumulator in the CO_2 reduction subassembly. The cells are maintained at

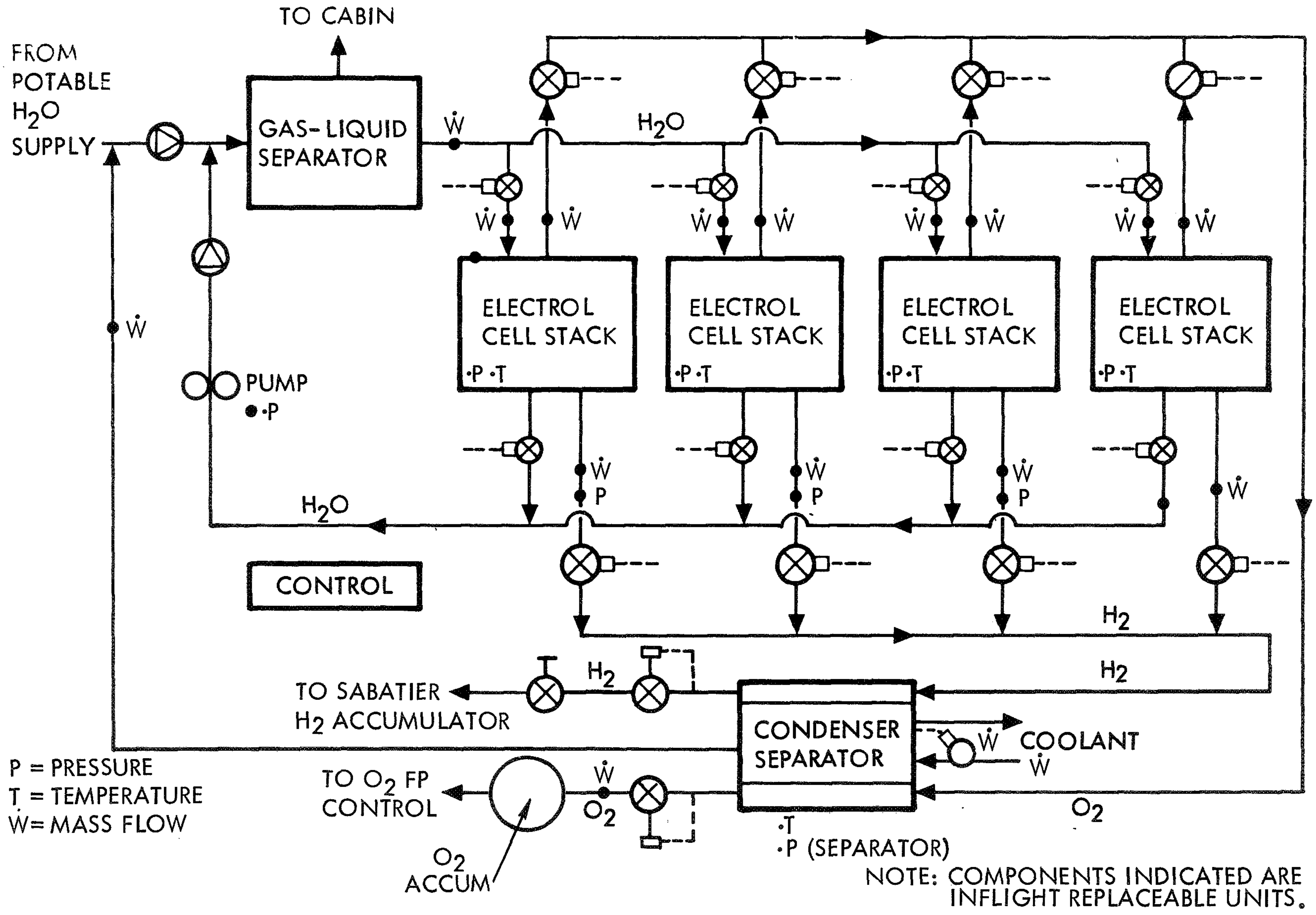


Figure 3-18. Wick Feed Water Electrolysis Subassembly

approximately 170 F, while heat is rejected by evaporation of feed water from the wicks. Gases evolved within the water compartments of the cells must be removed periodically by the circulation of feed water through a gas-liquid separator. In addition to the cell modules, the equipment includes a pump, a condenser-separator, a gas-liquid separator, and controls.

The subassembly is operated only on the light side of the orbit, when large amounts of electrical power are available from the electrical power system. Actuation of electrolysis is initiated through ISS commands when the cabin oxygen partial-pressure control system indicates a demand or capability to accept oxygen in the cabin without exceeding the desired maximum of O_2 partial pressure. For nominal oxygen supply requirements, the electrolysis unit operates for 60 minutes of the orbit.

Because oxygen demands can occur at any time in the orbital period, an accumulator is required to meet the demands during the dark side of the orbit.

The water supplied to the electrolysis assembly is drawn from potable storage to ensure that water to be electrolized contains the lowest possible concentration of dissolved gases that could impair water feed devices.

In normal operation, only three of the four electrolytic cell stacks shown are required. One cell stack is redundant and can be put on line in the event of failure of the operating stacks.

The primary performance parameters of the electrolysis subassembly for the 12-man crew are as follows:

Operating time	Light side of orbit; estimated 57 minutes per orbit (minimum)
Water supply	2.105 pounds per hour (light side)
Oxygen production	28.2 pounds per day (average); 1.87 pounds per hour (light side)
Hydrogen production	0.234 pound per hour (light side)
O_2 Accumulator capacity	3.0 pounds at 50 F and 50 psia
O_2 Accumulator volume	15 cu ft
Heat rejection	5500 Btu's per hour at 70 F coolant

WATER MANAGEMENT ASSEMBLY

The water management assembly consists of subassemblies for processing urine, wash, and experiments water, storage of processed water, and maintenance of sterility.

The wash and condensate recovery subassembly processes wash water from showers and sinks, as well as the condensate from the humidity control subassembly, in a reverse-osmosis unit. Reclaimed water and Sabatier reactor condensate water is transferred to the storage subassembly, while rejected wash water liquor is sent to the potable recovery subassembly. The potable recovery subassembly processes urine, dishwasher water, and reverse-osmosis-rejected brine in rotating vapor-compression stills. Reclaimed water is transferred from this subassembly to the storage subassembly. Water from all experiments, including the medical and dental areas, is processed by the central station vapor compression reclamation subassembly.

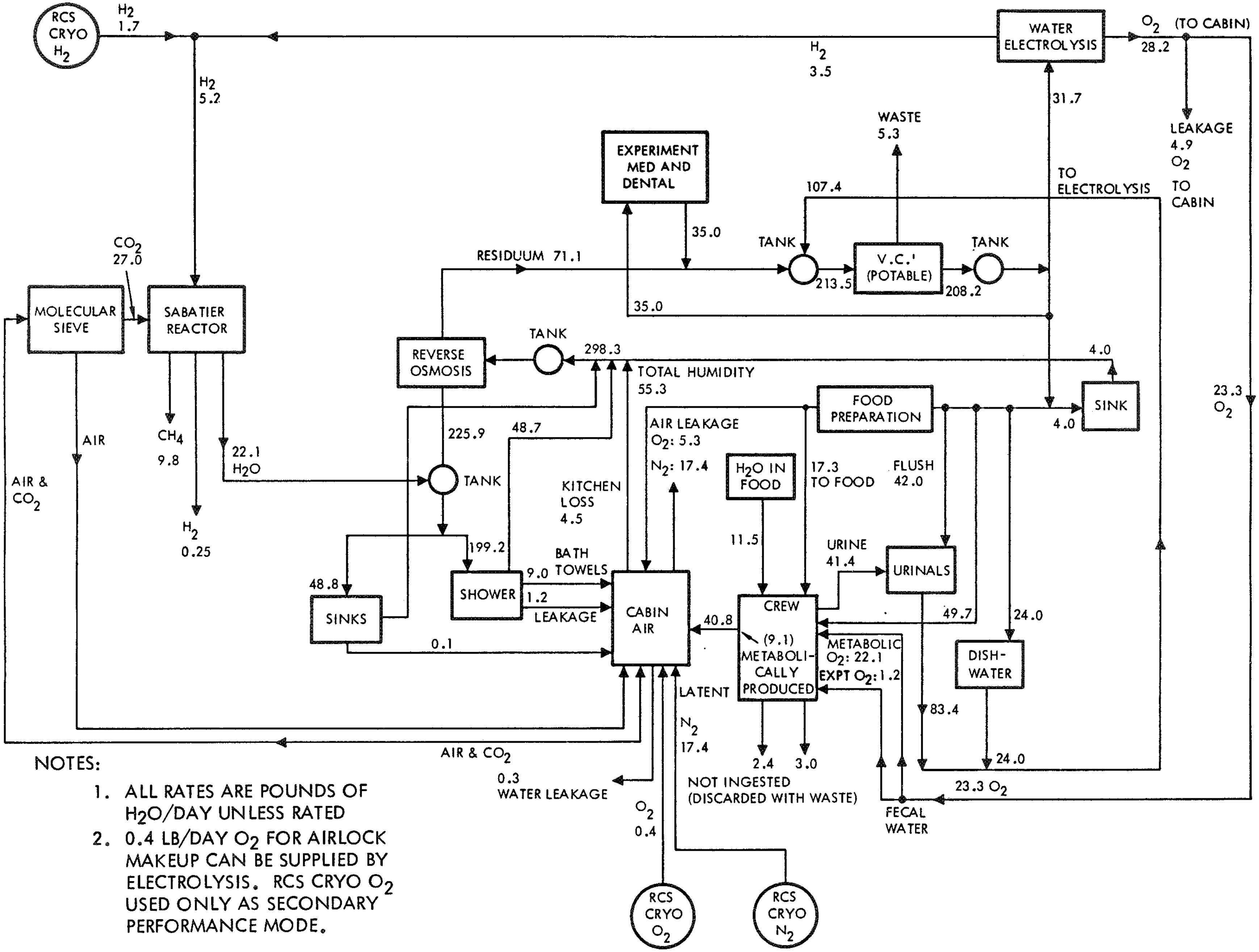
The clean-water storage subassembly consists of separate storage tanks for wash and potable water. This water is maintained at 160 F in all storage tanks for bacteria control through pasteurization. In addition, silver ions are added to the water in the distribution lines to retard the growth of bacteria.

The water management assembly has a potential interface with the resistojet subsystem through utilization of any excess water as a biowaste propellant. The mass balance for the space station ECLSS is given in Figure 3-19, which was abstracted from Reference 1, Volume II. For the case presented in Figure 3-19, no excess water is available. However, in the following sections detailed analyses will be presented for cases in which there may be excess water due to tolerances and possible conservatism in certain assumptions.

Potable Water Recovery

This subassembly employs the chemical pretreatment of urine, rotating-drum vacuum distillation units with integral but externally mounted vapor compressors, and a post treatment section of bacteria and charcoal filters (Figure 3-20).

Pretreatment chemical from storage tanks is added to urine and flush water from the urinals on Decks 2 and 3 to chemically fix the free ammonia and kill bacteria. This pretreated urine, reverse-osmosis residuum, waste experiments water, and the previously pretreated urine from the urinals on Decks 2 and 3 are held in the waste water tank.



NOTES:

1. ALL RATES ARE POUNDS OF H_2O/DAY UNLESS RATED
2. 0.4 LB/DAY O_2 FOR AIRLOCK MAKEUP CAN BE SUPPLIED BY ELECTROLYSIS. RCS CRYO O_2 USED ONLY AS SECONDARY PERFORMANCE MODE.

Figure 3-19. Twelve-Man Station Water Balance

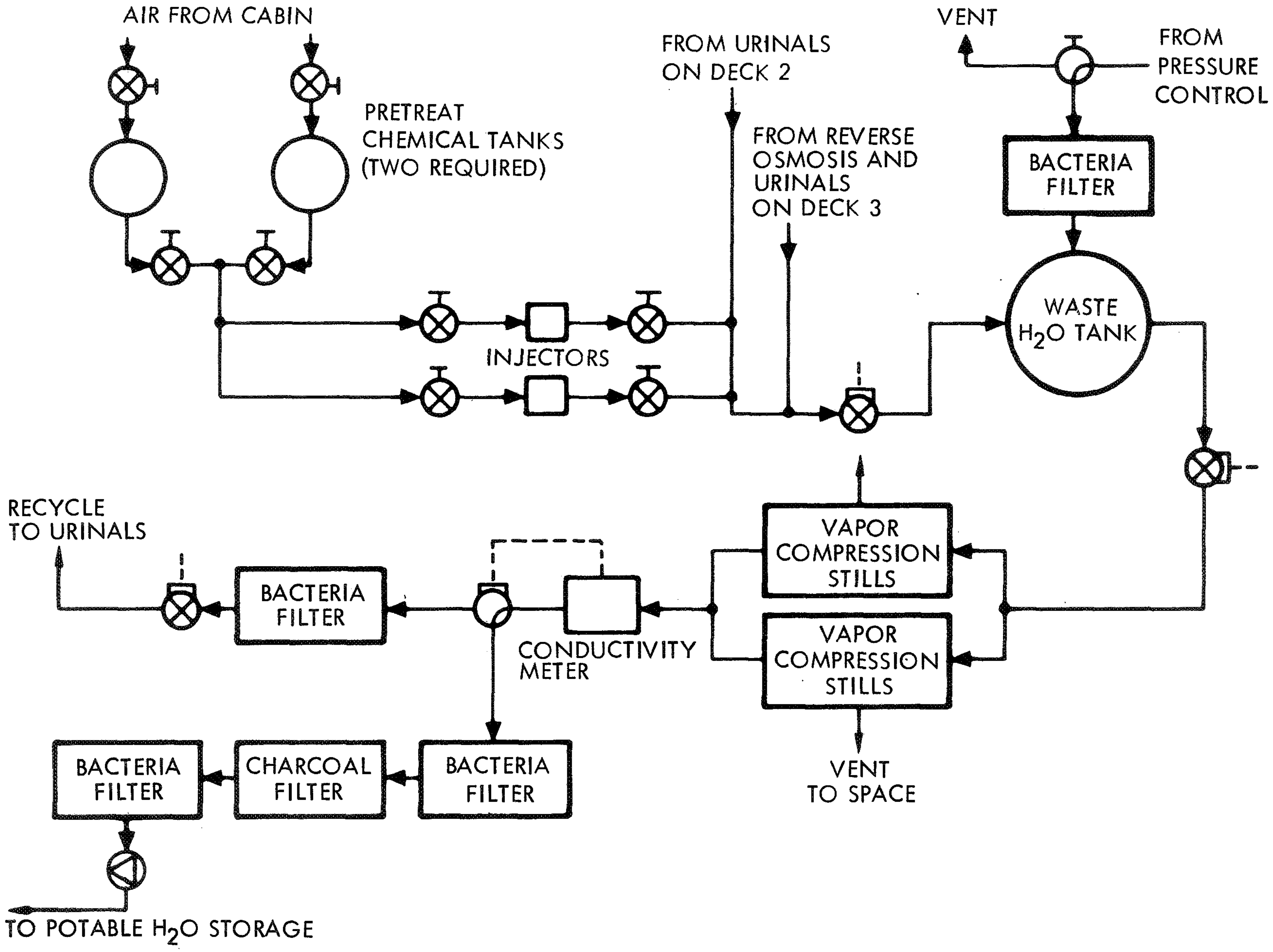


Figure 3-20. Potable Water Recovery Schematic

Because of the unknown composition of the experiments water, the amount and type of pretreatment cannot be predicted. Individual pretreatment integrated with each of the sinks serviced by the experiments loop should be considered, especially treatment for bacteria control in the medical and dental sinks.

As the waste is processed in the vapor compression stills, the water vaporizes at near ambient temperature and reduced pressure within the evaporator. In the compressor, the vapor pressure and temperature are raised above the levels in the evaporator to provide a temperature differential between the condenser and the evaporator. Thus, when condensation takes place, the heat of condensation is transferred by conduction to the evaporator, and is therefore conserved. The remaining liquor, after most of the water within the still is recovered, is transferred to a solids dryer, which is integrally associated with the still. The solids remain in the dryer, and the vapor is returned to the evaporator section of the still. With this arrangement, 97.5 percent of the water is recovered.

The primary potable water recovery subassembly on Deck 2 recovers water from all urine, experiments, and dishwater. It contains two stills that operate 24 hours per day at the nominal process rate. The redundant subassembly on Deck 3 also contains two stills and is operated as follows:

- During crew exchange (when the processing rate must be doubled)
- During depressurization of Decks 1 and 2 (when scheduled maintenance is impossible)
- During maintenance of the primary subassembly, if necessary
- To handle higher than nominal usage rates

The performance characteristics for the potable water recovery components are as follows:

Operating design time	Continuous
Process rate	8.9 pounds per hour
Heat rejection	1490 Btu's per hour

Detailed requirements and analysis are given in Reference 1, Volume IV.

Wash and Condensate Water Recovery

Reverse osmosis is a semipermeable membrane process in which 200 to 300 psi of pressure is employed to reclaim water (Figure 3-21). The semipermeable membrane prevents the passage of solids and other contaminants, but allows the transfer of water.

In this subassembly, waste water consisting of wash water, humidity, and Sabatier condensate is received and stored in holding tanks. The waste water is drawn from the tank and pressurized by a pump for insertion into the reverse-osmosis circulation loop. Recirculating flow is provided by a low pressure rise/high flow pump. In the reverse-osmosis unit, the high pressure forces the water through the semipermeable membrane against the osmotic pressure, leaving the solids in the circulation loop. The reclaimed water is continuously removed and pumped through a series of charcoal and bacteria filters. The concentrated waste liquor that builds up in the circulation loop is routed to the potable water recovery subassembly upon a signal from the solids sensor. The conductivity meter activates a solenoid valve and returns the water to the tank for recycling if the conductivity is too high (denoting impurities).

A single reverse-osmosis subassembly is provided with the waste-water portion of Deck 2 and the clean-water portion located on Deck 3. Redundant charcoal and bacteria filters can be brought on line remotely if the primary filters require replacement when a volume is depressurized.

The subassembly is designed to operate at the nominal process rate for 18 hours per day. The remaining six hours are allocated to maintenance and/or extended operation to account for greater-than-nominal usage rates.

The performance characteristics for the wash and condensate recovery subassembly are as follows:

Operating design time — 18 hours per day

Process rate — 16.5 pounds per hour

Heat rejection — 510 Btu's per hour

Water Storage and Purity Control

The water storage and control subassembly provides the following functions:

- Water storage and inventory control
- Water distribution

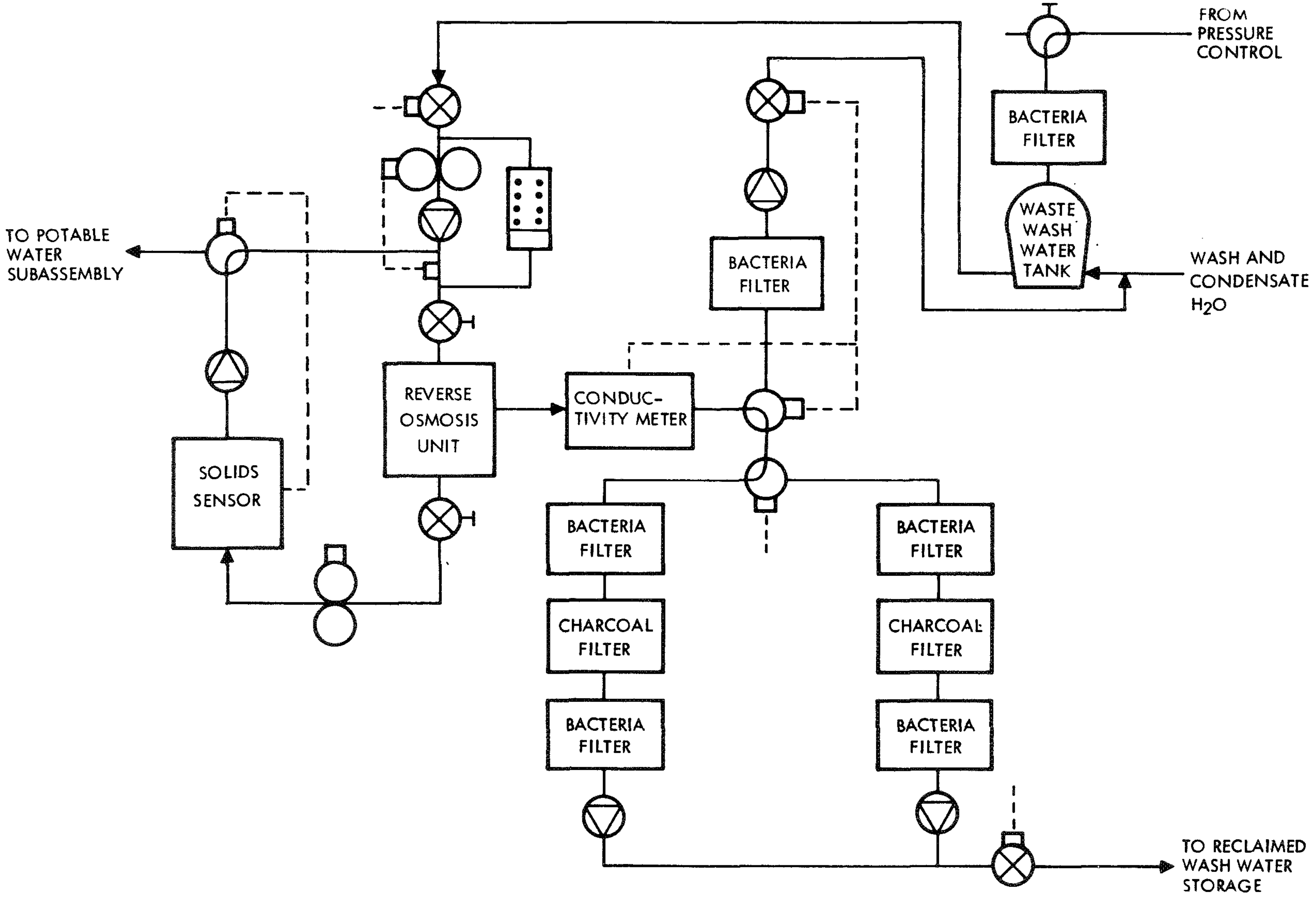


Figure 3-21. Reverse Osmosis Subassembly

- Water-quality monitoring
- Bacteria control

It should be noted that waste-water storage is not included in this subassembly, because this function is an integral part of the processing subassemblies.

One of these subassemblies is provided for each of the three major water loops: primary potable, redundant potable, and wash water. Each subassembly consists of heated water-storage tanks, a water-quality monitoring system with a circulating pump and auxiliary equipment, valves and controls, and distribution plumbing. Water-quality and redundancy requirements of each loop dictate the number of storage tanks required. Where water quality and use are critical — such as in the potable loop — two tanks are used. Two tanks were selected for the wash water even though this is not a critical function.

Bladder-type tanks were selected as the baseline approach. Water stored in the tanks is maintained at a pasteurization temperature of 160 F. Circulation in the storage tanks is provided by the pump used to obtain water samples for monitoring purity (Figure 3-22). This circulation prevents localized stagnation and potential bacteria growth and provides for a homogeneous water sample for purity testing.

During normal operation of a two-tank loop, one tank is on line providing a continuous supply, while the second type is being filled with the newly processed water to avoid potential contamination of the first tank by the processed water inflow. Tank pressurization for expulsion is provided by the nitrogen pressure control subassembly.

The water is cooled to room temperature (65 to 80 F) downstream of the storage tanks by a heat exchanger on the cabin coolant loop subassembly. A silver ion generator is installed immediately after the heat exchanger for additional purity protection, and ion collectors are installed at the use ports. In addition, bacteria filters are installed at each use port.

The purity monitoring unit provides on-line monitoring of the stored water to ensure that only potable water is supplied. Definition of the purity monitoring unit is a significant technology item. A potential design solution is presented in Figure 3-23. The processed water in the space station has three possible types of contaminants: inorganic salts, organic chemicals, and microorganisms.

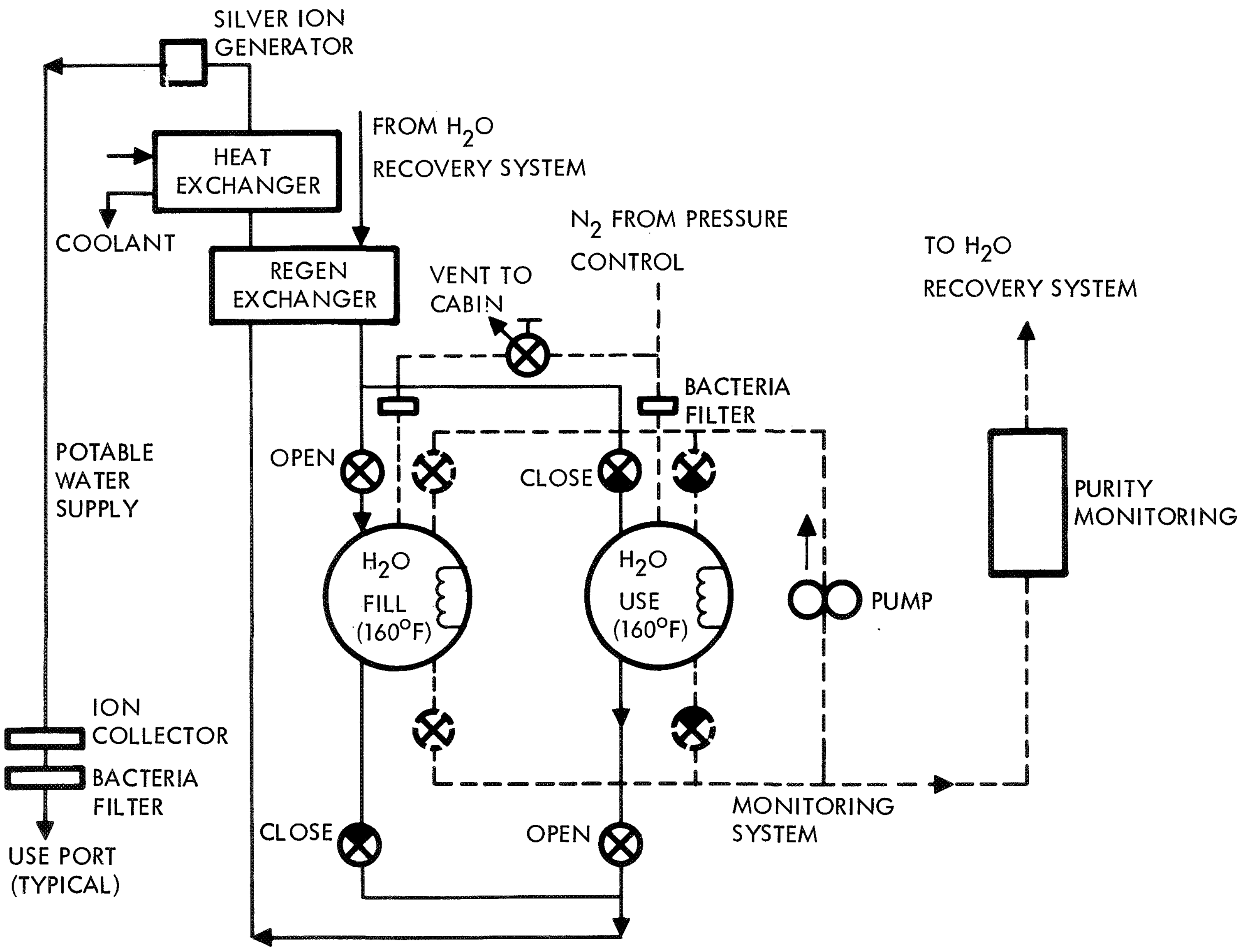


Figure 3-22. Water Storage and Purity Control Schematic

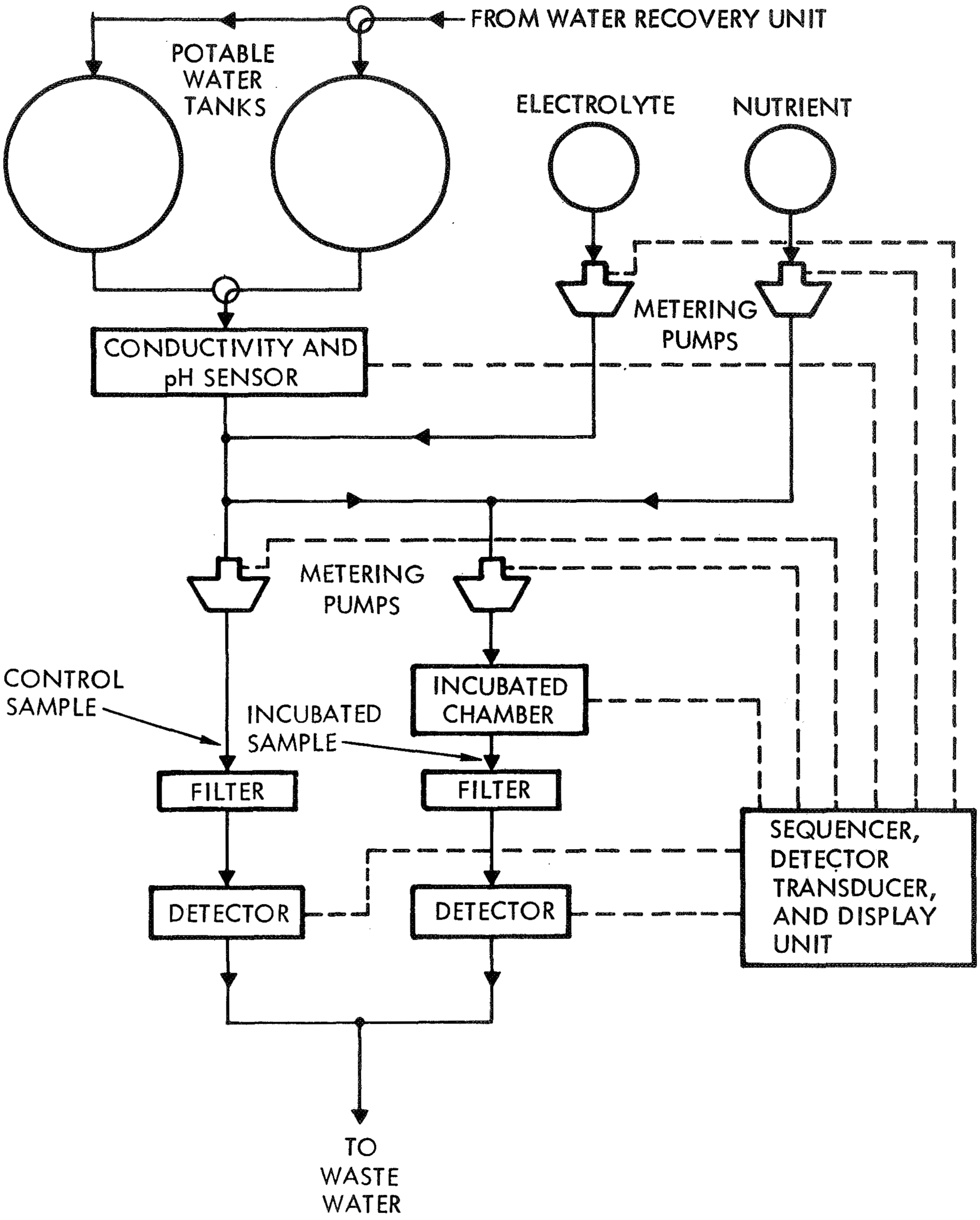


Figure 3-23. Water Purity Monitoring

A three- to four-hour incubation period is required for the detector system to determine water potability. One storage tank supplies previously tested water to the space station, while the second reservoir is isolated during filling and testing.

The detection system withdraws a sample from the isolated reservoir and feeds it through a conductivity and pH sensor to determine the concentration of inorganic salts. A small quantity of electrolyte is added to the sample stream, which is then equally divided into a control sample and a determining sample, with a nutrient added to the latter. The sample streams discharge into small-diameter tubes to ensure plug flow from the equal volume metering pumps. The determining sample goes through an incubation chamber, where any existing microorganisms will multiply. The control and determining samples pass through separate detectors, and a differential reading would indicate the presence of microorganisms.

The detector elements consist of a small-diameter orifice (2 to 20 diameters of the maximum microorganism size), with electrodes for applying a voltage across the orifice. If no microorganisms are present, both samples will have equal conductivity. If microorganisms are present, the determining sample will be less conductive because of the incubated increase of the nonconducting organisms. The voltage for a fixed current flow will be greater for this sample. Predetermined limits on the voltage differential indicate unacceptable purity of the water.

The nonviable organic concentration in the water will be determined by referring the control sample detector to a predetermined voltage for water containing no organics. The above method does not identify the type of contaminant, so it may be possible for one contaminant to build up to toxic levels within the allowable total contaminant level. Further study and research are required in this area to determine if the water reclamation process will allow selective contaminant buildup. The water-purity monitoring unit will provide a positive GO/NO-GO indication of overall water quality. This indication will be both qualitative, by means of an alarm, and quantitative, through a readout of specific parameters. Separate water-purity monitoring units are provided for each loop: primary vapor compression, redundant vapor compression, and reverse-osmosis wash water.

WASTE MANAGEMENT ASSEMBLY

The waste management assembly consists of subassemblies for crew fecal and urine collection and for general station trash collection, processing, and disposal. Two toilet subassemblies, each equipped with a urine collection device, and two standup urinals have been provided in each pressure volume. The fecal collection unit features vacuum drying of the feces, an expendable collection tank, and conventional wipes.

Redundant trash collection and processing centers are provided in the galley on Deck 1 and in the experiments laboratory on Deck 4. A drying chamber is utilized to sterilize wet wastes at 250 F each crew night. Dry wastes are compacted and stored in expendable containers for return to earth via the ALS. The trash processing unit is based on a waste quantity of approximately 30 pounds per day and an uncompacted volume of 2 cubic feet. Trash management is designed as a utility system and accepts experiment waste, food packaging and waste food, expended crew supplies, used clothing, and subsystem wastes, such as filters, spare part packaging, and teletype paper.

The waste management assembly has been designed to emphasize two distinct goals: (1) minimization of contamination both inside and outside the station and (2) a high degree of user acceptance and minimum handling. From a performance point of view, the venting of gases that might condense on the exterior surfaces (radiator, solar panel, or telescope lenses) has been minimized by using low-temperature processing.

The urine collection subassembly is not discussed in detail since the interface with a resistojet assembly would be through the water management assembly.

Fecal Collection

The fecal collection subassembly incorporates an expendable tank for feces storage, conventional wipes, and room-temperature vacuum drying. Because collection, processing, and storage functions are accomplished in one container, complexity and crew handling requirements are minimized.

At defecation, the feces are carried by a transport air flow into the container. The feces then contact a rotating element (slinger), which shreds and accelerates the fecal material outward to form a thin layer around the inner periphery of the container. The rotating slinger also provides phase separation of the feces and transport air. The slinger rotates only while the toilet is occupied by a crewman. After the crewman exits, the container interior is exposed to space vacuum. This dries the thin feces layer, inactivating the fecal bacteria. Actually, the process is one of freezing (by evaporation of a portion of the feces water content) followed by sublimation. The transport air (during toilet use) is returned to the cabin ambient via a mechanical-type bacteria filter and an activated charcoal bed. The fecal collection subassembly schematic is given in Figure 3-24.

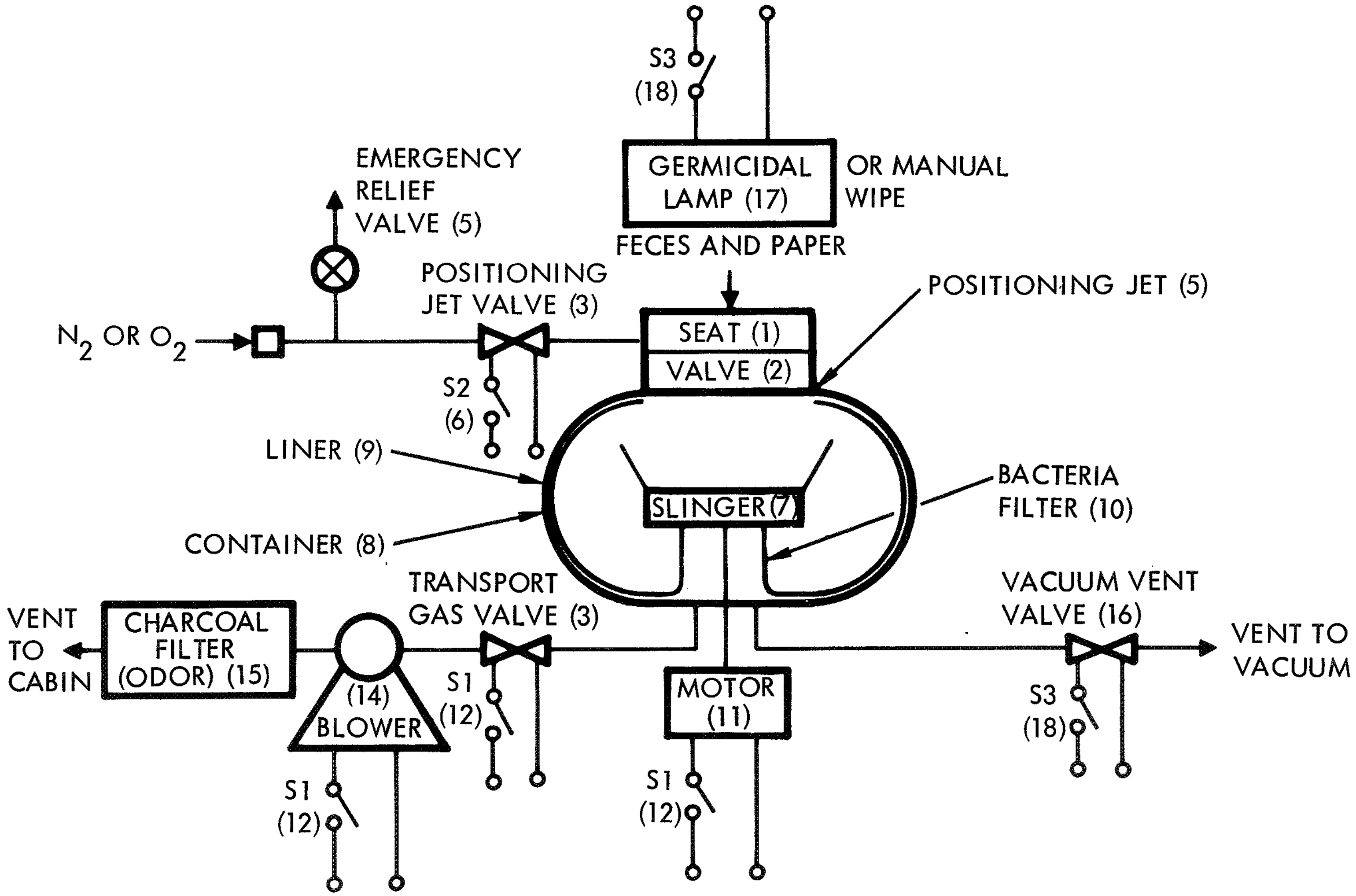


Figure 3-24. Fecal Collection Subassembly

The fecal collection subassembly has the following performance characteristics:

Atmosphere flowrate (operating)	10 cfm minimum
Air filter rating	0.08 micron
Container storage capacity	12 man-months equivalent
Feces drying time/use	2 to 6 hours, 90-percent dry, no crew-use restriction
Atmosphere loss per vacuum exposure	2 cubic feet
Structural penetration for vacuum exposure	1 inch diameter

Component-level trades are involved to determine the following: (1) Are tank liners or tanks expendable? (2) Should the motor be packaged in the tank unit? (3) Should ultra-violet light be installed for seat sterilization? (4) Should heat application be used to increase the fecal drying rate? (5) Is pumpdown of the tank volume required to conserve weight?

Air dump to space varies from 110 pounds per 180 days to 320 pounds per 180 days; therefore, pumpdown may be required. The frequency for replacement of a collection tank depends upon the tank size. Tank storage capacity may be increased to as much as a 24-man-month capability.

Waste Processing

The waste processing subassembly includes provisions for collection of trash, drying and sterilizing, compaction, and storage prior to earth return by ALS. The waste processing center consists of a drying chamber, a compactor with a compressor motor/drive screw unit, access doors, and a storage chamber. Separate processing equipment is intalled on Deck 1 in the galley and on Deck 4, and each equipment unit is capable of servicing the entire station.

Wet waste or trash susceptible to bacteriological growth is inserted into the drying chamber during the crew day. Waste drying and sterilization at 250 F is accomplished during an eight-hour period each night. Dried waste is mechanically compacted and delivered into a storage chamber. The transfer from the drying chamber to compaction and storage is accomplished automatically. The storage chamber is equipped with a removable liner.

Compacted waste is removed and placed in remote storage (the torus area or a cargo module) every seven days. The waste is returned to earth via ALS.

Intermediate waste collection containers, equipped with a chemical additive for odor and bacteria control, are provided throughout the station for short-term storage (two days).

The waste processing subassembly has the following performance characteristics:

Trash quantity	30 pounds per day (wet)
Trash type	See Table 3-2
Trash volume	2 cubic feet per day (uncompacted)
Drying temperature	250 F
Drying time	Eight hours maximum
Compaction	75 psi
Atmosphere loss per vacuum exposure	2 cubic feet
Structural penetration	1-inch diameter

The waste processing subassembly is a conceptual design only. No significant development or design drawings have been made of this concept.

The Whirlpool trashmasher provides a feasibility check for the compactor. Further evaluation must be made of the waste processing subassembly to determine whether the drying chamber, compactor, and storage bin should be separate units or combined into a single unit. It is recognized that the processing center must feature easy access for the trash, careful seal design to prevent cabin atmosphere leakage overboard, and an easy-to-clean design. The liner in the storage bin is scheduled for replacement every seven days. The galley processing center allows for waste insertion from the galley and replacement of the storage container from an aisle outside the galley.

Table 3-2. Station Waste Model

Source	Description	Basic Rate (lb/man-day)	12 Men (lb/day)
Crew	Urine solids	0.13	1.56
	Fecal	0.38	4.56
Food management	Food waste	0.40	4.80
	Food packaging	1.18	7.2
	Utensils, soap, etc.	0.01	0.12
Crew related	Wipes	0.20	2.4
	Hair, nails, skin	0.05	0.62
	Toilet tissue	0.014	0.167
	Medical supplies	0.02	0.24
	Housecleaning supplies	0.02	0.2
	Soap, hygiene	0.033	0.4
	Dental	---	0.1
	Hair control	---	0.1
ECLSS process	Filters, charcoal	---	4.0
	Wicks, cartridges	0.033	0.4
	Water treatment	0.067	0.8
	Used catalysts	0.033	0.4
	Waste treatment and bags	---	0.35
	Clothing, towels, etc.	0.58	7.0
Subsystems	Teletype paper	---	0.1
	Microfilm, magnetic tape	---	-
	Spare part packaging	---	0.5
Experiments	Photo lab	---	0.8
	Bioscience lab, etc.	---	1.0
	Space processing-physics	---	0.4
	Contaminated water (non-normal)	---	3.5

The vent products from the 250 F sterilization process must be evaluated, and consideration should be given to the addition of supplementary filters and equipment to prevent contamination of exterior surfaces. Zero-gravity collection and intermediate storage of waste in the laboratories, the staterooms, and personal hygiene facilities must be adequate to control odor and significant bacteria growth.

WASTE FLUIDS FOR RESISTOJET PROPELLANT

The previous section described the operation of ECLSS subassemblies which might provide waste fluids to be utilized by a resistojet assembly as propellant. In this section, the types and quantities of fluids are defined.

Biowaste Gases

The most accessible fluids, in reasonable quantities, are obtained from the Sabatier condenser-separator. The Sabatier condenser effluent consists primarily of methane and hydrogen and secondarily of varying quantities of CO_2, N_2, H_2O, O_2, and airborne contaminents.

The resistojet system is particularly adaptable to a wide range in the propellant supply model, both in terms of the gases present and the mixture ratios. This property of resistojets makes the operation of a real system relatively simple and the ECLSS relatively noncritical in some respects. However, knowledge of the variation in the supply model is necessary to accomplish the following:

1. Verify the detailed resistojet performance
2. Evaluate the long-life characteristics of the resistojet (condensation, corrosion effects)
3. Verify that only safe gas mixtures are involved
4. Evaluate resistojet plume contamination on the vehicle and environment

The major sources of variation in the waste gas supply are the crew CO_2 production rate and the effectiveness of the CO_2 management assembly.

Baseline Biowaste Supply Model

The baseline biowaste model assumes perfect reactions and 100-percent efficiency of subsystem components. Variations in supply are due to CO_2 production rate only.

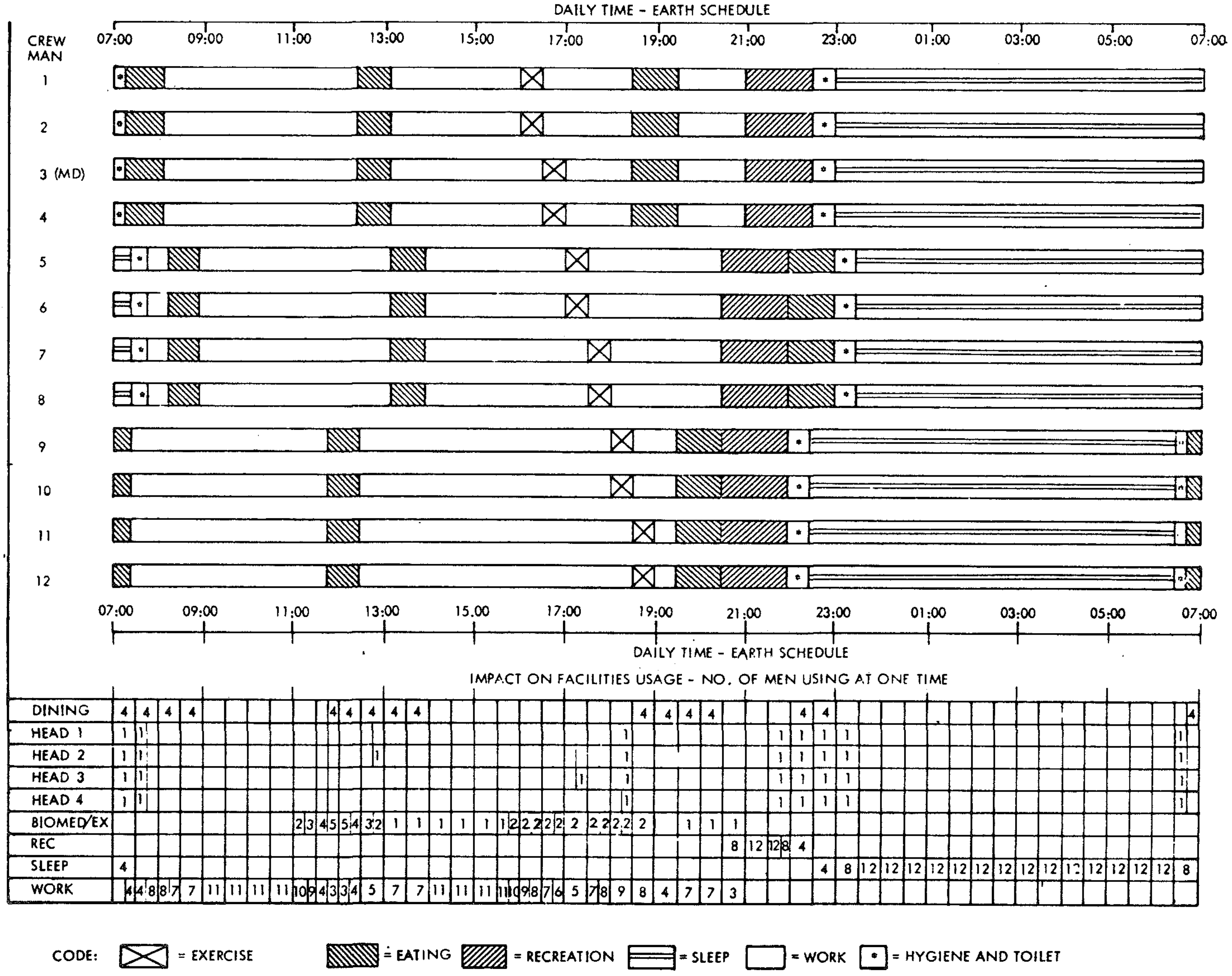
Crew CO_2 production varies primarily with crew activity, crew age, and physical size, diet type, and environment. A comprehensive description of these influences is contained in the Bioastronautics Handbook (Reference 4). The space station employs a nominal crew of 12 men representing a range of technical and scientific disciplines. The crew activities will include all the normal operations, maintenance, and emergency repair associated with an independently operating vehicle. In addition, the crew will conduct an extensive program of research, investigation, and development operations. A comprehensive description of crew activities and operations is contained in the Space Station Crew Operations Definition (Reference 5).

As crew size and mission duration increase, the need for detailed definition of crew personal requirements assumes added importance. In U.S. space flights to date, the task demands of mission time lines, although fulfilled remarkably well by the various crews, have often exceeded desirable levels for long-term space flight. For extended-duration missions, the problem is one of pacing. Preliminary studies suggest that the safest course is to aim for conventional, earth-based-type schedules, unless the particular type of mission or experiment strongly demands alternative scheduling. This means that crews should normally maintain a regular, diurnal schedule, obtain more than seven hours of sleep per day, and work no more than ten hours per day. If due attention is paid to these principles, the probability of mission success should be enhanced. Total disregard of these rules would almost surely produce physical inadequacies within the crew, resulting in serious mission degradation or failure.

Figure 3-25, from Reference 5, is a breakdown of a nominal daily schedule for a 12-man crew. While discrete times are shown for all events, actual scheduling should be less rigid, except as constrained by availability of facilities.

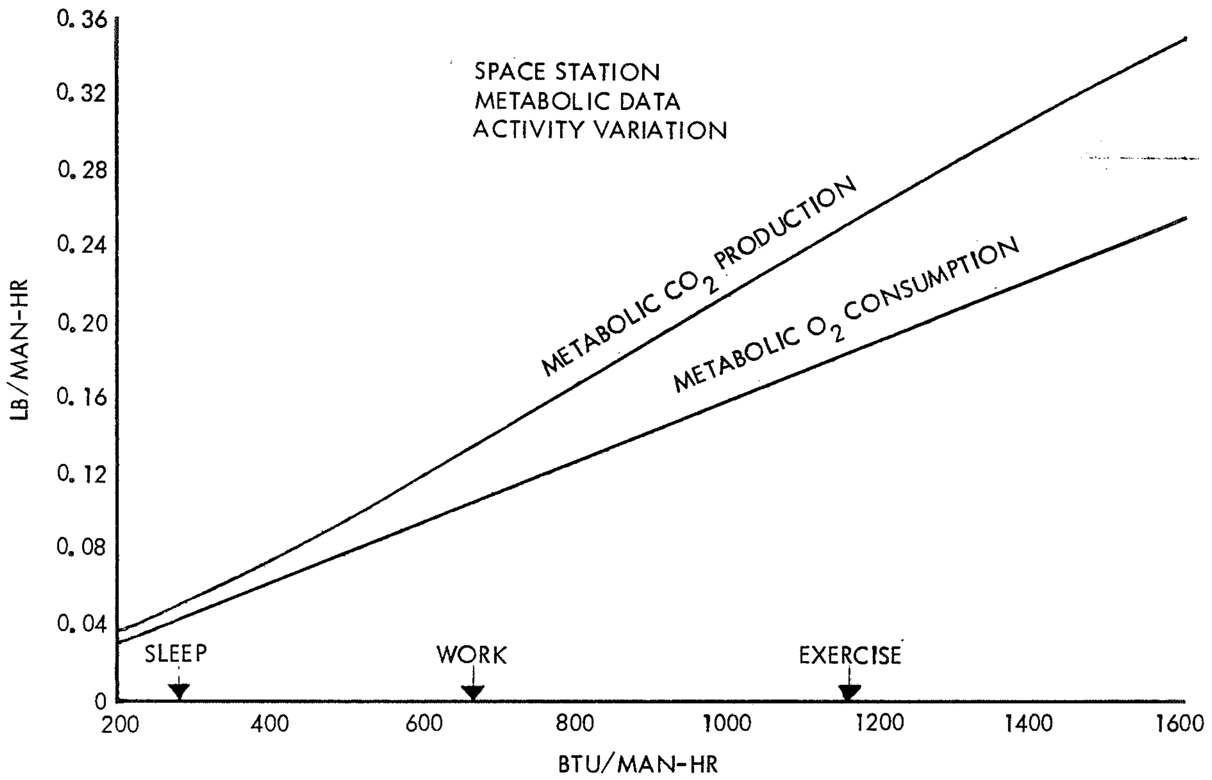
Metabolic O_2 consumption and CO_2 production as a function of crew activity level are presented in Figure 3-26, which indicates nominal energy expenditures for sleep, work, and exercise. Exercise energy peaks to 3000 Btu per hour for short durations (minutes). The 1160-Btu-per-hour exercise level is averaged over a 90-minute time period. Energy expenditure for various activity levels is tabulated in Table 3-3.

The maximum change in metabolic production between sleeping and working was "bound" by using a timeline in which all men were assumed sleeping concurrently and working concurrently. The CO_2 and CH_4 production, assuming 100-percent reaction of CO_2, is shown in Figures 3-27 through 3-30. The term "PERS" indicates time dedicated to personal hygiene, eating, and recreation.



NOTE: ADDITIONAL USE OF HEAD (PERSONAL HYGIENE FACILITY) BEFORE AND AFTER MEALS, AFTER EXERCISE, AND AT RANDOM

Figure 3-25. Nominal Crew Duty Cycle for Routine Day



NOTE:

- O_2 DATA FROM BIOASTRONAUTICS DATA BOOK

RESPIRATORY QUOTIENT VARIED FROM 0.82 TO 1.0

Figure 3-26. Metabolic Data as a Function of Crew Activity Level

Table 3-3. Nominal Energy Expenditure Levels

Activity	Btu per Man-Hour
Sleeping	280
Eating	450
Working (light activity)	600
Exercise (moderate to heavy)	1100 - 1600
Recreation relaxation)	400
Personal hygiene activities	465
EVA/IVA (suited)	1200

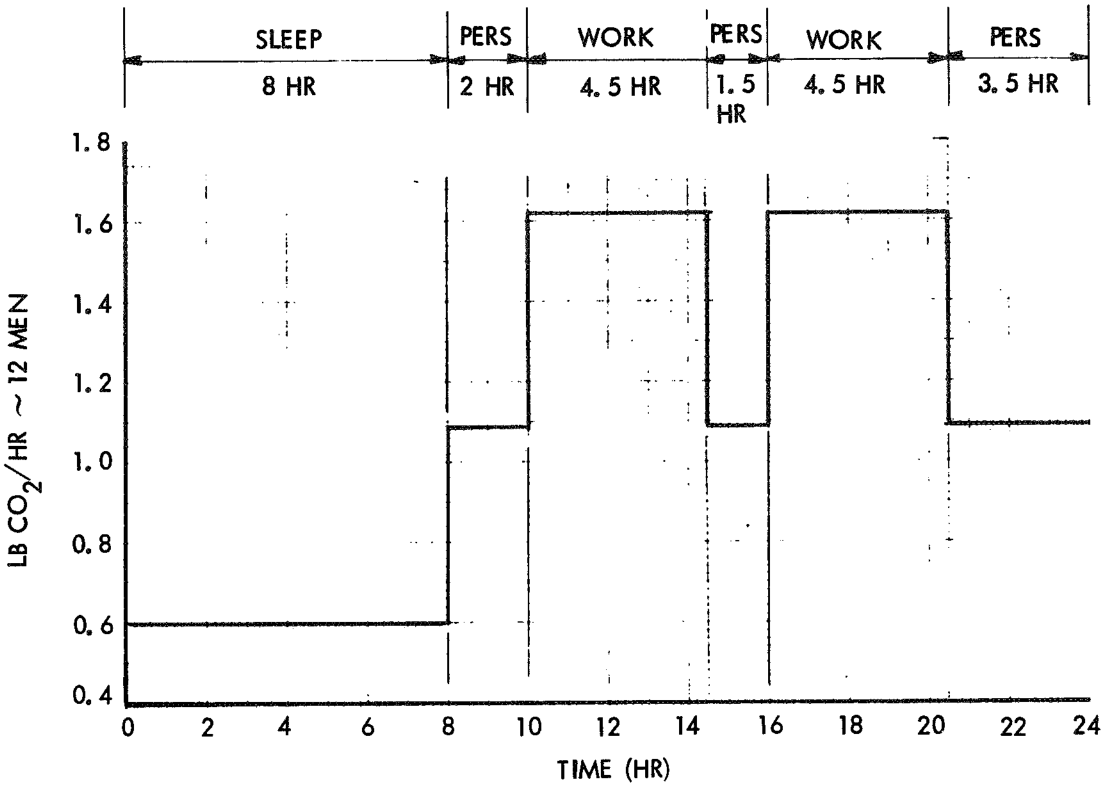


Figure 3-27. Nominal Activity Timeline CO_2 Production, 12 Men

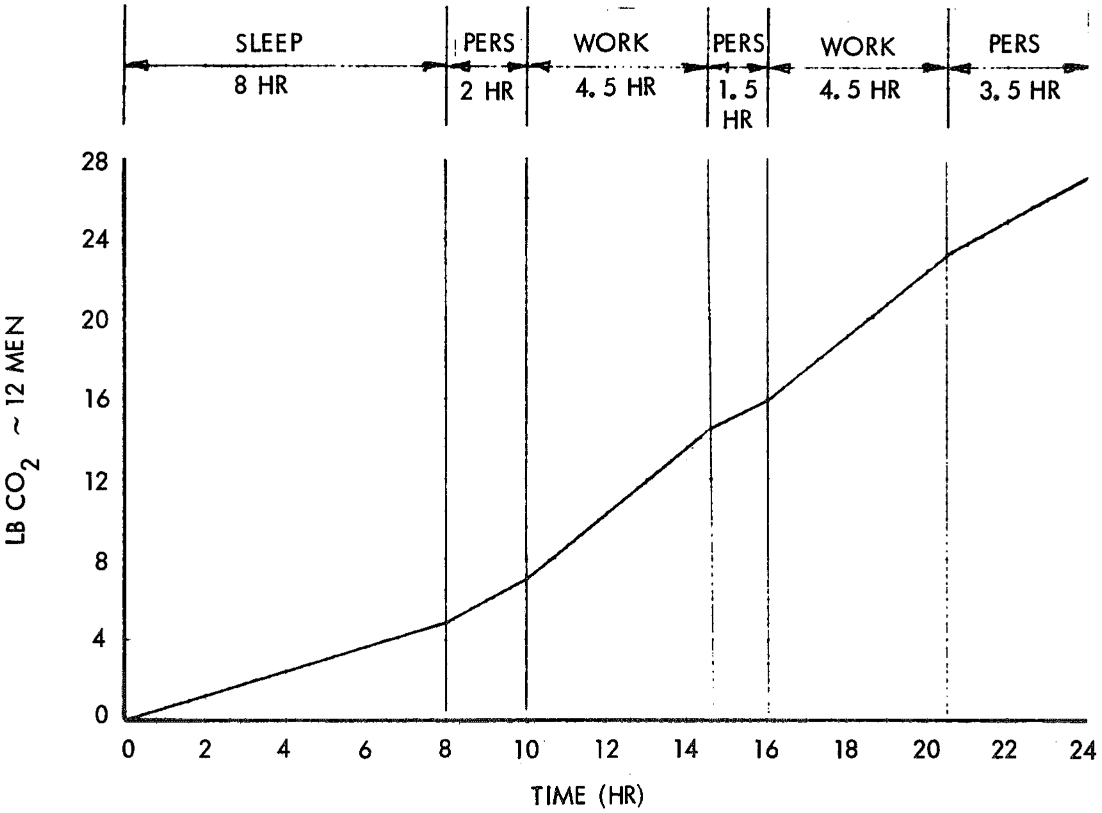


Figure 3-28. Nominal Activity Cumulative CO_2 Production, 12 Men

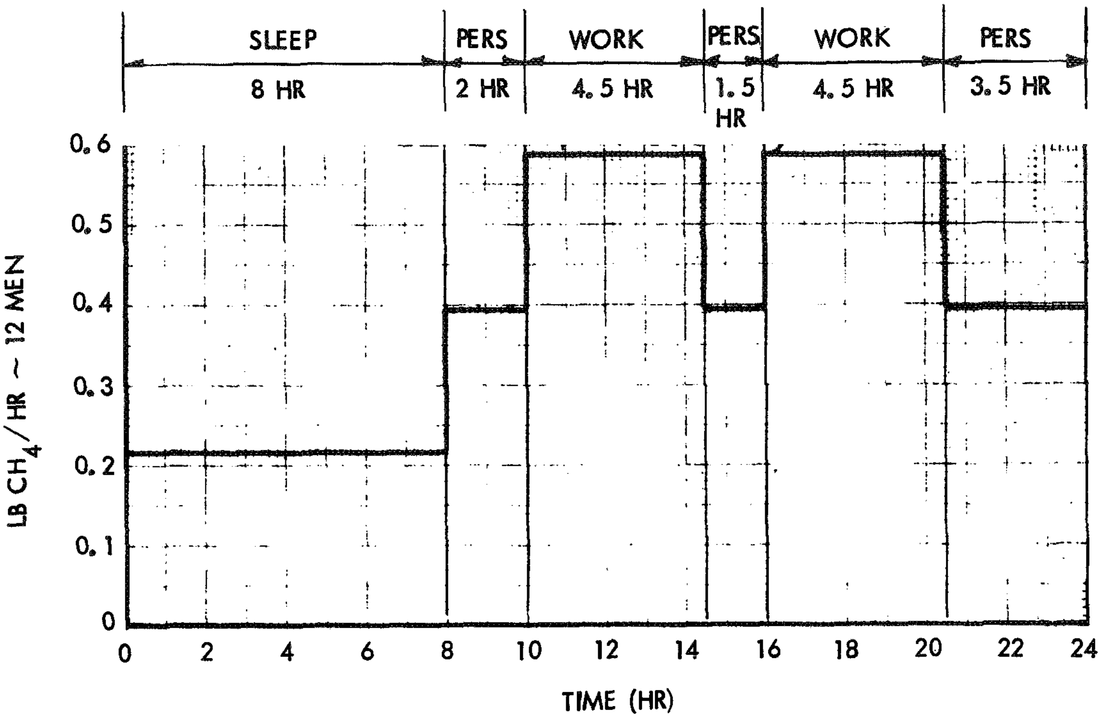


Figure 3-29. Nominal Activity Timeline Ideal CH_4 Production, 12 Men

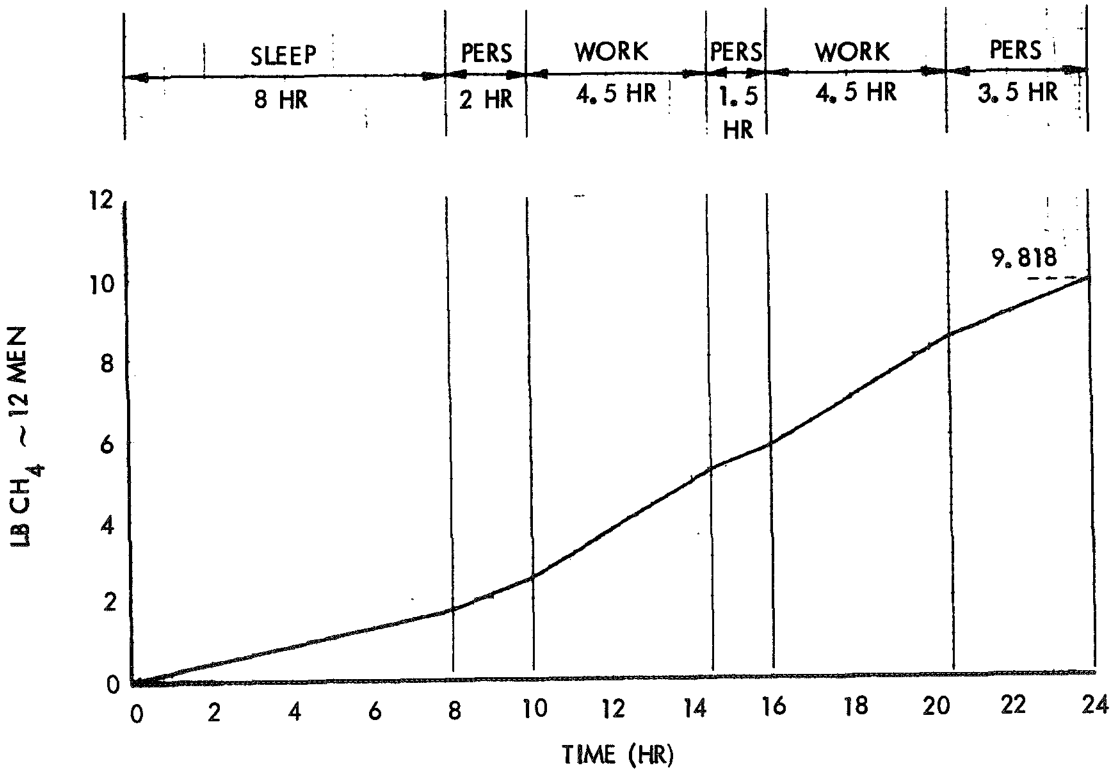


Figure 3-30. Nominal Activity Cumulative Ideal CH_4 Production, 12 Men

Because the molecular sieve operates on the light side of the orbit only, the CO_2 collection is periodic. The CO_2 accumulator, however, is sized to take out this transient and provide a continuous flow of CO_2 to the Sabatier reactor. The methane production is essentially as shown in Figures 3-29 and 3-30.

The long-duration, steady-state CO_2 production rate for the space station is 2.25 pounds per man-day. Agreement has not been reached on the nominal metabolic model. A survey of metabolic data used for previous significant aerospace programs is given in Table 3-4. The CO_2 production rate for nominal design is seen to vary from 2.12 to 2.55 pounds per man-day. The resistojet system design should consider that the basic long-duration CO_2 production of 2.25 pounds per man-day probably has a tolerance of +0.30 and -0.13 pound per man-day.

The CO_2 reaction efficiency in the Sabatier reactor is primarily a function of the quantity of H_2, the reactor geometry and catalyst type, and the thermal control of the reactor. NR preliminary design effort indicates that approximately 5-percent H_2 over the stoichiometric requirement is required to improve CO_2 conversion efficiency. The baseline biowaste model for preliminary sizing purposes for the 12-man space station is given in Table 3-5.

The gas composition given in Table 3-5. is the average daily production based on 27 pounds of CO_2 produced per day, 100-percent CO_2 conversion with 5-percent excess H_2, and no gases other than CO_2 desorbed from the molecular sieve subassembly. The H_2O results from assuming saturated conditions in the Sabatier condenser-separator at 70 F, 15 psia, and 100-percent gas-liquid separation. The biowaste gas production for time intervals less than a day may be obtained by using Figure 3-29 for the methane production with the same ratio of hydrogen and water as shown in Table 3-5. This baseline model is considered adequate for most preliminary performance and sizing calculations.

Nominal Biowaste Supply Model

Evaluation of materials compatibility, external vehicle contamination, and safety considerations requires a more detailed biowaste gas composition than that provided by the baseline model.

For the purpose of establishing the variation in the biowaste gas composition from the CO_2 management assembly, studies were conducted of the performance of the molecular sieve subassembly, the Sabatier reactor, and the Sabatier condenser; and a survey was made of the significant research test programs to date. It was observed that several of the Sabatier effluent variations were caused by specific design problems which

Table 3-4. Nominal Design Metabolic Data Survey of Previous Aerospace Programs

Metabolic Data (lb/man-day)	Apollo 1963	MORL 1964	ILSS 1966	MPF 1967	BSM 1967	SSP 1970	90-Day Test	Station MDAC	Station NR
Average activity Btu/man-day	11,200	10,850	11,112	13,600	11,200	11,200	----	11,200	11,900
O_2 intake	1.84	1.92	1.87	2.2	1.84	1.84	1.86	1.92	1.84
H_2O intake	6.61	6.17	7.72	9.75	6.13	6.30	5.95	6.17	6.32
Food intake (dry)	1.4	---	1.38	---	---	1.30	1.47	1.516	1.50
CO_2 output	2.12	2.32	2.32	2.55	2.12	2.20	2.25	2.30	2.25
Respiration and perspiration	3.97	2.78	5.9	7.3	3.09	3.44	4.25	2.783	3.45
Urine H_2O	2.65	3.92	4.13	3.1	3.45	3.45	2.02	3.915	3.45
Fecal H_2O	---	0.26	0.33	0.3	0.25	0.25	0.26	0.26	0.25
Metabolic H_2O	0.66	0.79	0.72	0.95	0.66	0.66	---	0.78	0.78

MORL = manned orbiting research laboratory, MDAC, 1964
ILSS = integrated life support system, NASA-Langley, 1966
MPF = manned planetary flyby, NR, 1967
BSM = basic subsystem module, NASA-MSC, 1967
SSP = Space Station prototype, NASA-MSC, 1970
90 Day = 90-day test, MDAC, NASA-Langley, 1970

Table 3-5. Baseline Biowaste Gas Composition

Biowaste Gas	Production Rate (lb/day)
CH_4	9.818
H_2	0.246
H_2O	0.328

can reasonably be improved for the station system. Consequently, the proposed design models reflect performance extrapolation to a 1977 space station launch.

The sources of variation in the resistojet supply, exclusive of the crew, are identified in Figure 3-31. The figure indicates that the primary sources of variation in the biowaste supply are (1) Sabatier reactor performance, (2) Sabatier condenser water vapor content, (3) adsorption of cabin gases in the molecular sieve, and (4) leakage of cabin gases into the ECLSS at locations which are below the cabin pressure. The secondary factors influencing the primary sources are also identified on Figure 3-31.

A survey of the following significant research programs provided a basis for predicting variations in biowaste supply:

1. North American Rockwell/AiResearch Sabatier research, 1961-1963 (References 6 and 7)

2. Integrated life support system (ILSS) 28-day test, NASA-Langley/General Dynamics, 1966-1967 (Reference 8)

3. Manned 60-day test, NASA-Langley/McDonnell Douglas, 1969 (References 9 and 10)

4. Manned 90-day test, NASA-Langley/McDonnell Douglas, 1970 (Reference 11)

5. Boeing/NASA-Langley Sabatier research, 1970 (Reference 12)

6. Hamilton Standard/NASA-MSC Sabatier research, 1970 (Reference 13)

7. AiResearch/NASA-MSC molecular sieve research, 1970 (Reference 14)

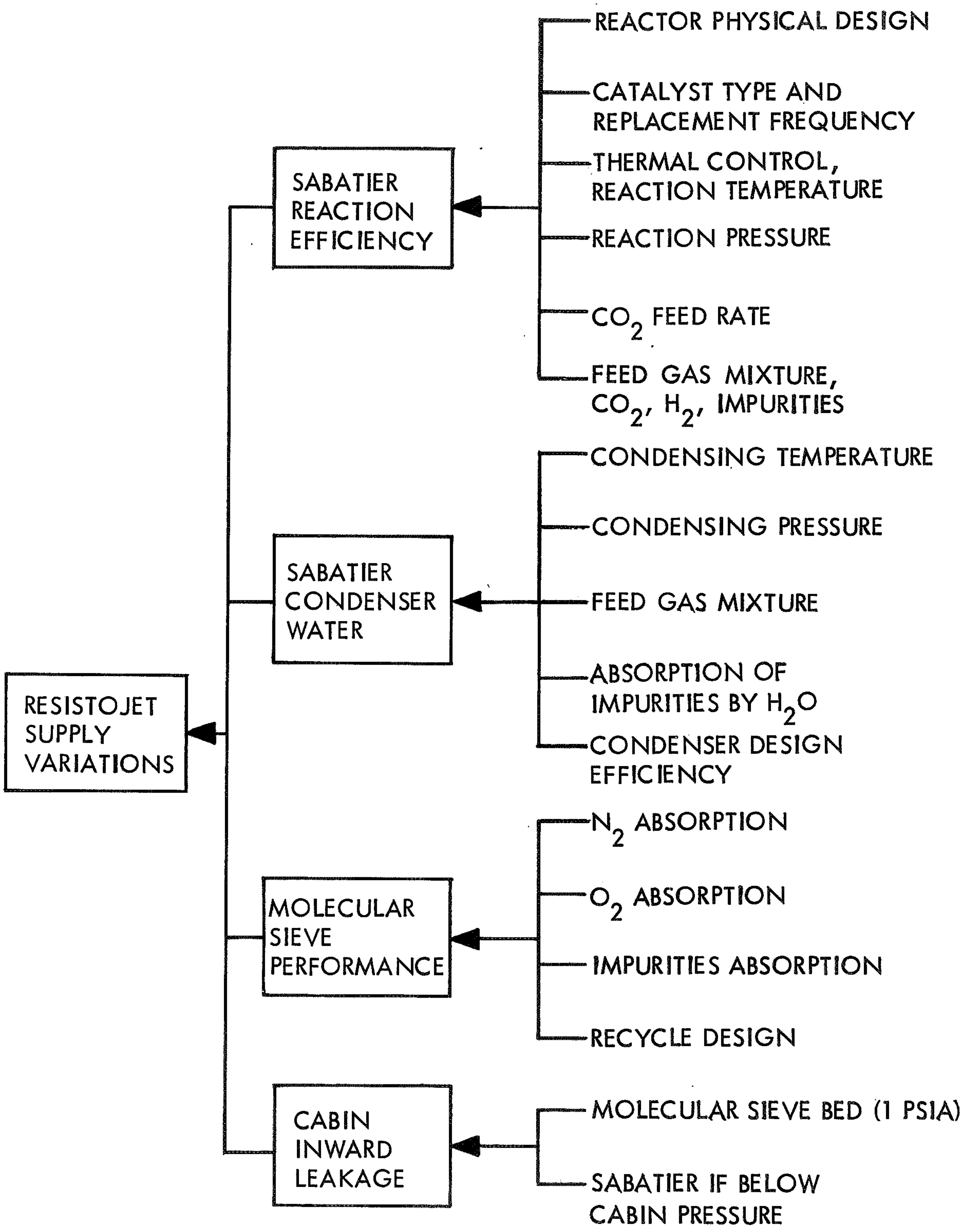


Figure 3-31. Sources of Variation in the Biowaste Gas Supply Exclusive of the Crew

This survey and the conclusions are discussed in detail in the appendix. Survey results are summarized in the following paragraphs.

As a result of the literature survey, a nominal biowaste gas model was developed. The nominal Sabatier performance condition is defined as 99-percent CO_2 conversion at 5-percent excess H_2 over stoichiometric conditions. The 99-percent CO_2 conversion efficiency is an estimate for the station Sabatier hardware and is extrapolated primarily from the results of Boeing (Reference 12), AiResearch (Reference 7), and the space station Phase B program (Reference 1, Volume II). The water in the biowaste supply is based on a 54 F condenser outlet saturation temperature at 15 psia, which is the design condition reported in Reference 1, and 100-percent gas-liquid separation in the condenser-separator. This latter assumption is considered reasonable, because the variation in the amount of saturated water vapor in the gas outlet due to variations in condenser temperature, pressure, and gas composition is considered to be the predominant factor in water loss from the Sabatier assembly. This variation is discussed later.

The N_2 in the biowaste supply, based on work by AiResearch (Reference 14), is 1 pound per day. The 90-day test results partially substantiate this conclusion about N_2. The O_2 in the biowaste supply assumes a station system configuration similar to that in the 90-day test program (Reference 11), where O_2 filters are placed on the inlet to the CO_2 and H_2 accumulators. Scaling the 90-day test results to the space station on the basis of CO_2 process rate results in 0.0193 pound of O_2 per day in the biowaste gases. Trace contaminants in the biowaste supply are estimated to be 0.0044 pound per day based on the 60-day test (Reference 10). The composition of the nominal biowaste model is shown in Table 3-6.

Variation in the Biowaste Supply

The minimum performance model in Table 3-6 represents a lower CO_2 conversion efficiency and an increased amount of impurities in the biowaste supply. The maximum performance model represents a higher CO_2 conversion efficiency and a minimum amount of impurities in the Sabatier effluent. The CO_2 conversion efficiency may vary to a minimum of 90 percent and a maximum of about 99.5 percent (estimated from the literature review). The H_2 supply for the NR space station is estimated to vary from stoichiometric to 10-percent rich. In Table 3-6, stoichiometric H_2 is paired with 90-percent conversion efficiency and 10-percent excess H_2 with 99.5-percent efficiency. The variation in the product CH_4 is predicted from the reaction equation utilizing the variation in efficiency stated above.

Table 3-6. Space Station Biowaste Supply Models

(12-Man Crew, Nominal Metabolic Rate)

Biowaste Gas	Nominal Model			Minimum Performance Model		Maximum Performance Model	
	Lb/Day	Weight Fraction	Mole Fraction	Lb/Day	Weight Fraction	Lb/Day	Weight Fraction
Methane, CH_4	9.720	0.8445	0.7519	8.840	0.5258	9.770	0.8779
Hydrogen, H_2	0.294	0.0255	0.1816	0.490	0.0292	0.600	0.0539
Carbon dioxide, CO_2	0.270	0.0234	0.0076	2.700	0.1606	0.150	0.0135
Water, H_2O*	0.200	0.0174	0.0137	0.680	0.0404	0.102	0.0092
Nitrogen, N_2	1.000	0.0868	0.0441	4.000	0.2379	0.500	0.0449
Oxygen, O_2	0.020	0.0017	0.0008	0.100	0.0059	0.005	0.0004
Trace contamination	0.005	0.0004	0.0002	0.005	0.0003	0.000	0.0000
TOTAL	11.509			16.815		11.127	

*Saturation at 70 F and 10 psia for minimum performance model and 40 F and 20 psia for maximum performance model and 54 F and 15 psia for the nominal model.

The water in the biowaste supply is a function of the condensing temperature and pressure (Figure 3-32) and the composition of gases in the condenser. The condensing temperature may vary from 40 to 70 F. The condensing pressure for the station may vary from 10 to 20 psia. The gas composition will vary as described in this section. The variation in the water is listed in Table 3-7 for several cases.

The N_2 in the biowaste supply due to adsorption in the zeolite may vary from 0.5 to 4.0 pound per day (based on scatter in the data from Reference 14). The molecular sieve desorption operation is a two-phase operation. In the first desorbing phase, atmospheric gas filling the void volume in the zeolite canister is cycled to the active adsorbing bed, and the canister pressure is reduced to 1 psia. This low pressure causes partial desorption of air and CO_2, which is recycled with the void gas volume. This ullage and desorbed air recycling is done to assure delivery of high-purity CO_2. Air and contaminants will be delivered to the Sabatier subassembly depending on the completeness of this recycling phase. The second phase of desorbing diverts the compressor discharge to the CO_2 accumulator, and heat is applied to the zeolite to aid desorption.

Nitrogen can also enter the system by means of inward leakage from the cabin through plumbing fittings and connections where the molecular

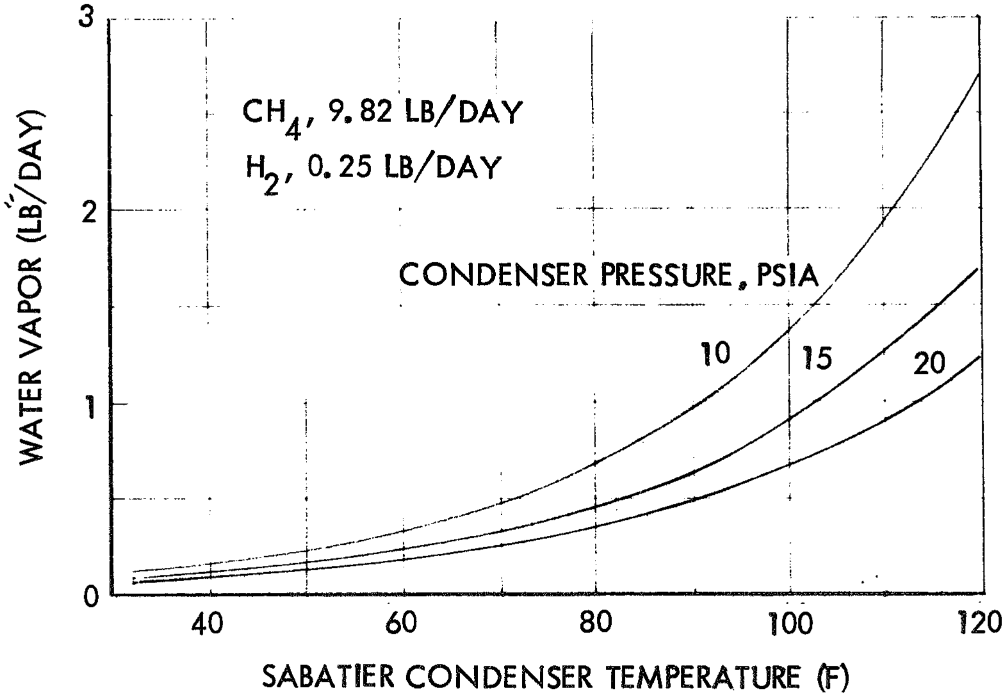


Figure 3-32. Condenser Saturated Water Vapor Content Versus Temperature and Pressure

Table 3-7. Variation in Biowaste Gas Water Vapor Content

Gas Composition	Pressure (psia)	Temperature (F)	Biowaste Water Content (lb/day)
Nominal model	10	70	0.54120
	20	40	0.08778
Minimum performance model	10	70	0.68010*
	20	40	0.10560
Maximum performance model	10	70	0.63220
	20	40	0.10240*
*Used in Table 3.6			

or Sabatier subassemblies are at pressure lower than the cabin. The zeolite bed and the line leading to the compressor are at 1 psia. The line, therefore, is a candidate for leakage. If N_2 leaked into the system equivalent to the cabin partial pressures, more than 10 pounds per day could result. This large leakage rate of N_2 would be considered a failure and repaired. Consequently, for purposes of the biowaste model, that N_2 predicted from adsorption in the zeolite should "bound" the N_2 variation.

The O_2 in the biowaste supply will vary from approximately 0.005 to 0.10 pound per day, based on Reference 14. For safety reasons, the quantity of O_2 in the Sabatier inlet will be limited by application of filters.

Further study must be made of the trace contaminants to define meaningful variations. Temporary larger quantities of contaminants may exist as a result of failures. Typical contaminants are listed in the appendix.

CO_2 Dump to Space

The CO_2 management assembly contains two molecular sieves and associated plumbing and ducting to provide operation of either molecular sieve with a single Sabatier reactor and electrolysis unit. For normal 12-man crews, only one molecular sieve is operating. The nonoperating sieve becomes installed redundancy required by the criticality of the CO_2 removal function. For crews greater than 12 during crew exchange, both molecular sieves are operated. One unit operates in a normal mode sending CO_2 to the Sabatier reactor; the other operates in a normal mode where CO_2 is dumped to space. A single Sabatier is incorporated because loss of its function for the short time required to implement maintenance does not constitute a critical situation. These two conditions, crew overlap (greater than 12 men) or maintenance of the Sabatier reactor, result in CO_2 being vented to space.

Crew overlap normally occurs when the space station crew is rotated. Some overlap might also result from special cargo handling requirements during resupply. Since the latter case should rarely occur, it will not be considered further. Reference 5 states:

> "Because of unknown medical problems associated with long-duration space missions, it is impossible to predict, with any degree of assurance, an acceptable crew stay time at an earth-orbiting space station ....
>
> "Overlap time in orbit required for replacement of flight crews should be minimized by simulation, training, mission planning, and station-to-ground and ALS communication. For the nominal case, crew overlap will consist of less than one work shift, with the capability of special operations or contingencies allowing on the order of five days."

Reference 5 also states that the crew duty tour could vary from two to six months. For ECLSS design purposes, Reference 1, Volume II, calls for the following:

> "Crew exchange will require support of up to 24 (12 nominal plus 12 exchange) total crewmen for periods up to five days. Frequency of exchange can occur as often as every 60 days."

For the ECLSS design case, 135 pounds of CO_2 could be dumped every 60 days, an average of 2.25 pounds per day. This is an extreme value, however, and a more nominal value would be for eight hours (9 pounds CO_2) each 90 days or an average of 0.1 pound per day lost.

Estimated maintenance times are also given in Reference 5. Scheduled maintenance of the Sabatier subassembly occurs every 30 days for 1.6 hours. Unscheduled maintenance time is predicted to be one hour per month average. At 2.6 hours per month, a negligible quantity of CO_2 would be lost to space. It is possible that the CO_2 accumulator might retain this small quantity with no loss of CO_2.

Potable Water

As suggested earlier, excess water that might be utilized for resistojet propellant could result from tolerances and/or conservatism in certain assumptions made during the Phase B preliminary design of the water management assembly. The following considerations might influence the station water balance:

1. Water reclamation efficiency
2. Water use requirements
3. Crew metabolic production
4. Water in the food supply
5. Sabatier condenser characteristics

Reclamation Efficiency

The vapor compression efficiency is defined as the ratio of the water flow rate leaving the vapor compression subassembly to the water flow rate entering. For the mass balance shown in Figure 3-19, an efficiency of 97.5 percent was assumed, which results in a water loss of 5.3 pounds per day. However, Hamilton Standard reports a baseline vapor compression efficiency of 98 percent, which would result in a 2-percent water loss in the solids dryer or

$$213.5 \times 0.02 = 4.3 \text{ pounds per day}$$

This results in a system water excess of 1 pound per day (assuming the system balanced with an efficiency of 97.5 percent). Note that a change in the vapor compression process rate will also affect the quantity of waste water lost in the solids dryer.

Water Use Requirements

A change in the water use requirements affects the system excess water. Potential changes in the station water use requirements include:

1. More or less water to electrolysis for oxygen supply
2. Reduction in the shower frequency
3. Reduction in the urine flush requirements

4. Elimination of experiments water recovery

5. Reduction in the galley latent production

Water electrolysis is used as the primary station oxygen supply concept. Cryogenic oxygen from RCS storage tanks is used as an emergency supply source and for module repressurization. This is indicated in the mass balance of Figure 3-19, which shows 0.4 pound per day of cryogenic O_2 supply for airlock repressurization. In the Phase C design stage, a probable change to the system would be to supply this oxygen by water electrolysis, which would decrease the water system excess by 0.45 pound per day. However, the major variation in water required for O_2 production (other than crew size) will be the cabin leakage rate. The cabin leakage assumed for Phase B station design is 20 pounds per day at 15 psia. If the actual leakage is less, or decreases with flight time (a probable situation since particles in the cabin atmosphere will tend to plug small holes), there will be excess water available, as indicated in Figure 3-33.

Reduction in the shower frequency from seven showers per man-week to two showers per man-week would reduce the wash water requirement from 248 to 106 pounds per day. Because of the system configuration, however, there would be no change in the excess water, since the brine delivered from the reverse-osmosis unit to the vapor compression unit remains the same. This is because the supply of Sabatier water and humidity condensate water to the wash water system is fixed (function of crew size), and the system does not provide for a buildup of water. Consequently, changes in wash water use requirements do not change the system excess water.

The system excess water is affected by changes in the potable water use requirements. The urine flush water requirements of 3.5 pounds per man-day is conservative and probably could be reduced to 1 or 0.5 pound per man-day. If the urine flush requirements were 0.5 pound per man-day, the vapor compression process rate would reduce by 36 pounds per day, yielding an additional water excess of 0.7 pound per day.

If station experiments are operating in a mode which does not require water (such as may exist during some periods for weeks or months), the vapor compression process rate would decrease 35 pounds per day. This would provide an additional 0.7 pound of excess water per day. Elimination of the food preparation water evaporation (4.5 pounds per day) would result in a negligible increase of 0.1 pound per day in excess water.

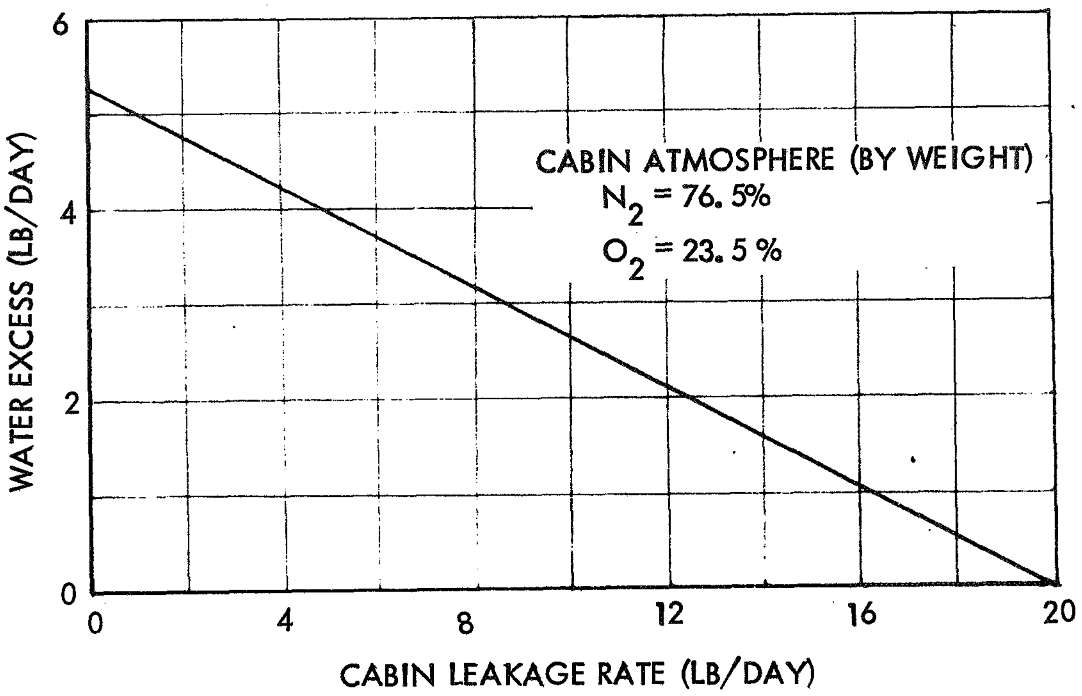


Figure 3-33. Water Excess Versus Cabin Leakage

Crew Metabolic Model

The crew metabolic water production for design was selected as 0.78 pound per man-day. Realistic variations in this design rate are 0.66 pound per man-day minimum to 0.95 pound per man-day maximum. The system water excess for 0.66 pound per man-day metabolic water is -1.4 pounds per day. At 0.95 pound per man-day, there would be an increase of 2 pounds per day in the excess water.

An increase in the urine production should result in a corresponding decrease in the latent water production for a zero net water production change.

Food Supply Water

The station food system incorporates the normal dried foods, frozen foods, and canned foods (thermostabilized). The frozen and canned foods contain a relatively large quantity of water and are supplied to the station independently of water balance considerations. Current design is based on 0.96 pound of water per man-day in the wet-pack foods. If the food mix were changed to increase the quantity of wet-pack foods in the diet, or if water in the wet pack food were increased, the station water excess would increase. The station food supply characteristics are as follows:

Pounds per Man-Day	
1.04	Dried foods
1.44	Water added to dried foods from water management system
0.64	Dry portion of wet-pack foods
0.96	Water portion of wet-pack foods (60 percent)

The potential variation of water in wet-pack foods was investigated. Water in thermostabilized, frozen, and fresh food varies from 60 to 85 percent, according to References 15 and 16. Assuming 75-percent water by weight, 0.64 pound per man-day or wet-pack foods (dry part) would contain 1.92 pounds per man-day of water. This would result in an additional water excess of 11.5 pounds per day. However, the wet-pack food quantity might be reduced to 1.5 pounds per man-day (dry plus water), corresponding approximately to a TV dinner. Assuming 75-percent water by weight, the composition would be 1.12 pounds per man-day water and 0.38 pound per man-day dry food portion. This results in a water excess of 1.9 pounds per day. The two cases described indicate the strong dependence of the water balance on the food composition.

Sabatier Condenser

As described in the earlier section on biowaste design models, the water vapor dumped with the biowaste gases from the Sabatier condenser is a function of the condenser temperature, pressure, and gas composition. The water balance assumes no water loss from this source.

Waste Water Availability

Station waste water scheduled for overboard dump or return to earth could be considered as an alternate source of additional biowaste propellant. However, additional hardware would be required to reclaim this water. Station waste water sources include the fecal collection tank, trash dryer, and water management assembly loss (solids dryer).

The feces are collected in a tank and dried by exposure to space vacuum. The feces contain 0.25 pound of water per man-day, 90 percent of which is vented to space. This contaminated water vapor is a potential source of biowaste propellant.

The station incorporates two trash drying chambers, sized to accommodate 30 pounds of trash per day. Waste is heated to 250 F for approximately eight hours each crew night to evaporate all water and sterilize the waste. Wet food waste will include 2.5 pounds of water per day. Other wet trash will nominally include 1 pound of water per day. The water lost from the water management assembly because of the efficiency of the vapor compression subassembly can be as much as 5.3 pounds per day at an efficiency of 97.5 percent. This water is accumulated in the solids dryer along with the liquor from the vapor compression still. The solids dryer cartridge is replaced approximately once a week.

The waste water sources described could provide more than 10 pounds of water per day for resistojet propellant. However, recovery of this water would require the design and development of additional hardware. Both the fecal water and trash water are vented to vacuum to facilitate vaporization at reasonable temperature. Recovery of this water would require a low-pressure condenser-collector or a change in the present design. The solids dryer water would require, in addition, a method of boiling the water from the solids dryer cartridge. The tradeoffs required to determine the feasibility of recovering the waste water are not within the scope of this study.

Experiment Waste Fluids

The experiment/functional program elements (FPE) provide another possible source of waste fluids that might be utilized as propellants for a resistojet thruster. Three factors must be considered in determining the feasibility of utilizing these fluids:

1. The FPE must be integral to the space station or be in an attached module.
2. The experiment must be of sufficient duration and have a sufficient quantity of usable consumables to justify the added complexity of recovering these consumables.
3. The fluids must be compatible with the resistojet assembly.

The Space Station Phase B definition documentation (Reference 17 and 18) was reviewed to determine the FPE's that meet these criteria. The following FPE's are possible candidates for resistojet integration:

1. FPE 5.1/5.5, X-Ray and Gamma Ray Stellar Survey. The X-ray (FPE 5.1/5.5A) and gamma ray (FPE 5.5B) stellar survey experiments are accommodated in an attached module and are scheduled for a five-year period beginning in the second year of station operation. The X-ray surveys are conducted in the first two and one-half years and require 75 pounds per month of liquid neon and 100 pounds per month of liquid hydrogen. During the second two and one-half years, the gamma ray survey requires 100 pounds per month of liquid nitrogen and 40 pounds per month of gaseous argon.

2. FPE 5.9, Small Vertebrates. The small vertebrates experiment is accommodated in an attached module for a two-year period beginning in the second year. For the first three months, there is a requirement for 235 pounds of atmosphere supply and 1235 pounds of water supply. Subsequent support will require 10 percent of these initial requirements. Generally, the atmosphere and water for the experiments are recovered and recycled by the station ECLSS. However, there are indications that the above quantities are expendables.

3. FPE 5.15, *Life Support and Protective Systems*. The life support and protective system (LS/PS) FPE consists of a number of subexperiments, all integral to the space station. Although the scheduling of these subexperiments is not clear, it appears there are two 90-day periods in the first two years which require 85 pounds per month of an unidentified gas for calibration purposes.

4. FPE 5.22, Component Test and Sensor Calibration. This FPE is also integral to the station and consists of a number of subexperiments. One of these tests is for advanced fuel cells and batteries. Again, the scheduling of the subexperiment is not definite but would appear to be a six-month period in the first two years. During this six-month period, 825 pounds per month of cryogens (mostly LH_2-LO_2) will be used. It is presumed that the resultant water would be excess to the station water management assembly.

The remaining FPE's are either in detached modules or have insufficient consumables to be of value.

The Space Station Phase B definition study defined only one experiment module (FPE 5.11, Earth Surveys) to the preliminary design level. The fluids described, therefore, should be considered as indicative only of the fluids and quantities that might be available to the resistojet assembly for propellant utilization. There is no definition presently available of the interface pressures, temperatures, etc., at which these fluids could be made available. For this reason, it is not possible to establish the practicality of recovering these waste fluids or to propose a model for resistojet development testing.

The water required for experiment purposes is supplied in most instances by the station ECLSS. The capability to provide and reclaim 35 pounds of potable water per day for experiment purposes is provided by the potable water recovery subassembly. Experiment water with a more restrictive purity requirement is to be considered an expendable item and handled as a logistics supply material. Experiment water which cannot be accommodated by the station distillation reclamation assembly because of unusual chemicals or contaminants will be considered a waste product.

Experiment water contaminant content is presently undefined. It was assumed for the Phase B study that the contaminants would be compatible and removable with urine-processing-type equipment. Therefore, the majority of the experiment water requirement is satisfied by the ECLSS potable water supply and is reclaimable by the vapor compression distillation units. A possible exception is FPE 5.9, the small vertebrate experiment, which might provide a significant quantity of waste water. Other instances may exist, but they are probably isolated cases which would produce relatively small quantities of waste water. Definite conclusions cannot be drawn until the experiments are defined in detail.

RESISTOJET ASSEMBLY

The Space Station Phase B Definition Study of a 33-foot space station conducted by North American Rockwell Corporation under Contract NAS9-9953, did not result in the selection of a biowaste resistojet system as a primary space station subsystem. It was suggested that such a system could be flight qualified on the space station for use on the space base. A number of factors could change this decision. Indeed, several space station concepts are still under study at NR which could include the biowaste resistojet concept. Since the space station design is still in a state of flux, it is desirable that the biowaste resistojet system development program being planned at the NASA Langley Research Center be sufficiently flexible to encompass all possibilities.

The NR solar-array battery-powered space station represents one of the many variations that might be encountered. In particular, the ECLSS CO_2 management assembly recovers essentially all of the metabolic CO_2 produced by the crew because of the availability of extra hydrogen to the Sabatier reactor from the O_2/H_2 medium thrust RCS. This section describes the design and operation of a biowaste resistojet system for this station concept.

RESISTOJET PERFORMANCE

The resistojet thruster concept is quite simple and is exemplified by the Marquardt Corporation design presented in Reference 19. A conceptual drawing of this resistojet thruster is shown in Figure 3-34. The thruster consists basically of two functional parts:

1. An electric-gas heat exchanger
2. A nozzle for accelerating the resultant high-temperature gas to produce thrust

The electrical flow is through the outer case, case end, inner heating elements, and nozzle. A strut connector provides an electrical connection between the two main heating elements, while concurrently allowing gas to flow through the thruster. Approximately 85 percent of the ohmic heating takes place in the inner heating element. The gas flows between the inner and outer case, intercepting the radial-thermal flow and carrying much of the heat back toward the center of the device. The gas then passes through

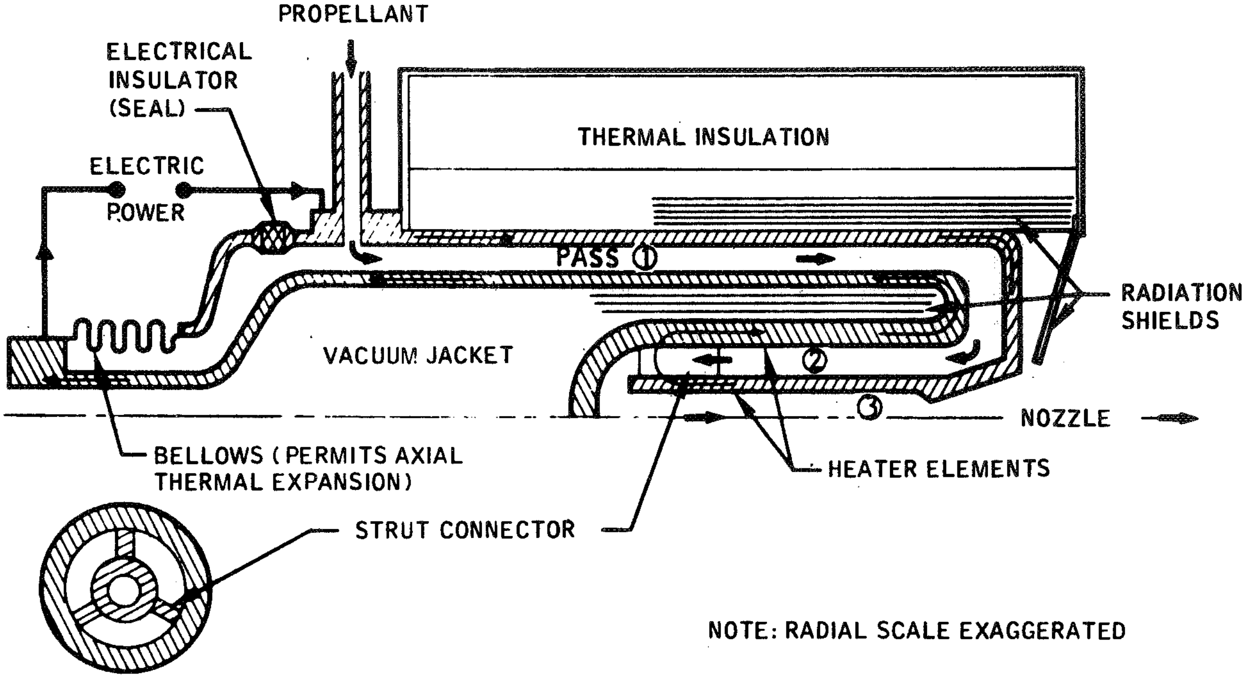


Figure 3-34. Typical Resistojet Thruster

the annulus between the inner and outer heating elements where a significant amount of gas heating takes place. The final gas pass is down the center tube where the gas very closely approaches the heating element wall temperature. The gas is then exhausted through the nozzle.

Biowaste Gas Propellants

Initial performance calculations for the study were based on the baseline biowaste dry gas composition given in Table 3-5 (without water vapor). Performance maps for design thrust levels of 0.10 and 0.05 pounds are presented in Figures 3-35 and 3-36, respectively.

The predicted resistojet performance is based on projected delivered specific impulse compared to ideal frozen flow specific impulse and the throat discharge coefficient. The value of these two parameters as a function of Reynolds number is shown in Figure 3-37. The data for these curves were obtained from References 20 and 21 for Reynolds numbers less than 10^4 and from Reference 22 for Reynolds numbers between 10^4 and 10^5.

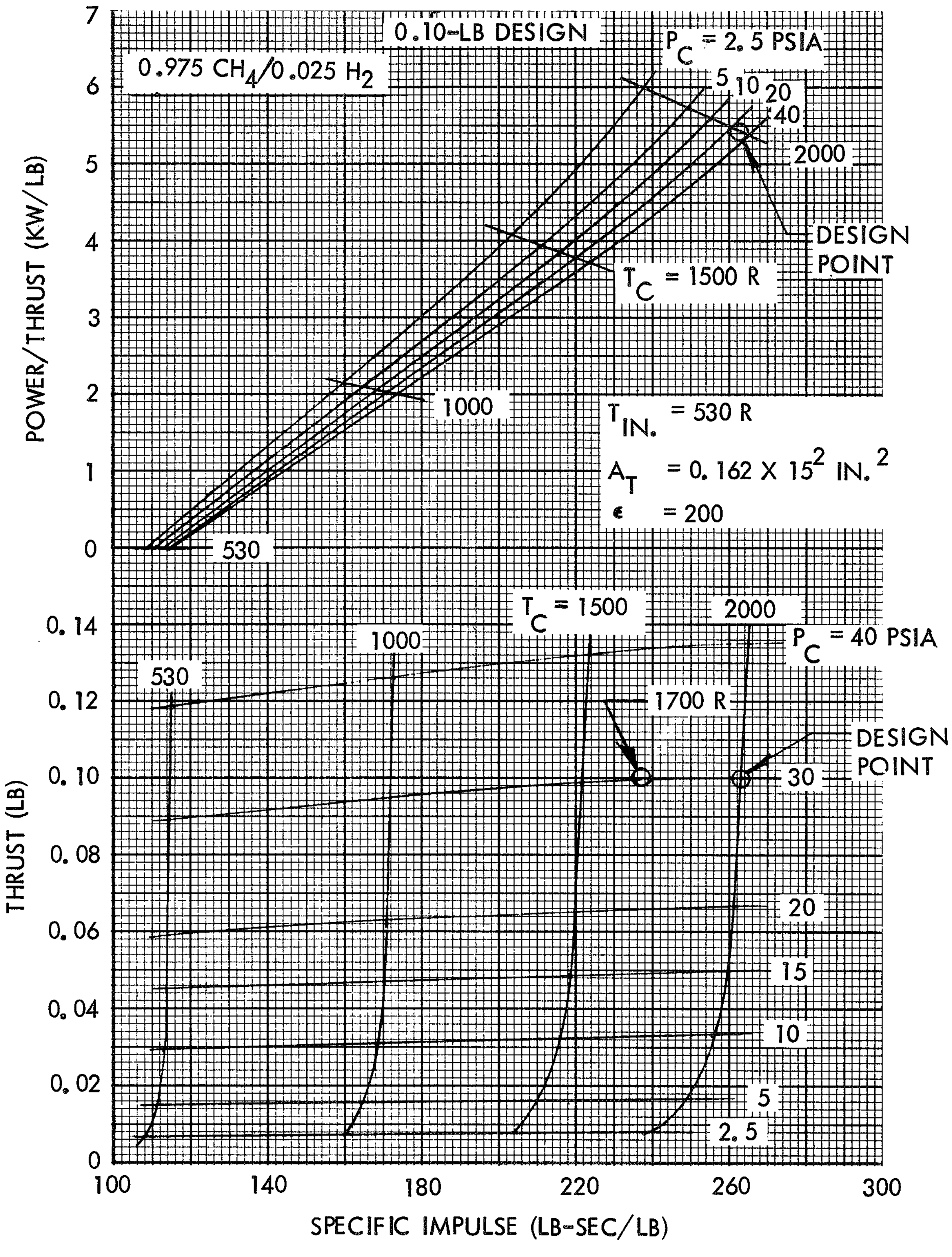


Figure 3-35. Resistojet Performance Map, 0.1-Pound Thruster

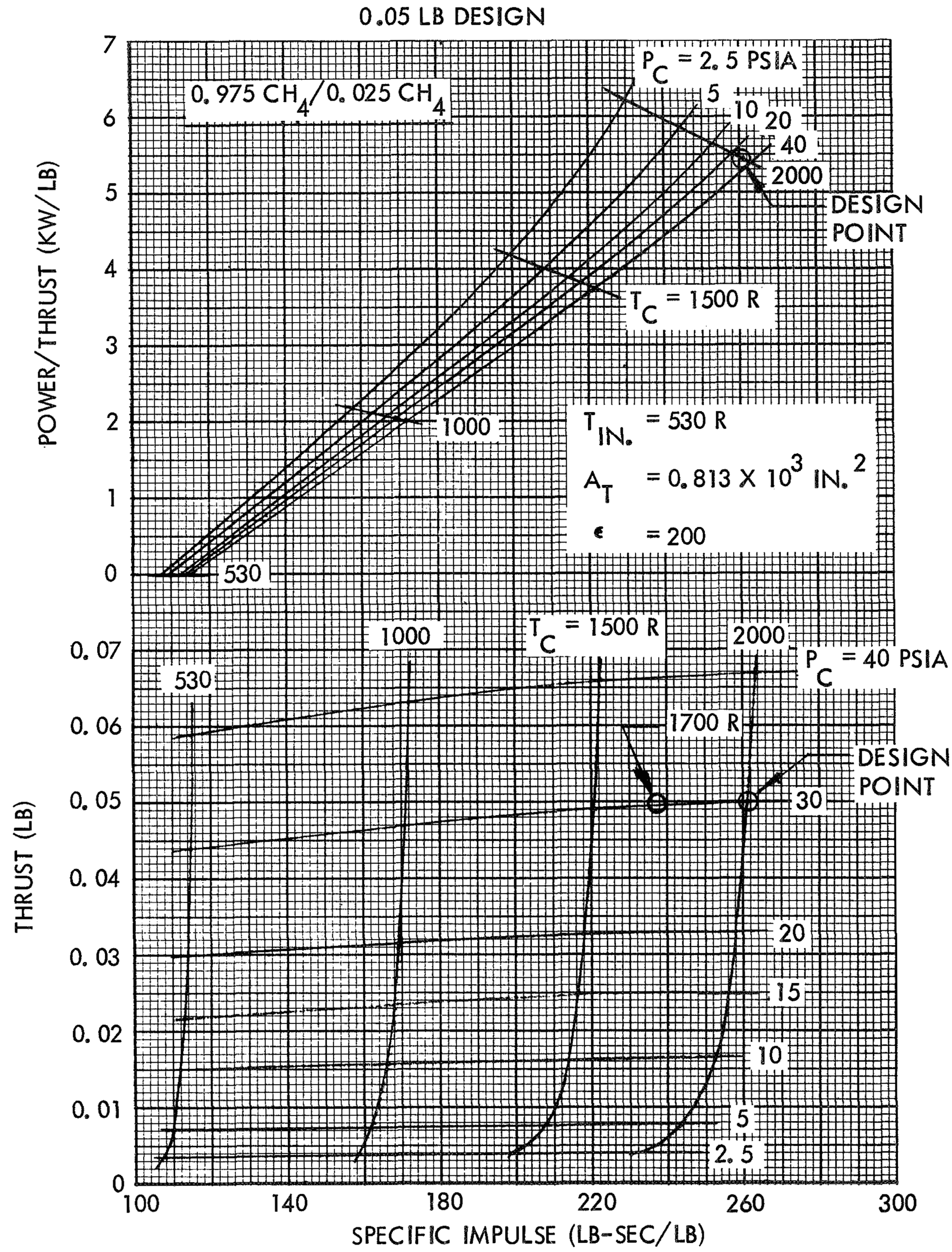


Figure 3-36. Resistojet Performance Map, 0.05-Pound Thruster

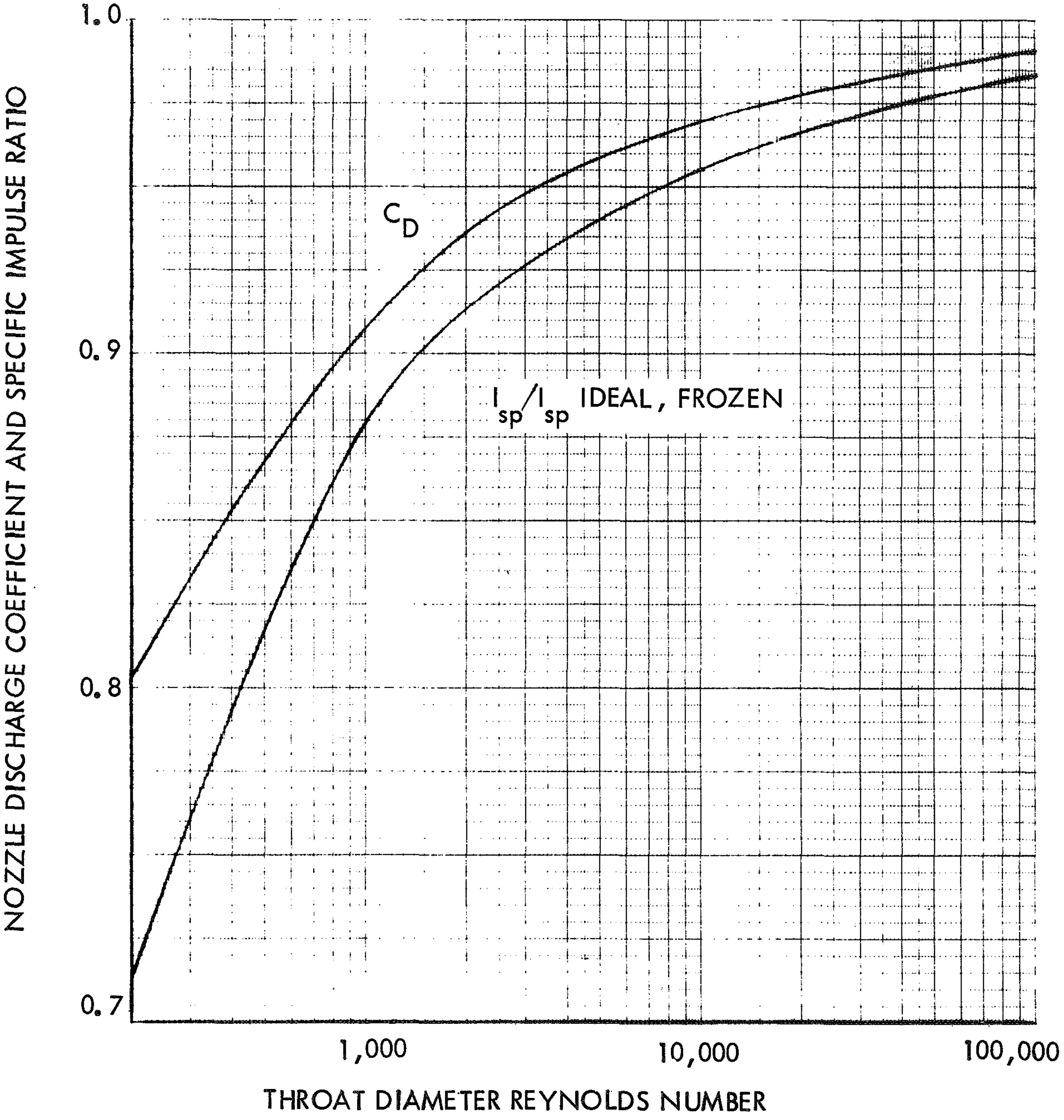


Figure 3-37. Predicted Resistojet Nozzle Performance

Gas mixtures containing methane are limited in temperature due to decomposition of methane to form carbon. Carbon deposition in the thruster reduces the thruster life and also results in loss of performance. For this study a design upper limit of 2000 R (gas temperature) was assumed for methane mixtures. Data in Reference 23 indicate that this may be optimistic. A conservative value would be 1700 R. From Figures 3-35 and 3-36, it can be seen that 1700 R results in a 10-percent loss in specific impulse.

The specific impulse for the range of biowaste gas mixtures given in Table 3-6 was also predicted. A summary of the impulse available from the various biowaste gas compositions is given in Table 3-8.

The nominal composition of Table 3-6 is considered the best estimate for the Sabatier effluent gases under normal circumstances. Therefore, the use of an impulse of 2600 lb-sec/day (baseline at 2000 R) in this study is, if anything, conservative.

Water-Vapor Propellant

For waste propellants other than methane compositions, Reference 23 indicates that a gas temperature of approximately 2700 R is a reasonable upper limit. The temperature limit in this instance is a function of thruster material compatibility with the oxidizing propellants (H_2O, CO_2, etc.) at high temperatures.

Table 3-8. Impulse From Biowaste Compositions

Composition	Quantity (lb/day)	Gas Temperature (R)	Specific* Impulse (lb-sec/lb)	Total Impulse (lb-sec/day)
Baseline (Table 3-5)	10.1	2000	263	2660
	10.1	1700	238	2400
Nominal (Table 3-6)	11.5	2000	254	2920
	11.5	1700	230	2640
Minimum (Table 3-6)	16.8	2000	232	3900
	16.8	1700	210	3530
Maximum (Table 3-6)	11.1	2000	274	3040
	11.1	1700	248	2750

*0.1-lb thruster

There is some indication that the addition of a significant quantity of water vapor to a methane composition will inhibit the methane decomposition and allow a higher temperature limit for methane (greater than 2000 R). This theory will be tested by the Marquardt Company under contract to the NASA Langley Research Center, Contract NASl-9470, "Technology Development of a Biowaste Resistojet." The results of this test are not available at this time, however, and for this study it will be assumed that the water vapors will be used independently of the biowaste gases, unless stated otherwise.

Since the quantity of excess water available to the space station resistojet is in question, it is assumed that the resistojet thruster would be optimized for operation with the biowaste gases. Using the thruster design of Figure 3-35, the specific impulse of water vapor at 2700 R is predicted to be 242 lb-sec/lb. Due to the difference in gas properties between water vapor and the methane/hydrogen compositions, the thrust obtained at a chamber pressure of 30 psia with water vapor would be 0.094 pounds. To obtain 0.1-lb thrust the water-vapor chamber-pressure would have to be increased to 31.8 psia. If 10 lb/day of excess water could be made available an impulse of 2420 lb-sec/day could be obtained from the water, or a total of 5000 lb-sec/day including the biowaste gases.

ELECTRICAL POWER CONSIDERATIONS

The electrical power subsystem (EPS), defined for the space station in Volume II of Reference 1, is comprised of solar arrays for supplying power requirements during the light orbital periods and nickel-cadmium batteries for the eclipse power. The solar array, with 10,000 ft^2 of total area, is divided into four identical panels permitting channelization of the electrical power subsystem. A functional block diagram of a single channel is shown in Figure 3-38. Each panel has a beginning of life (BOL) rating of 22.8 kw and consists of a 2500 ft^2 roll-up array unit mounted on the boom of the space station. When deployed, the panel has a nominal three-wire output of ±112 vdc. The ±112 vdc output is connected to an inverter-regulator located in the vicinity of the panel. The inverter-regulator converts the dc power to a regulated 416 volt, 3-phase ac power prior to transmission through feeders to a primary bus located in the torus area. A 10-kva step-down autotransformer, located at the secondary bus, provides transformation of double voltage to standard voltage. A tertiary winding of the autotransformer supplies low-voltage ac to a rectifier-filter unit, which, in turn, furnishes 56 volts dc to the dc bus. The secondary bus contains the multiplexing and load-circuit protection equipment (solid-state circuit breakers) necessary to perform, under the command of the ISS, the control and distribution of electrical power to selected loads in the adjacent areas.

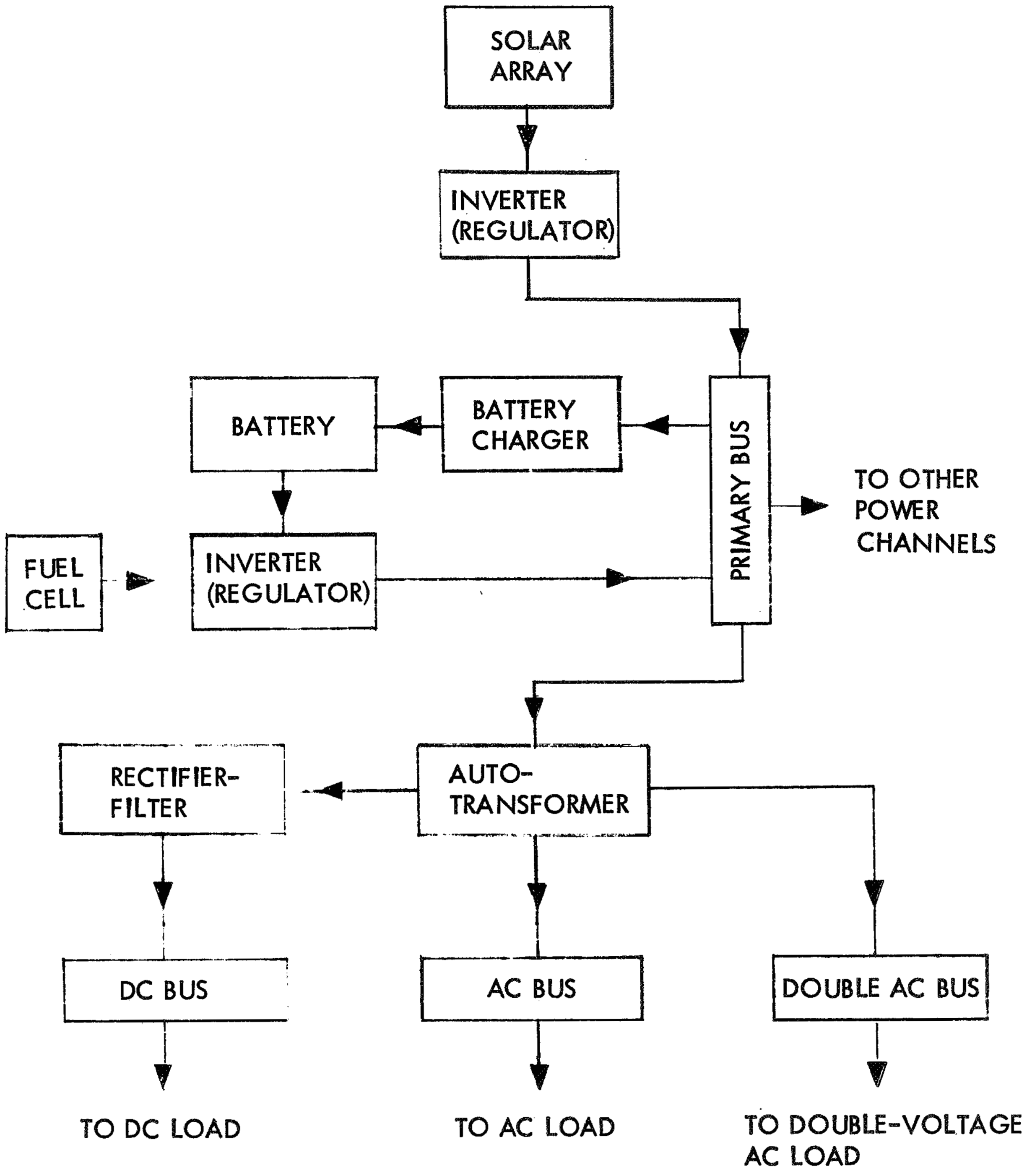


Figure 3-38. EPS (Solar Array Battery) Functional Block Diagram

Nickel-cadmium batteries provide 300 amp-hr capacity per power channel to supply the space station power during the eclipse periods. The battery output is connected to an adjacent inverter-regulator that converts the dc voltage to regulated 416-volt, 3-phase ac power and this powers the primary bus. Battery recharging is accomplished by a computer-controlled battery charger receiving its power from the primary bus during light orbital periods.

The subsystem electrical power load for routine zero-g operation, defined by Reference 24, is 25 kw, averaged over a 24-hour period. For the minimum light/dark ratio (sun line in the orbit plane) the solar-array power output must be 66 kw to provide the average 25-kw subsystem requirement. The power generated by the solar array is a function of time. An estimate of the degradation of power generated is given in Figure 3-39. Combined with the 66-kw requirement, the power-available curve indicates a useful life of approximately 3.7 years.

It is more efficient to utilize electrical power directly from the solar arrays, rather than the batteries. Therefore, subsystem loads which can be scheduled on a periodic basis are scheduled for the light period. Operation of the EPS during one orbit is typified in bargraph A of Figure 3-40. The design orbit period is 1.559 hours with a dark/light ratio of 0.592/0.967 (sun line in the orbit plane). Area 1 represents continuous subsystem power loads, area 2 represents continuous plus periodic subsystem loads, and area 3 is the energy required to charge the batteries to meet the eclipse period requirement of area 1. The ratio of area 3 to area 1 is approximately 1.40.

The resistojet subsystem electrical power requirement consists primarily of a near-continuous requirement for compressors (areas 4 and 5 of bargraph B) and a periodic requirement for resistojet operation (area 6). The addition of the resistojet subsystem therefore requires an additional energy input during the light period. This additional energy is represented by area 8 in bargraph B of Figure 3-40 and is equal to

$$\text{Area } 8 = \text{Area } 4 + \text{Area } 6 + 1.4 \times \text{Area } 5 \qquad (3.2)$$

Assuming that (1) the power loss from the primary bus to the subsystems is 22 percent, (2) the power loss in the resistojet conditioning and heater components is 5 percent, (3) the theoretical thrust to power ratio of the

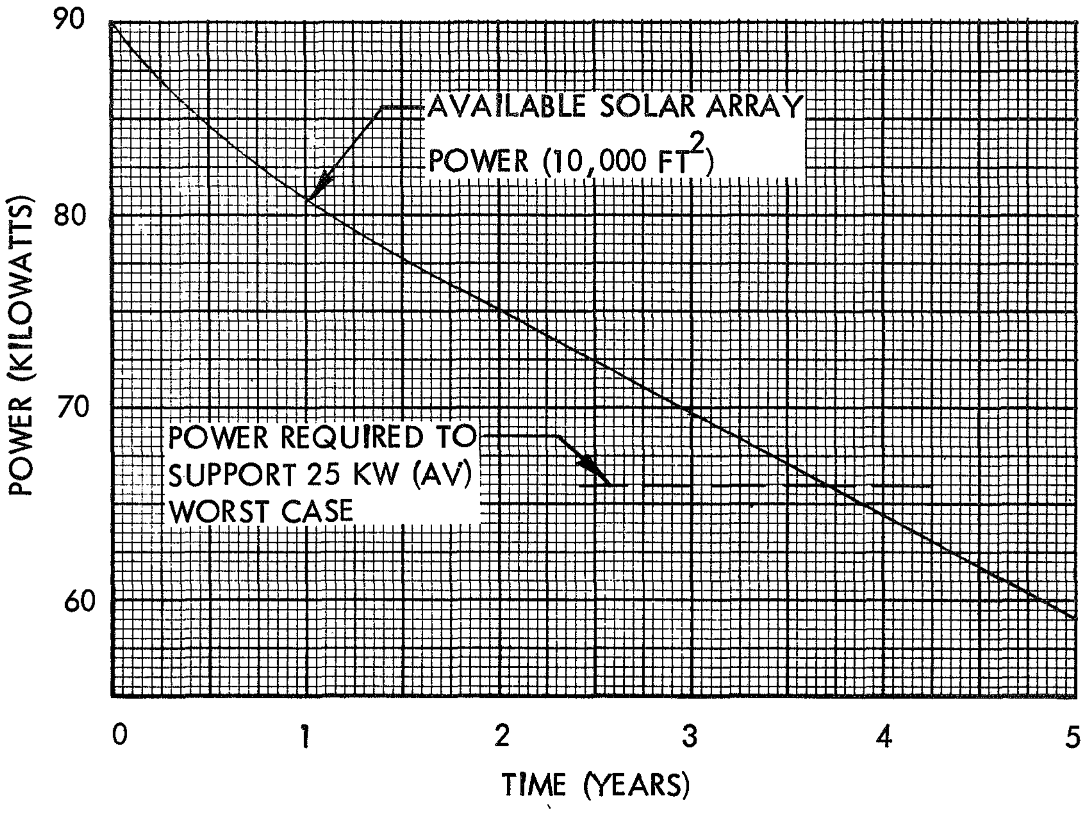


Figure 3-39. Solar-Array Power/Lifetime Relationship

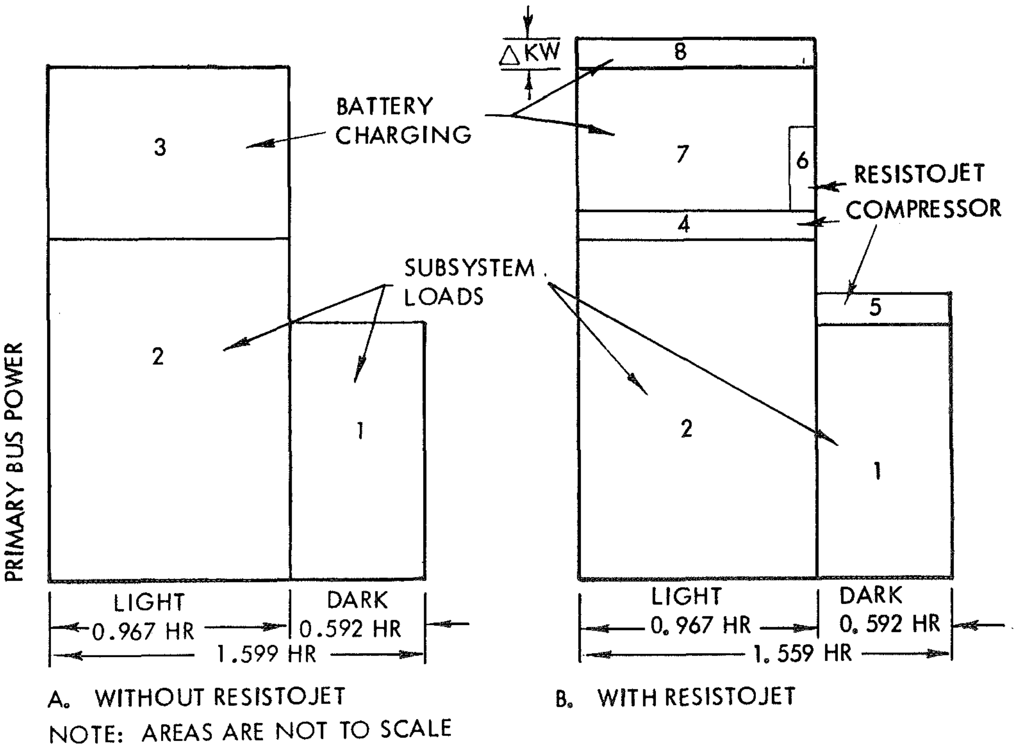


Figure 3-40. Resistojet Impact on EPS

resistojet is 0.185 lb/kw, (4) the compressor power required is 0.1 kw, and (5) the total impulse capability of the resistojet subsystem is 2600 lb-sec/day (biowaste gases only), the impact of the resistojet subsystem on the EPS can be approximated.

$$\text{Area 4} = \frac{0.1\ (0.967)}{0.78} = 0.124 \text{ kwh/orbit} \tag{3-3}$$

$$\text{Area 5} = \frac{0.1\ (0.592)}{0.78} = 0.076 \text{ kwh/orbit} \tag{3-4}$$

$$\text{Area 6} = \frac{(2600)(1.559)}{24(0.185)(3600)(0.95)(0.78)} = 0.342 \text{ kwh/orbit} \tag{3-5}$$

$$\text{Area 8} = 0.124 + 0.342 + 0.076(1.40) = 0.572 \text{ kwh/orbit} \tag{3-6}$$

$$\Delta\text{kw} = \frac{0.572}{0.967} = 0.592 \text{ kw} \tag{3-7}$$

There is additional loss of 17 percent from the solar array to the primary bus. Therefore, the solar-array power-requirement increase is 0.72 kw. This increase in power would require an insignificant change, if any, to EPS components. From Figure 3-39, the slope of the solar-array life curve is -0.19 years/kw at 66 kw. The decrease in solar-array life due to the additional 0.72 kw is 0.14 years or approximately 4 percent.

If 10 lbs/day of water were made available to the resistojet in addition to the biowaste gases, a total impulse of 5000 lb-sec/day could be obtained. This would result in a delta solar-array output of 1.5 kw and a decrease in solar-array life of 0.28 years.

The above is a simplified analysis to approximate the impact of a biowaste resistojet subsystem on the solar-array electrical power subsystem defined in Reference 1. The impact indicated is considered conservative for the following reasons:

1. The resistojet impulse requirement may be significantly less than 2600 lb-sec/day at the solar-array end of life depending on the launch date, orbital altitude, solar flare activity, and actual solar-array replacement cycle.

2. The sun line is in the orbit plane on a periodic basis, so that the light-to-dark ratio is usually larger than the design point. The batteries, therefore, can discharge somewhat during the short light/dark ratio period and utilize the longer light periods to recharge without any increase in the power required.

If the thrusting is to be done in sunlight only, it is desirable that the orbit-maintenance thrusting be accomplished in equal impulse periods at diametric positions in the orbit. With this criterion and the worst light/dark ratio, the maximum thrusting time per orbit and the total thrust required as a function of total impulse per day are shown in Figure 3-41. A maximum total thrust of 0.27 pounds is required to provide 5000 lb-sec/day. In actuality, this would probably be accomplished with three 0.1-pound thrusters. It is probable that under some circumstances all three thrusters would be operating with water vapor. The maximum peak power for resistojet operation, therefore, would be approximately 3 kw. This is about the maximum additional power that could be accommodated with the existing system without a serious EPS impact. Use of supplemental propellant in high-density years would require some operation on the dark side of the orbit, or resistojet operation at lower temperature with loss in specific impulse.

RESISTOJET OPERATIONAL MODES

The resistojet thrusters may be operated in various ways to provide the total impulse required at a particular time. Both the gas pressure and temperature may be varied together, independently, or held constant. The biowaste gases and the excess water may be combined or used separately. Unless stated otherwise, it will be assumed that for the remainder of the study only one propellant composition is used at a time.

For a perfect gas with isentropic inviscid flow, the thrust varies linearly with chamber pressure and the specific impulse varies linearly with the square root of gas stagnation temperature. Referring to Figures 3-35 and 3-36, for the ideal case the constant pressure lines would be horizontal straight lines; the constant temperature lines would be vertical straight lines; and the specific impulse versus power/thrust ratio would be a single line (independent of pressure). The deviations of the predicted performance shown in Figures 3-35 and 3-36 from the ideal are the result of real gas effects and viscous flow. Pressure, therefore, primarily controls the thrust level or duty cycle. Constant pressure operation requires a variable duty cycle to meet the varying impulse requirements. If specific operating times or fixed duty cycles are desired, variable pressure operation must be supplied. Because of the real gas and viscous effects, it is also necessary to have a variable pressure capability if a fixed thrust is required with a variable gas temperature. This could be desirable for the guidance and control subsystem.

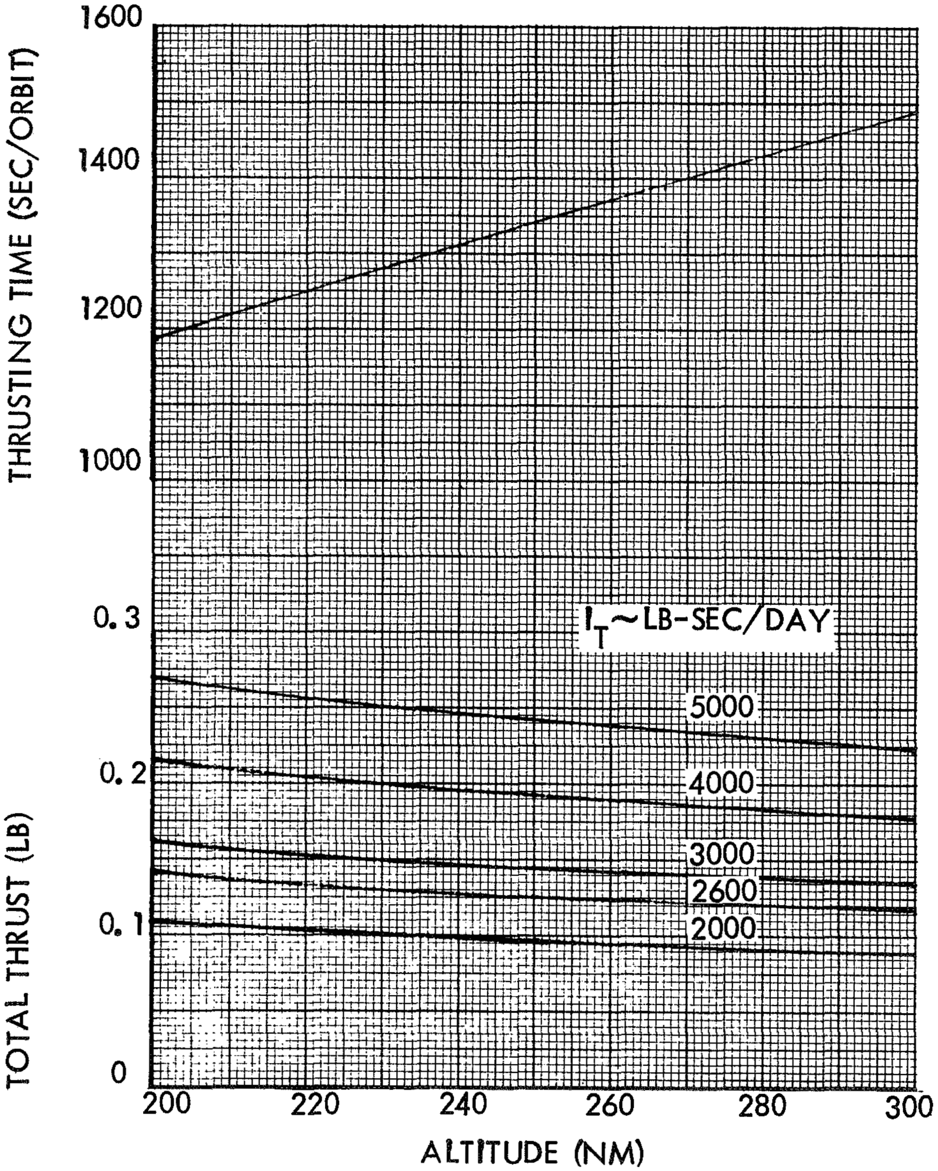


Figure 3-41. Total Thrust Required and Thrusting Time Versus Orbit Altitude

Since temperature primarily controls the specific impulse, a constant temperature results in a linear relationship between impulse produced and propellant used. During low-impulse (low atmospheric density) years, this results in excess waste fluids which must be vented in a nonpropulsive manner. By varying the temperature, the waste fluid availability can be matched to the impulse requirement (within the temperature limits of the propellant composition).

A summary of the various combinations is given in Table 3-9. All of these options fall into two categories, either fixed thrust or variable thrust. Option 2 is in the fixed-thrust category since thrust is not an independent variable but is fixed for a given temperature.

Figure 3-42 defines the thrust vector numbering, coordinate, and sign convention for the following equations. Since the resistojet assembly is not a part of the NR space station preliminary design, the locations shown should only be considered indicative of the general locations required. It should also be noted that only those vectors required for the primary X-POP orientation are shown. The relative locations for the center of gravity (c. g.) and center of pressure (cp) are representative of the combination of docked experiment and cargo modules presently anticipated in the space station study (Configuration H).

Assuming the space station is in the X-POP orientation with the velocity vector coincident with the Y axis, the impulse requirements are I_y for orbit maintenance and M_x for CMG desaturation. Torques about the Z axis are periodic and will be considered only in the selection of thrust vectors to minimize the peak value of M_z. Defining the following parameters,

$$a = (Z_g + 199)/12 \qquad (3\text{-}8)$$

$$b = (199 - Z_g)/12 \qquad (3\text{-}9)$$

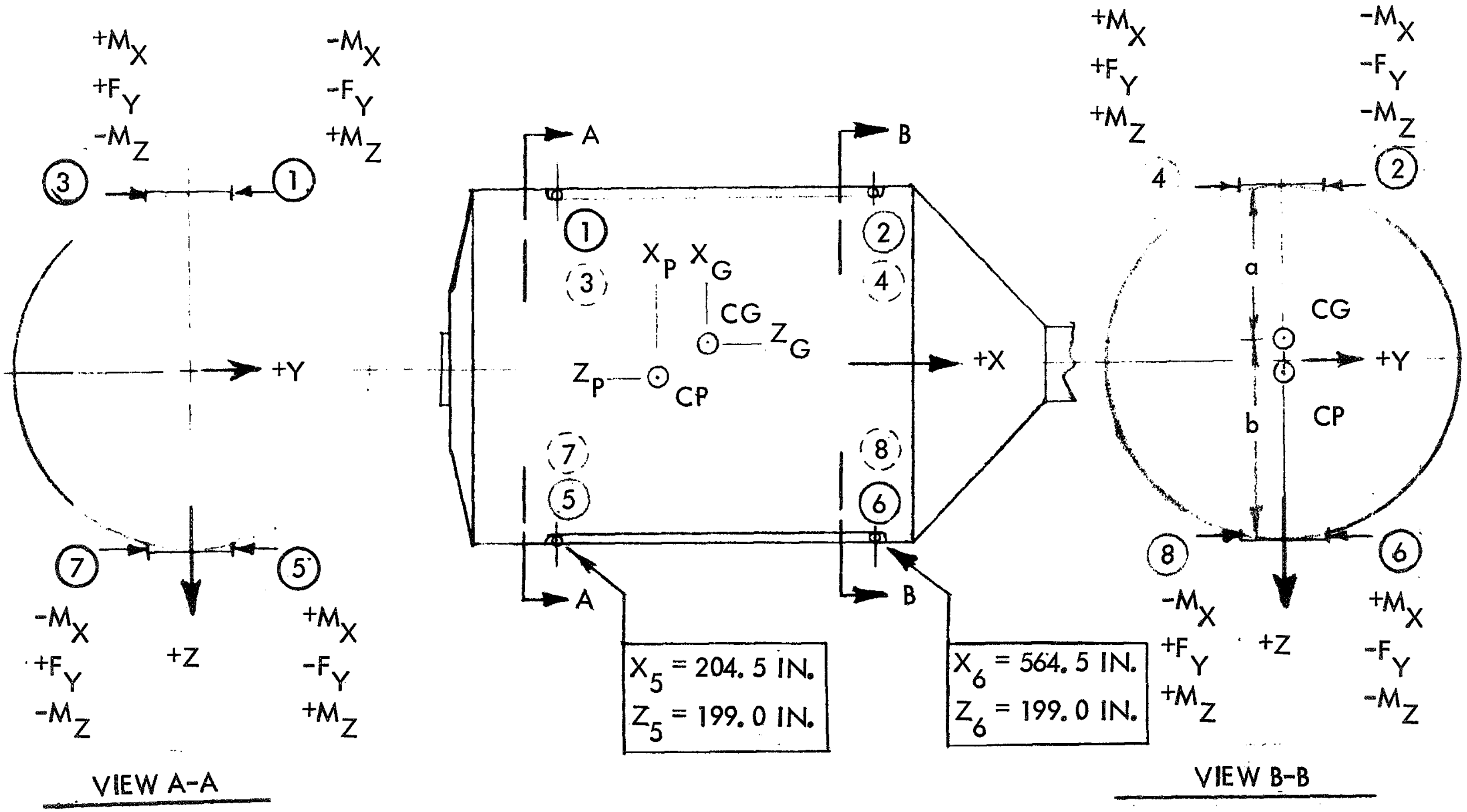
the general equations for CMG desaturation (M_z) and orbit maintenance (I_y) are

$$M_x = a\,(F_3t_3 + F_4t_4 - F_1t_1 - F_2t_2) + b\,(F_5t_5 + F_6t_6 - F_7t_7 - F_8t_8) \qquad (3\text{-}10)$$

$$I_y = F_3t_3 + F_4t_4 - F_1t_1 - F_2t_2 + F_7t_7 + F_8t_8 - F_5t_5 - F_6t_6 \qquad (3\text{-}11)$$

Table 3-9. Resistojet Operational Modes

Option	Pressure	Temperature	Remarks
1	Constant	Constant	Variable duty cycle; excess propellant in low-density years; simple control problem.
2	Constant	Variable to match propellant availability/usage	Variable duty cycle; approximately 10% thrust change over temperature range; power saving at lower temperature; increased thruster life due to lower temperature.
3	Variable to match impulse with specific operating time	Constant	Excess propellant in low-density years; requirement for fixed operating time (constant duty cycle) is not probable except for special case of continuous operating mode.
4a	Variable to maintain constant thrust	Variable to match propellant availability/usage	Same as Option 2 without thrust variation.
4b	Variable to match impulse with specific operating time	Variable to match propellant availability/usage	Same as Option 3 except continuous operation can be obtained without a buildup in propellants to be vented.



NOTE:

ATTACHED MODULES NOT SHOWN, CG AND CP LOCATIONS ARE REPRESENTATIVE ONLY

Figure 3-42. Resistojet Locations

where,

t_i = time associated with the i^{th} thrust vector

F_i = magnitude of the i^{th} thrust vector.

Each thrust vector may be composed of one or more thrusters. The angular momentum (M_x) required for CMG desaturation can be obtained from multiplying the impulse obtained from Figures 3-8, 3-9, 3-12, or 3-13 by the assumed moment arm of 16 feet. The orbit maintenance impulse requirement can be obtained directly from Figures 3-6, 3-7, 3-10, or 3-11, as applicable.

Fixed Thrust

For the fixed-thrust mode, assuming that all of the thrust vectors are equal, Equations 3-10 and 3-11 can be rewritten as

$$M_x = F\left[a(t_3 + t_4) + b(t_5 + t_6) - a(t_1 + t_2) - b(t_7 + t_8)\right] \tag{3-12}$$

$$I_y = F\left[(t_3 + t_4) + (t_7 + t_8) - (t_1 + t_2) - (t_5 + t_6)\right] \tag{3-13}$$

To obtain maximum utilization of the waste gases and/or supplemental propellants, it is necessary to minimize the total time (t_t) required to satisfy Equations 3-12 and 3-13 simultaneously.

$$t_t \min = \min \sum_{i=1}^{8} t_i \tag{3-14}$$

Assuming for the moment that the numerical values of M_x and I_y are both positive, it can be seen that, to minimize t_t, it is necessary that

$$t_1 = t_2 = 0 \tag{3-15}$$

$$t_3 \geq 0 \tag{3-16}$$

$$t_4 \geq 0 \tag{3-17}$$

since t_1 and t_2 result in negative momentum in both Equation 3-12 and 3-14, and t_3 and t_4 result in positive momentum in both equations. However, it is not immediately clear when thrusters five and six should be used versus thrusters seven and eight.

Since the ratio of any two time periods within a parenthesis (for example t_3/t_4) only affects the torque about the Z-axis, the following simplification of notation is made

$$t_{ij} = t_i + t_j \tag{3-18}$$

Since t_{56} and t_{78} tend to cancel one another in Equation 3-12 and 3-13, there are two possible solutions to Equation 3-14.

Case 1

$$t_{56} \geq 0 \tag{3-19}$$

$$t_{78} = 0 \tag{3-20}$$

$$\frac{M_x}{F} = at_{34} + bt_{56} \tag{3-21}$$

$$\frac{I_y}{F} = t_{34} - t_{56} \tag{3-22}$$

Solving Equations 3-21 and 3-22 for t_{34} and t_{56}

$$t_{34} = \frac{M_x + bI_y}{F(a+b)} \tag{3-23}$$

$$t_{56} = \frac{M_x - aI_y}{F(a+b)} \tag{3-24}$$

Case 2

$$t_{56} = 0 \tag{3-25}$$

$$t_{78} \geq 0 \tag{3-26}$$

$$\frac{M_x}{F} = at_{34} - bt_{78} \tag{3-27}$$

$$\frac{I_y}{F} = t_{34} + t_{78} \tag{3-28}$$

Solving Equations 3-27 and 3-28 for t_{34} and t_{78}

$$t_{34} = \frac{M_x + bI_y}{F(a+b)} \tag{3-29}$$

$$t_{78} = \frac{aI_y - M_x}{F(a+b)} \tag{3-30}$$

Since all values of t_i must be ≥ 0, inspection of Equation 3-24 and 3-30 give

$$t_{56} > 0 \tag{3-31}$$

for

$$M_x > aI_y \tag{3-32}$$

and

$$t_{78} > 0 \tag{3-33}$$

for

$$M_x < aI_y \tag{3-34}$$

and

$$t_{56} = t_{78} = 0 \tag{3-35}$$

for

$$M_x = aI_y \tag{3-36}$$

A similar solution can be obtained for negative values of I_y and/or M_x.

Since the center of gravity of the space station, along the X-axis is not generally equidistant from the paired-thrust vectors used above, the orbit maintenance and X-axis CMG desaturation RCS functions have an impact on the momentum about the Z axis. If the thrusters are operated equally on opposite sides of the orbit, as planned, the net momentum per orbit seen by the CMG's is zero; however, if only two thrust vectors were used (i.e., one vector per set) for each thrusting period, the additional Z-axis momentum for a single operating period could be as high as 1730 ft-lb-sec for an average RCS impulse capability of 2600 lb-sec/day. For half an orbit, 1730 ft-lb-sec is probably acceptable. However, by selecting the proper ratio of operating times for thrusters within a set, this Z-axis momentum due to RCS operation could be made equal to zero for each thrusting period. The G&C computer has the capability to make this calculation and this mode is recommended.

The thrusters must be sized to meet the maximum impulse requirement in a given unit of time. Assume that the maximum impulse capability is 5000 lb-sec/day and the minimum operating time is 1310 seconds per orbit (from Figure 3-41 at 240 nautical miles). From Figures 3-6 through 3-10 it can be seen that this large an impulse is only required during the high-atmospheric density years. During these years, the maximum CMG desaturation momentum (M_x) is 28,000 ft-lb-sec/day. Assuming that $a = b = 16$ feet,

$$aI_y = 16 \times 5000 = 80,000 \text{ ft-lb-sec/day} \qquad (3\text{-}37)$$

Again, assuming that M_x and I_y are both positive so that the previous analysis applies, Equation 3-34 indicates that thrust vectors 3, 4, 7, and/or 8 may be used. Several combinations of these vectors are possible. However, it is intuitive that the best mode of operation is to operate thrusters 3 and 4 equally for the total time available and operate 7 and 8 in a ratio to null the induced torque about the Z-axis. The required magnitude of the thrust vector may be calculated from Equation 3-29

$$F = \frac{M_x + bI_y}{(t_3+t_4)(a+b)} \qquad (3\text{-}38)$$

At 240 nautical miles, there are 15.45 orbits/day. The minimum thrust vector magnitude then, is

$$F = \frac{28000 + 80000}{(15.43)(1310+1310)(32)} = 0.084 \text{ pound} \qquad (3\text{-}39)$$

To allow some flexibility, a thrust vector magnitude of 0.1 pound is recommended.

The operating time per orbit of thrusters 3 and 4 would be

$$\frac{t_{34}}{2} = \frac{28000 + 80000}{2(15.43)(0.1)(32)} = 1094 \text{ sec/orbit} \qquad (3\text{-}40)$$

or a duty cycle of 0.195. The combined operating time of thrusters 7 and 8 would be

$$t_{78} = \frac{80000 - 28000}{(15.43)(0.1)(32)} = 1053 \text{ sec/orbit}$$

Since the sum of the operating times of thrusters 7 and 8 is less than the individual times of 3 and 4, thrusters 7 and 8 can be operated at separate times within the total operating period of 1094 seconds. In this way, a maximum of three thrusters are operating at one time.

The above assumes a single thruster per thrust vector. A reasonable option would be to provide two 0.05-lb thrusters per thrust vector. The only disadvantage to this is an increased packaging volume (two 0.05-lb thrusters are larger than one 0.1-lb thruster) and a very slight loss in specific impulse (0.8 percent). The advantage of dual thrusters is that only one 0.05-lb thruster per thrust vector is needed during low-atmospheric density years or during periods of larger light/dark ratios when the operating time per orbit can be increased. Operating a single 0.05-lb thruster reduces the peak electrical requirement. During these periods it would also be possible to delay repair of a failed thruster to a convenient time or until the second thruster failed.

Variable Thrust

Variable thrust operation provides the capability of matching the thrust to a specific operating time for a given impulse requirement. As with the dual thruster concept discussed above, this could be used to reduce the peak electric power load in low-atmospheric density years or when larger light/dark ratios exist. However, the change would be a continuous rather than a step change.

An analysis similar to that done for the fixed-thrust mode will result in the same set of Equations (3-14 through 3-36) except that the subscripts will be on thrust rather than time. The minimum thrust required for 100-percent design thrust is the same as given by Equation 3-39 (0.084 pounds).

Variable Specific Impulse

As discussed previously, the specific impulse of the resistojet thruster can be varied by varying the gas temperature. During low-atmospheric density years, the thrusters can be operated at lower temperatures. This results in lower peak electric power loads, lower average power requirements, and increases the expected thruster life.

A special case of variable specific impulse in conjunction with variable thrust is the continuous operational mode. The total thrust level required for continuous operations is much lower, e.g., 5000 lb-sec/day impulse is equivalent to 0.058 lbs continuous thrusting. This would be divided among three thrusters as before, so that the design 100-percent thrust level would be approximately 20 mlb (10 mlb if dual thrusters are desired).

In addition to power savings and increased thruster life, the continuous mode of operation would delete or significantly reduce the accumulator and compressor requirements. The problem of water-vapor condensation discussed in a later section would no longer be of concern. The major problem encountered is the design and control of the system to allow introduction of excess water and/or supplemental propellants into the continuous Sabatier effluent without affecting the back pressure of the Sabatier subsystem.

BIOWASTE GAS ACCUMULATOR

The primary function of the CO_2 accumulator in the CO_2 management assembly is to provide a continuous supply of CO_2 to the Sabatier reactor while the molecular sieve is operating in an on-off mode on the light-dark side, respectively, of the orbit. The flowrate, however, is not a constant value and will vary with the metabolic production of CO_2 similar to the rates given in Figure 3-27. Methane is then available in a timeline similar to Figures 3-29 and 3-30. Hydrogen is also included with the methane in the ratio of 0.246 pound of H_2 per 9.818 pounds of CH_4. There may also be some water vapor present but for simplicity in preliminary sizing of the biowaste gas accumulator, the water vapor is ignored.

Figure 3-43 shows the timeline of the amount of gas in an accumulator initially containing W_o lb with a flowrate in corresponding to Figure 3-29 (plus hydrogen) and a flowrate out corresponding to the daily average usage (10 lb/day). Since the resistojets operate on an intermittent duty cycle, the actual variation would have a sawtooth characteristic imposed on the curve shown. Assume that the accumulator is at a pressure corresponding to (W_o - 1.63) lb (ten hours on Figure 3-43) at 530 degrees R at the start of thrusting; that gas is flowing into the accumulator at the lowest flowrate corresponding to all the crew sleeping; and that the accumulator may blow

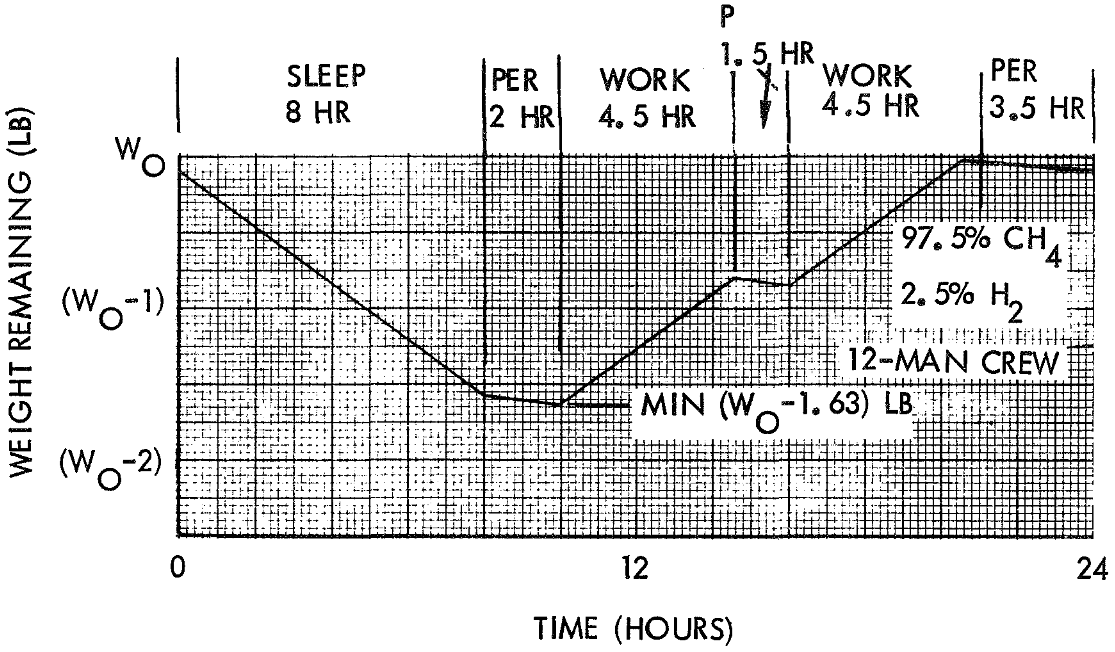


Figure 3-43. Biowaste Propellant Remaining With Average Usage

down to a final pressure of 40 psia during thrusting. Then Figure 3-44 shows the amount of propellant available as a function of accumulator volume. There is no significant difference in the amount of propellant available for two 0.1-lb thrusters or three 0.05-lb thrusters and Figure 3-44 is representative of both cases. Operating four 0.1-lb engines reduces the available propellant by about 3 percent. The lower dotted line in Figure 3-44 represents the amount of propellant required by resistojets operating at 2000 R, twice per orbit, to utilize 10 lb/day of waste gases. The other dotted lines represent additional propellant in the ratios of 1.5 and 2.0, representing longer times between resistojet operation. The upper dotted line would correspond to resistojet operation once per orbit.

The assumption that the accumulator is at a temperature of 530 R before thrusting is a conservative one. The accumulator is located in 530 R environment. The incoming flow is at a temperature greater than 530 R, depending on the compressor/cooling design, and its momentum provides mixing and convective heat transfer from the accumulator walls. There are only a few pounds of gas in the accumulator so little heat is required to warm it during repressurization periods.

The final accumulator temperature for the above case is shown in Figure 3-45 assuming that the gas entering the accumulator is 530 R and that there is perfect mixing. There is no significant difference in the final temperature due to the different flowrates corresponding to four 0.1 lb to three 0.05 lb thrusters and Figure 3-45 is representative of all intermediate cases.

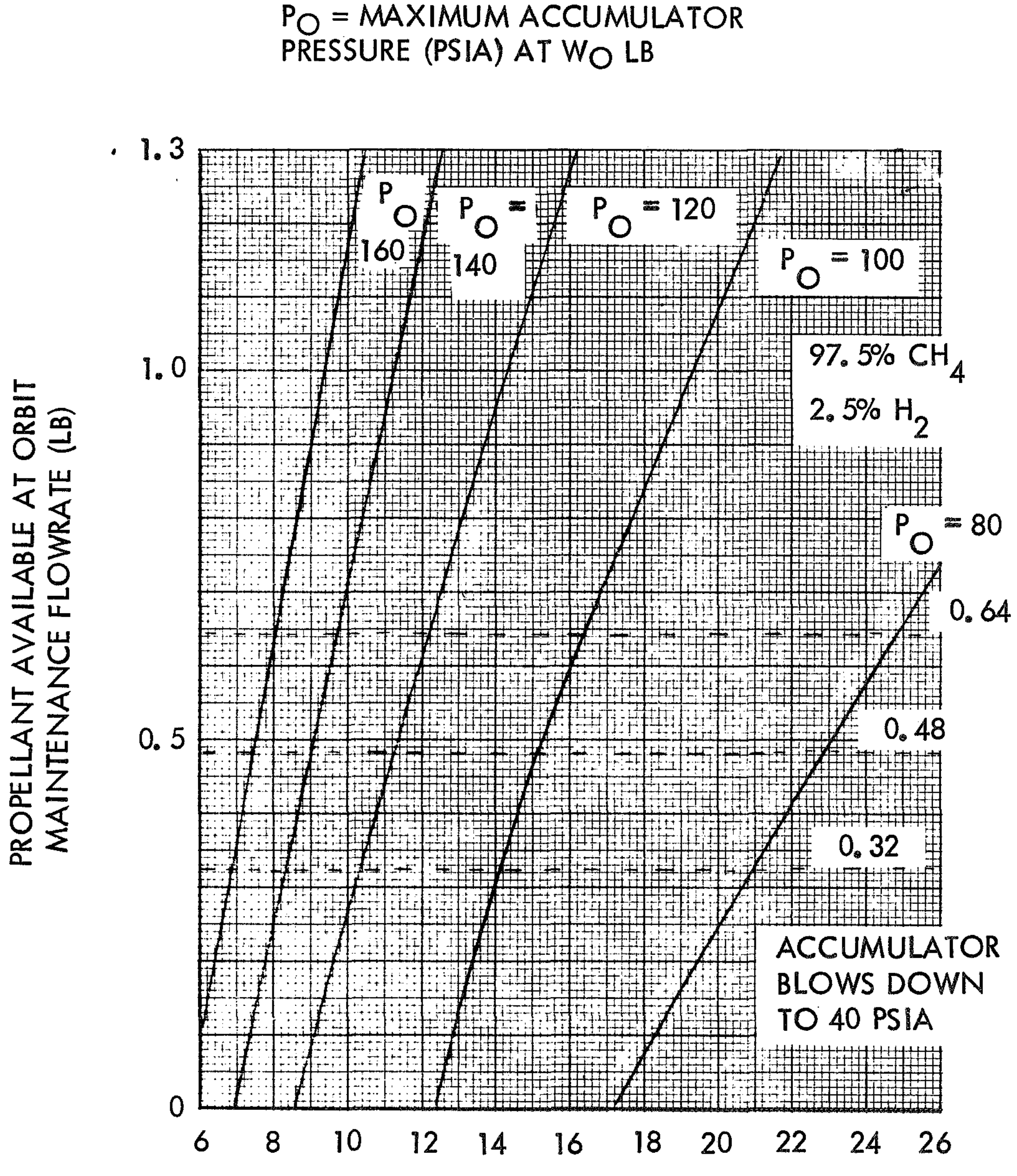


Figure 3-44. Propellant Available Versus Accumulator Volume

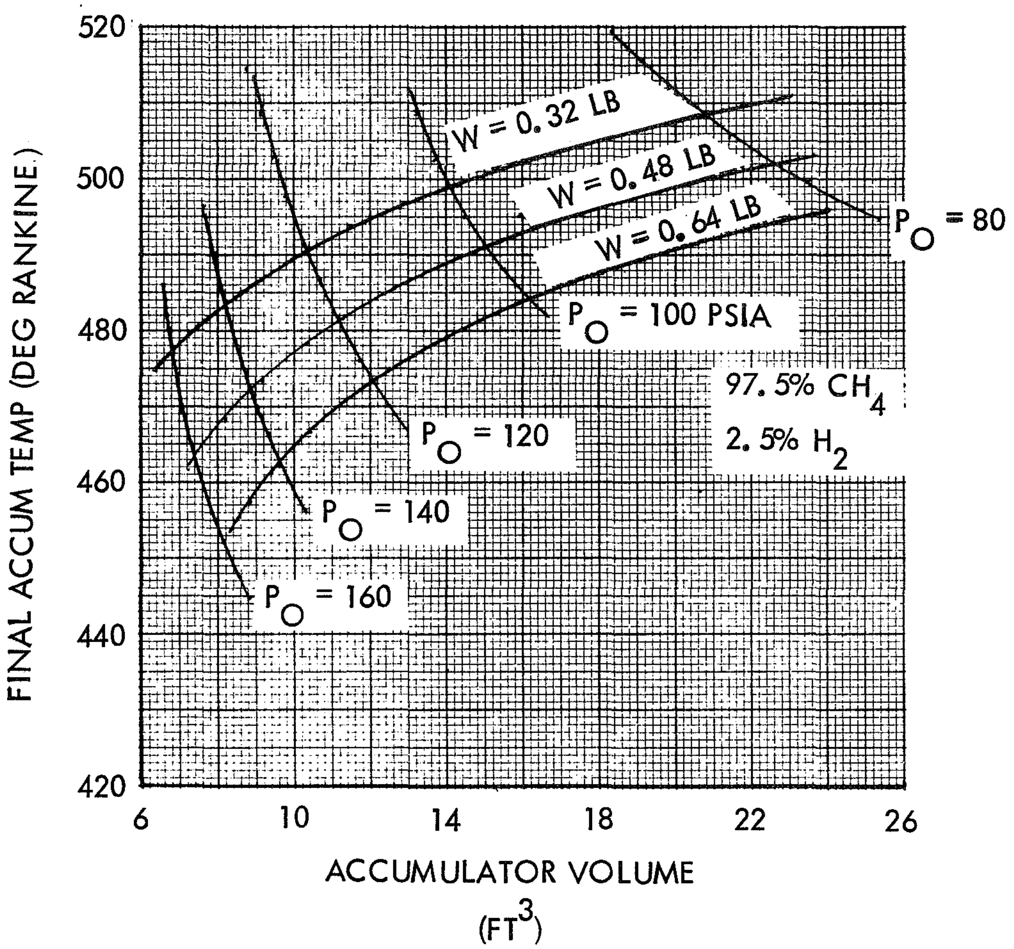


Figure 3-45. Final Accumulator Temperature

The effect of the gas temperature and of the accumulator size on resistojet power to achieve 2000 R in the resistojet is shown in Figure 3-46. The effect of compressor power requirements as a function of accumulator initial pressure (P_O) is shown in Figure 3-47. These differences in power requirements due to accumulator pressure and/or temperature were not considered significant enough to influence accumulator selection.

The effect of volume and initial pressure on accumulator diameter and weight is shown in Figures 3-48 and 3-49. Here again, the accumulator characteristics can vary over a wide range without a significant change in weight or diameter. The characteristics of the hydrogen accumulator selected during Phase B space station preliminary design for the medium-thrust RCS O_2/H_2 subsystem are listed in Table 3-10.

This accumulator is more than adequate for the biowaste gases and would be used to reduce costs.

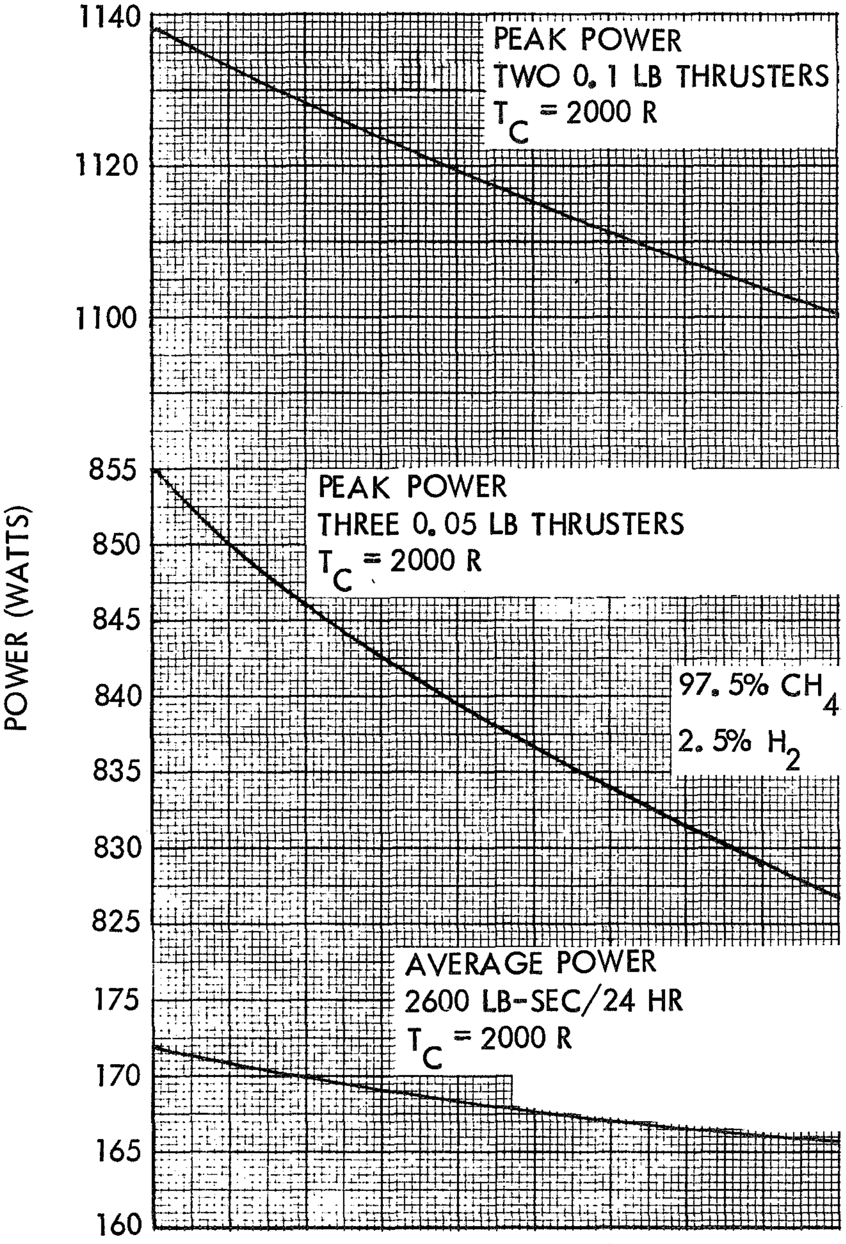


Figure 3-46. Effect of Inlet Temperature on Power Required

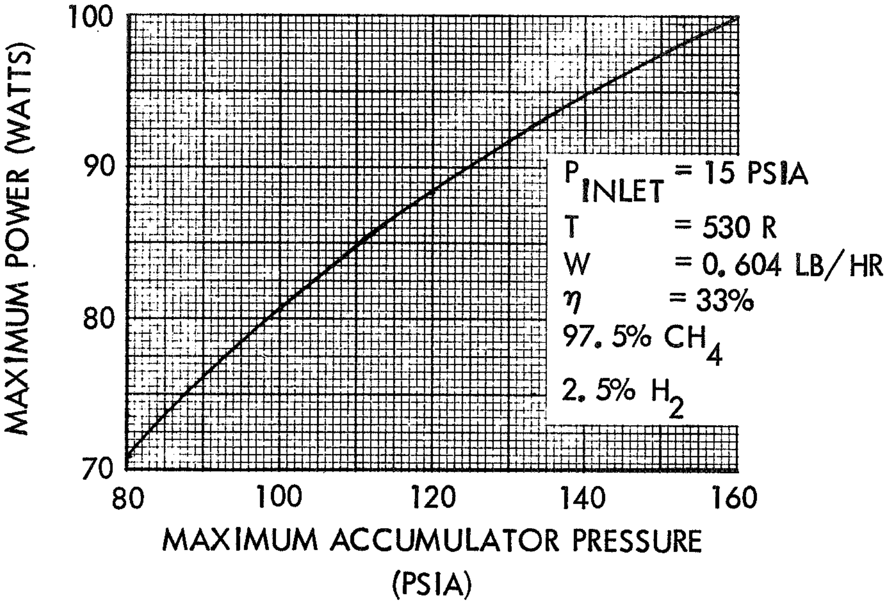


Figure 3-47. Peak Compressor Power

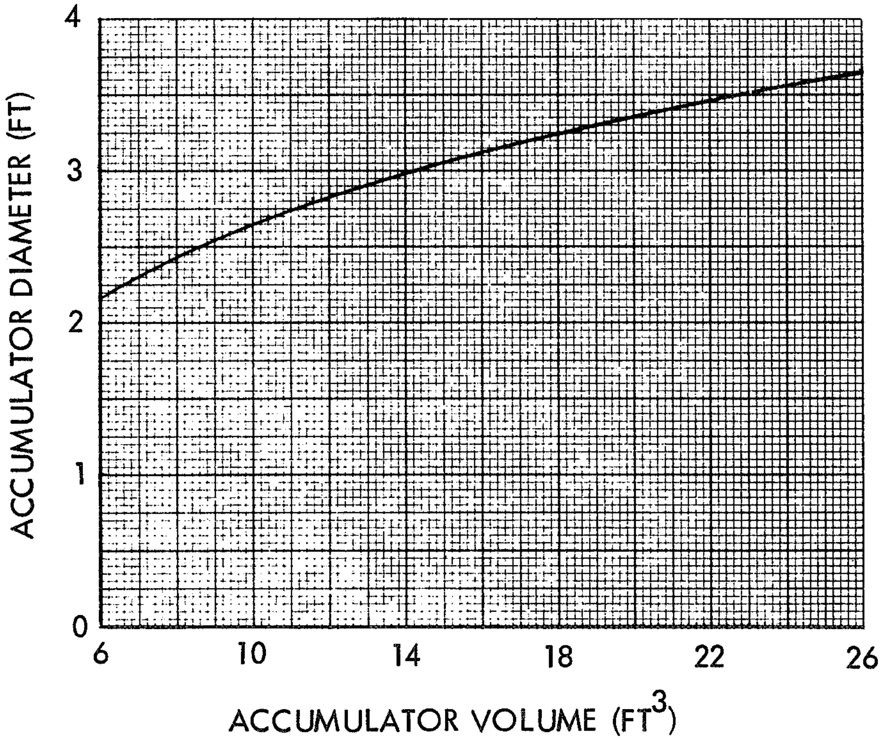


Figure 3-48. Accumulator Diameters

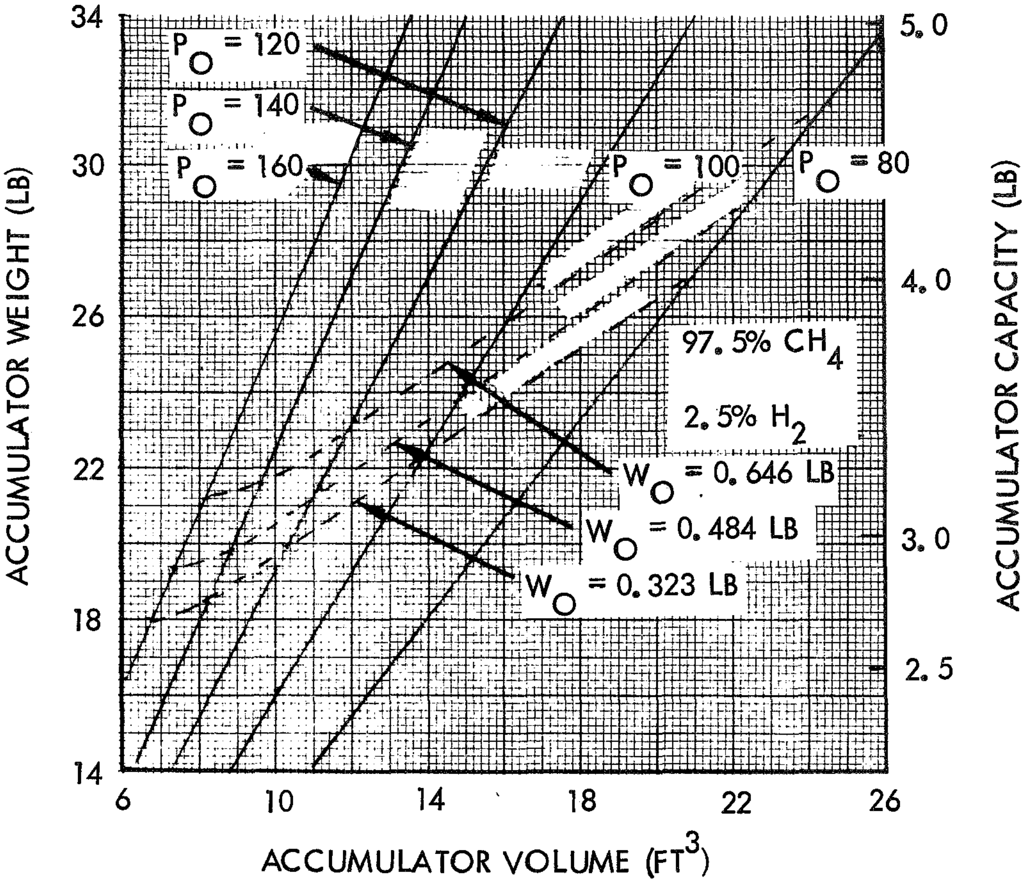


Figure 3-49. Accumulator Weights

Table 3-10. Accumulator Characteristics

Material	2219 aluminum
Weight	24.12 pounds
Volume	14.39 ft^3
Dia	3.00 ft
Max. operation press.	120 psia
Proof pressure	150 psia

WATER CONDENSATION

The initial resistojet subassembly concept is shown schematically in Figure 3-50. The flow of biowaste gases from the Sabatier condenser is controlled by a shutoff valve (normally open) through a filter and a regulator

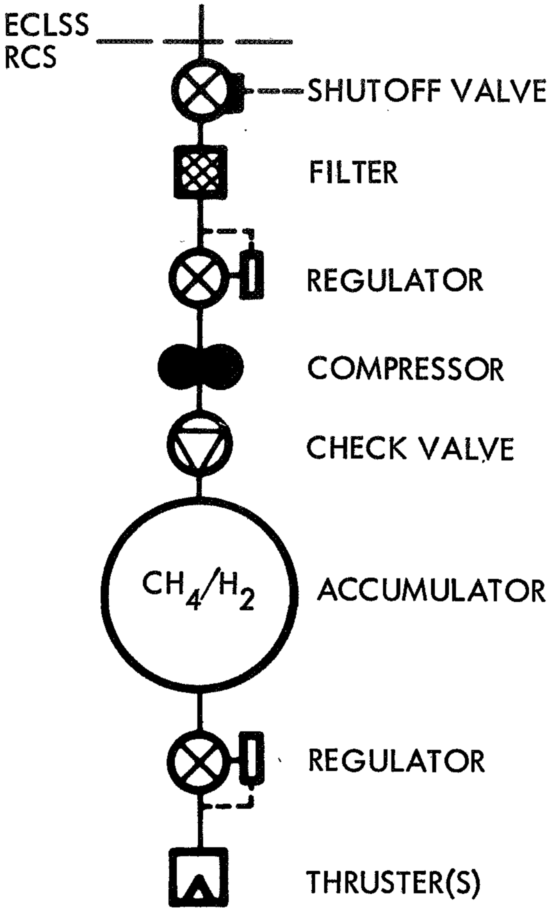


Figure 3-50. Resistojet Assembly (Dry Gas)

to maintain the pressure in the upstream system at approximately 15 psia. The regulation can be done by a separate component or could be part of the compressor. The gases are compressed and stored in the accumulator at 100 psia. On demand from the thrusters, the gases flow from the accumulator through pressure regulators to the thrusters. The thruster inlet pressure is approximately 40 psia and the stagnation pressure at the thruster throat is assumed to be 30 psia. A small accumulator or manifold may also be included in each thruster cluster to dampen initial pressure transients but this is not mandatory.

This initial concept is based on a dry-gas mixture from the Sabatier subassembly. However, the waste gases obtained from the Sabatier condenser-separator contain water vapor as described in previous sections. The amount of water present will correspond to saturation conditions at the condenser-separator outlet pressure and temperature (nominally 15 psia and 54 F). If this gas mixture is subsequently compressed and allowed to cool, some portion of this water vapor will condense. The amount of condensation depends on the final temperature and pressure in the accumulator. This poses two possible problems:

1. If compression is done isothermally, condensation could occur in the intercoolers resulting in two-phase flow in later compression stages. The severity of this two-phase flow would depend on compressor type and individual design.

2. In the accumulator, at a significantly higher pressure (>100 psia) than the condenser-separator outlet pressure and at ambient temperature (70 F), a significant quantity of this water vapor will condense. In the low-gravity environment it is impossible to predict the actual buildup of water in the accumulator. However, it is reasonable to assume that statistically some of these droplets will collide and coalesce to form larger drops before reaching the accumulator outlet. It is not unreasonable to assume that a large buildup of liquid could occur in the accumulator over a period of time. When a slug of water enters the accumulator outlet, pressure and flow surges will result downstream.

Several design options have been studied which will prevent condensation in the accumulator. For design calculations the Sabatier condenser separator outlet conditions are assumed to be 70 F and 15 psia. In Option 1 (Figure 3-51), chemical dehumidification is provided as in the ECLSS molecular sieve. The incoming stream passes through a silica gel bed which adsorbs the water vapor. Two beds are used. One bed is open to the incoming stream until it becomes saturated. It then is isolated and heated to drive out the water. The two beds alternate functions, one bed adsorbs while the other is dried. In Option 2 (Figure 3-52), mechanical and chemical dehumidification are combined. Since the gases must be compressed and cooled in any case, the silica gel beds can be made lighter and use less power if most of the water is condensed during compression and cooling. By compressing the incoming mixture to 120 psia and cooling to 70 F, approximately 88 percent of the incoming water vapor can be condensed and separated. The remaining water is adsorbed by silica gel beds as in Option 1. In Option 3 (Figure 3-53), dehumidification is provided by purely mechanical means. The incoming stream is compressed to a higher pressure and cooled to a lower temperature than in the other cases. In this manner, sufficient water is condensed and removed to prohibit condensation in the accumulator at the lowest temperature reached during blowdown ($\approx$ 2 F). After passing through the condenser, the gas pressure is reduced and it is reheated to 70 F. In all of the above options, the water could be stored, as shown, for use in the resistojet; it could be returned to the ECLSS water management assembly; or it could be dumped overboard. In Option 4 (Figure 3-54), the accumulator temperature is maintained sufficiently high by electric heating and insulation to allow blowdown without reaching a temperature low enough to cause condensation.

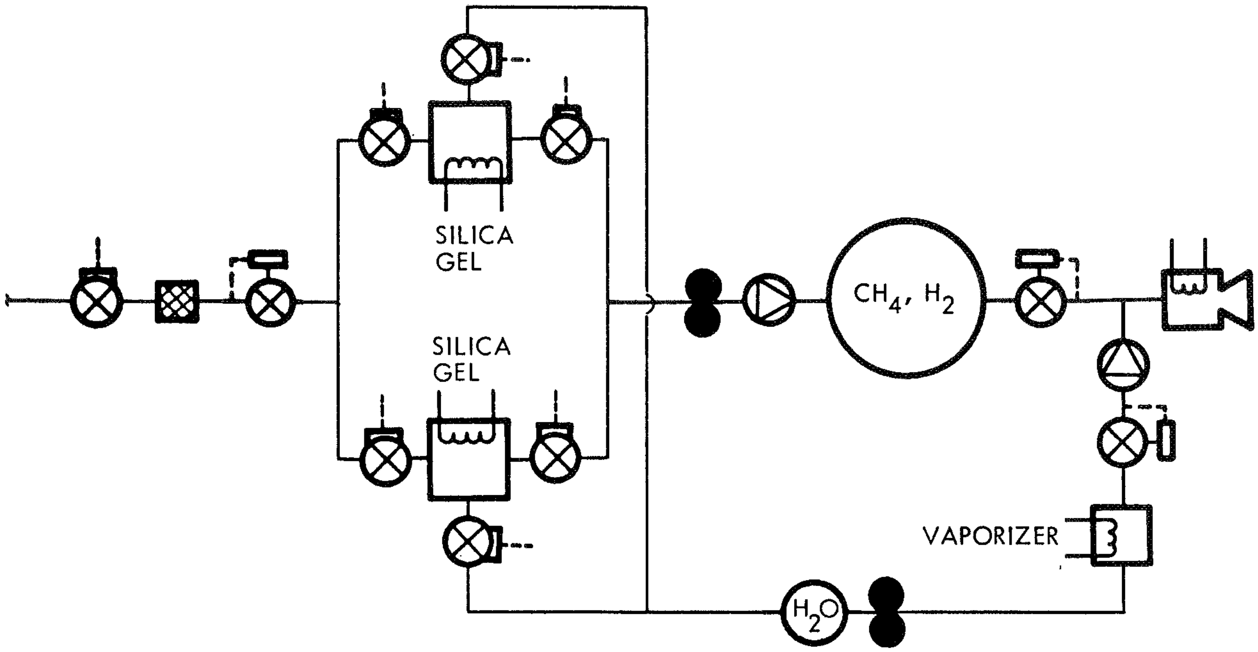


Figure 3-51. Resistojet Assembly Option 1

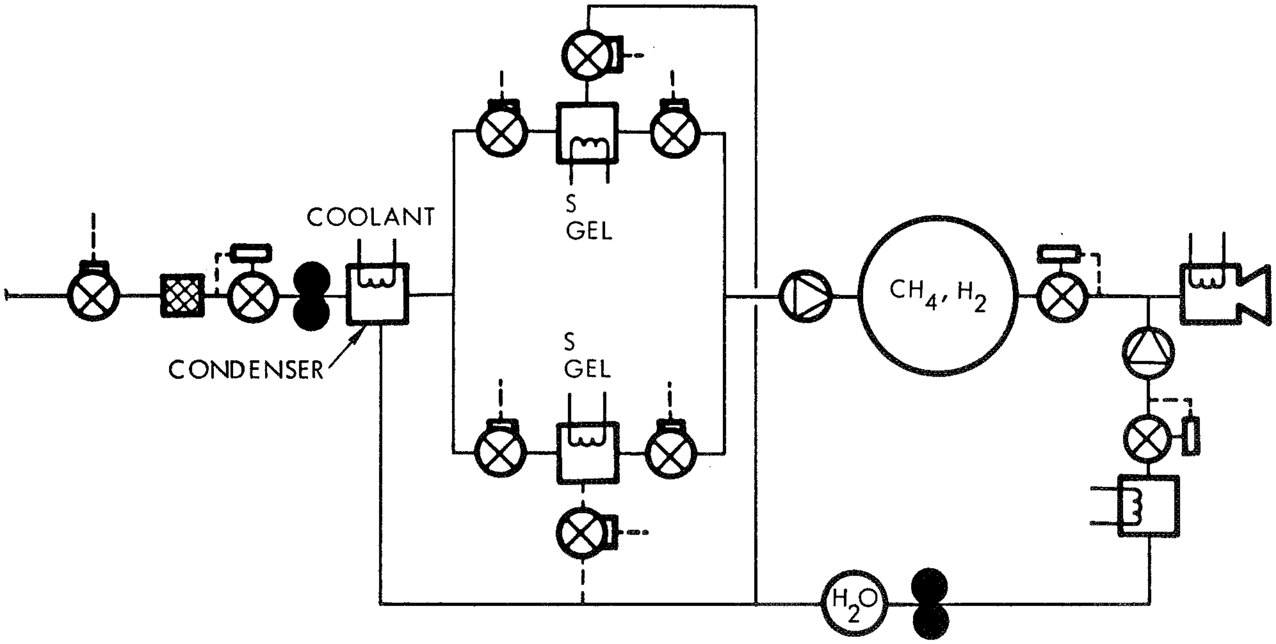


Figure 3-52. Resistojet Assembly Option 2

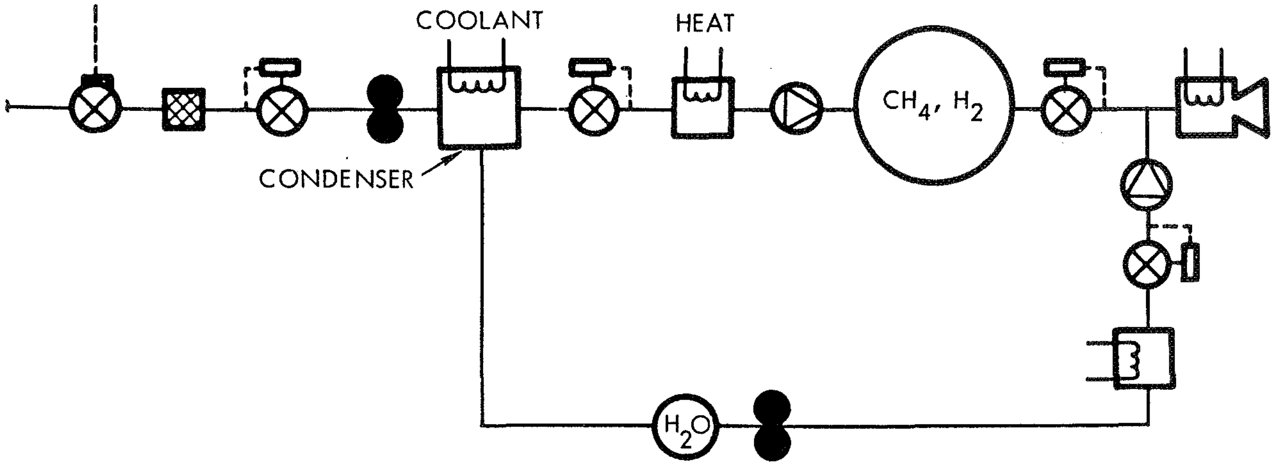


Figure 3-53. Resistojet Assembly Option 3

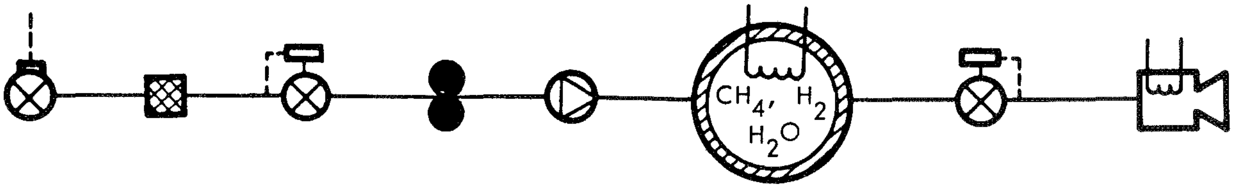


Figure 3-54. Resistojet Assembly Option 4

The weight, power, and cooling requirements for the initial design and the four options are presented in Table 3-11. The power required to warm the accumulator in Option 4 is a function of insulation weight as shown in Figure 3-55. The cooling loads given in Table 3-10 are the amount of cooling required for isothermal compression and condensation if applicable. Option 4 uses isentropic compression in order to minimize accumulator heating requirements. Water pumps and vaporizers (downstream of the water accumulator) in Options 1 to 3 are sized for flowrates corresponding to usage of $CH_4/H_2/H_2O$ in the resistojet in the same proportion as they are available from the ECLSS (94.4 percent CH_4, 2.4-percent H_2, 3.2-percent H_2O).

With the exception of heaters and water vaporizers, all the components are common for the four options considered or are used by the ECLSS and will require little or no additional technology development. Any development would only involve scaling to a different size. Option 1 requires heavy silica gel beds and a large continuous power requirement for drying. These disadvantages are reduced in Option 2 but with the additional complexity of a condenser. Option 3 eliminates the complexity of the silica gel beds without additional weight. The continuous power requirement is as high as Option 1. Option 4 is the least complex of the options, however; it requires heavy insulation or high continuous power.

For a system designed to utilize excess or supplemental water as resistojet propellant, in addition to the biowaste gases, the water accumulator, pump, vaporizer, etc., of Options 1 to 3 will be required in any case. Of these three, Option 3 is recommended because of lighter weight and less complexity.

Another alternative is to utilize the biowaste gases continuously. If the gases are used without compression there should be no condensation of vapors. Even if some compression is provided the condensate would be carried along in the gas stream and would not have an opportunity to accumulate. The system could be designed to accommodate this small quantity of liquid in the gas stream. The schematic of this system would be similar to the basic schematic of Figure 3-48 without the accumulator and downstream regulator. The compressor may or may not be required depending on the flexibility desired in thruster chamber pressure range. The major problem with this system is the dual utilization of excess or supplemental water concurrently with the biowaste gases. It is believed that this is not a serious design problem and it is recommended that the integrated ECLSS-resistojet-CMG demonstration program include the capability of testing this option.

Table 3-11. Option Characteristics

	Option Number				
	Basic	1	2	3	4
Total weight (lb)*	50	160	74	71	50 plus insulation**
Continuous power (watts)	88.5	138.5	98.5	144.5	88.5 plus heater**
Additional power required during thrusting (watts/0.1 lb)	545	561	561	561	545
Cooling required (BTU/hr)	83 at 70 F	83 at 70 F	102 at 70 F	113 at 50 F	0.0

*Does not include redundant components

**See Figure 11 for heater power versus insulation weight

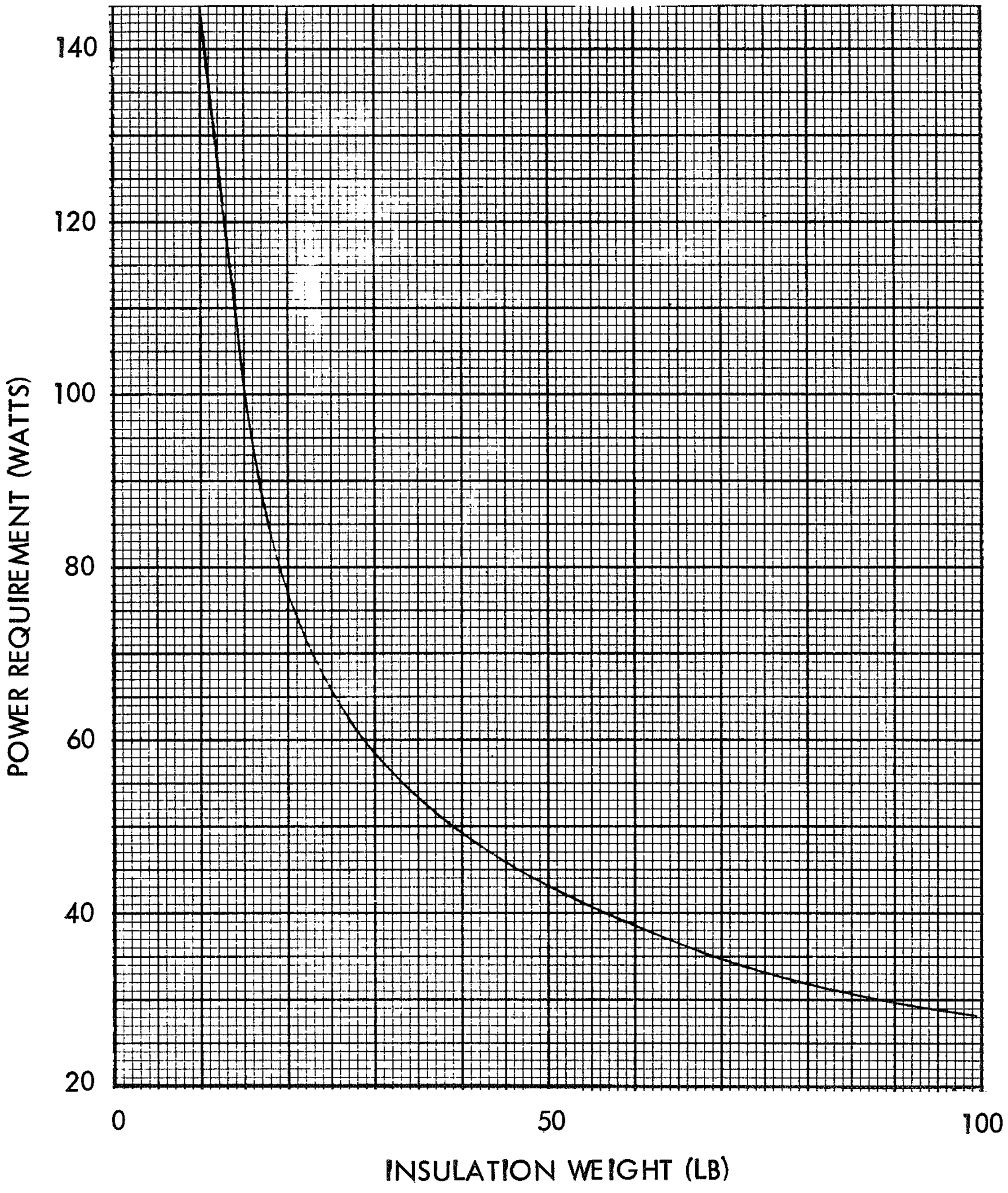


Figure 3-55. Power Versus Insulation Weight for Option 4

RESISTOJET ASSEMBLY DESIGN FOR DEVELOPMENT TEST

The Space Station Phase B Definition Studies are continuing. In addition to the 33-foot-diameter stations defined in the past year (powered by solar-array batteries, nuclear reactor, and radioisotope), other configurations and concepts are to be studied in the coming year. Of particular interest in the upcoming studies is the modular station, which will be built up in stages by modules launched in the cargo bay of the advanced logistics shuttle.

Since neither the final space station concept nor the configuration can be predicted at this time, it is not possible to define the resistojet assembly in detail. However, there is one concept pertinent to the biowaste resistojet which appears to be common to all of the NR space station designs. The CO_2 management assembly, in all cases, recovers all of the metabolic CO_2 (within the capability of the Sabatier reactor design). If the medium-thrust RCS is an O_2/H_2 bipropellant system, the extra hydrogen for the Sabatier reactor can be supplied from the RCS hydrogen boil-off (cryogenic storage). If the medium-thrust RCS is a hydrazine monopropellant, the ECLSS will use hydrazine decomposition to provide nitrogen for leakage makeup and hydrogen for the Sabatier reactor, as described in the Space Base section of this report. The following design is representative of the resistojet assembly necessary to develop this type of ECLSS/resistojet integrated subsystem. To provide flexibility in the development program, it is assumed that excess water will be available to the resistojets. The biowaste gas section is based on Option 3 of the previous section; however, the additional hardware necessary to test the continuous mode of operation is also shown.

Sabatier Reactor Subassembly

The Sabatier reactor subassembly is not normally part of the resistojet subassembly; however, the biowaste gas composition to the resistojet is directly a function of the Sabatier reactor subassembly design and operation. It is also necessary that the resistojet assembly operation have little or no effect on the Sabatier reactor pressure and flow rates. To properly assess these interactions, it is strongly recommended that a Sabatier reactor subassembly be designed specifically for the resistojet development program and be included on line with the resistojet assembly.

It is desirable but not absolutely necessary that the Sabatier reactor subassembly be designed for the 12-man space station. A revised schematic representative of the test assembly is shown in Figure 3-56. The instrumentation shown is for normal operation and does not include all test requirements.

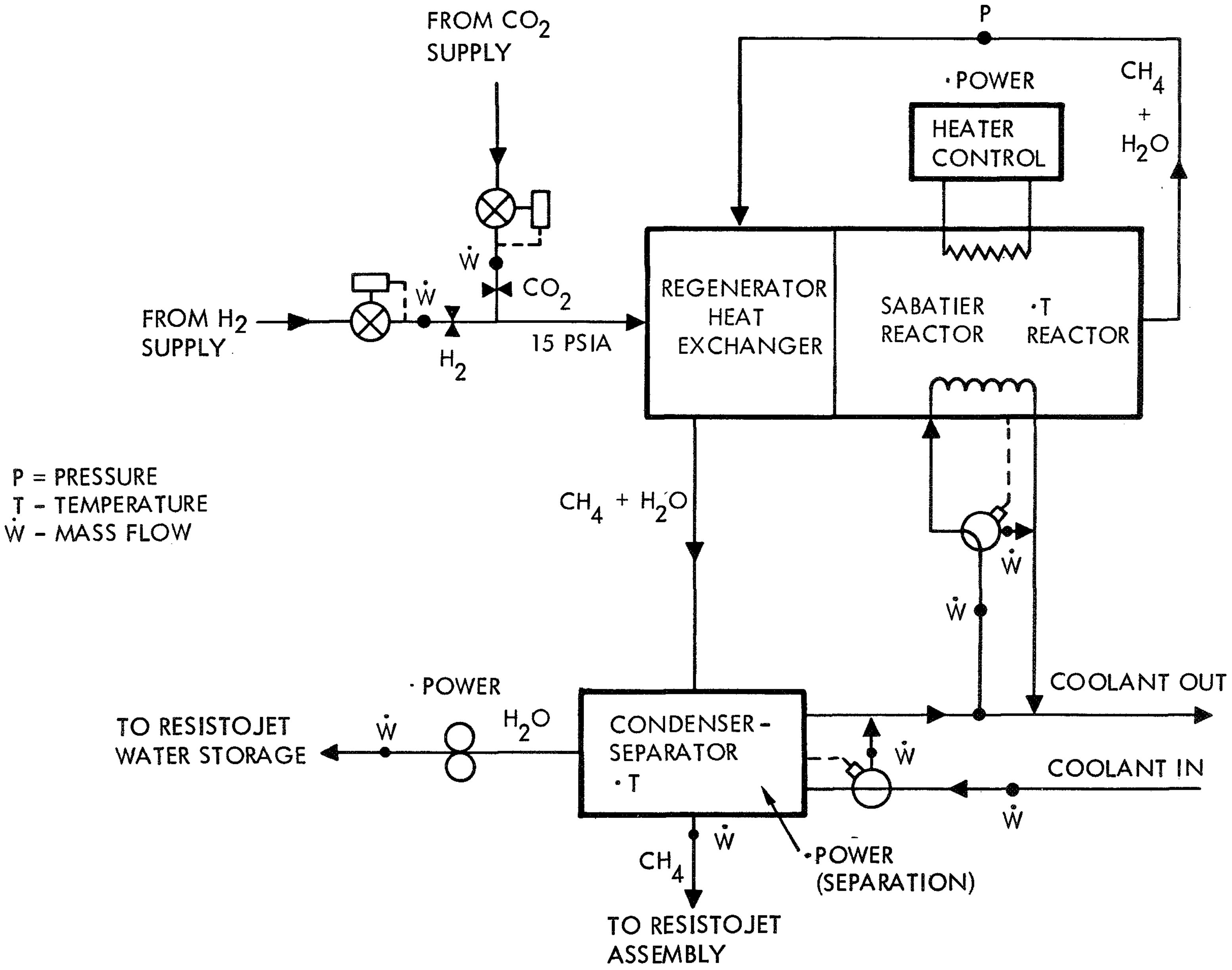


Figure 3-56. Sabatier Reactor Development Test Assembly

It is preferable that the CO_2 be supplied from a manned ECLSS test. However, adequate simulation can be obtained by providing mixtures based on the results of previous manned tests. A commercial source of hydrogen is considered adequate for test purposes. Performance requirements for the subassembly are as follows:

Operating time -- continuous

CO_2 flow rate -- 1.13 pounds per hour

H_2 flow rate -- 0.207 pounds per hour

Heat rejection -- condenser: 300 Btu/hr at 50 F; reactor 210 Btu/hr at 90 F

System pressure -- 15 psia

Biowaste gas outlet temperature -- 54 F

Biowaste gas outlet composition -- See Table 3-6

Water from the Sabatier reactor subassembly can be utilized as required for the water side of the resistojet assembly.

Resistojet Assembly

The proposed resistojet assembly schematics are shown in Figures 3-57 and 3-58. The propellant storage subassembly is shown in Figure 3-57. In an actual space station design, both the biowaste gas and the water loops would have the capability of providing CMG desaturation. Since CMG desaturation is the only time-critical function, it would not be necessary to provide redundant storage subassemblies. The propellant storage subassembly would be located in the lower toroid section of the 33-foot-diameter space station, in the vicinity of the Sabatier reactor. Line lengths between components would be on the order of a few feet.

For test purposes, the biowaste gas loop provides the capability for either intermittent or continuous operation. It is doubtful that both options would be provided in an actual space station design. A vent is provided so that the biowaste resistojet assembly can be shut down without shutting down the Sabatier reactor subassembly.

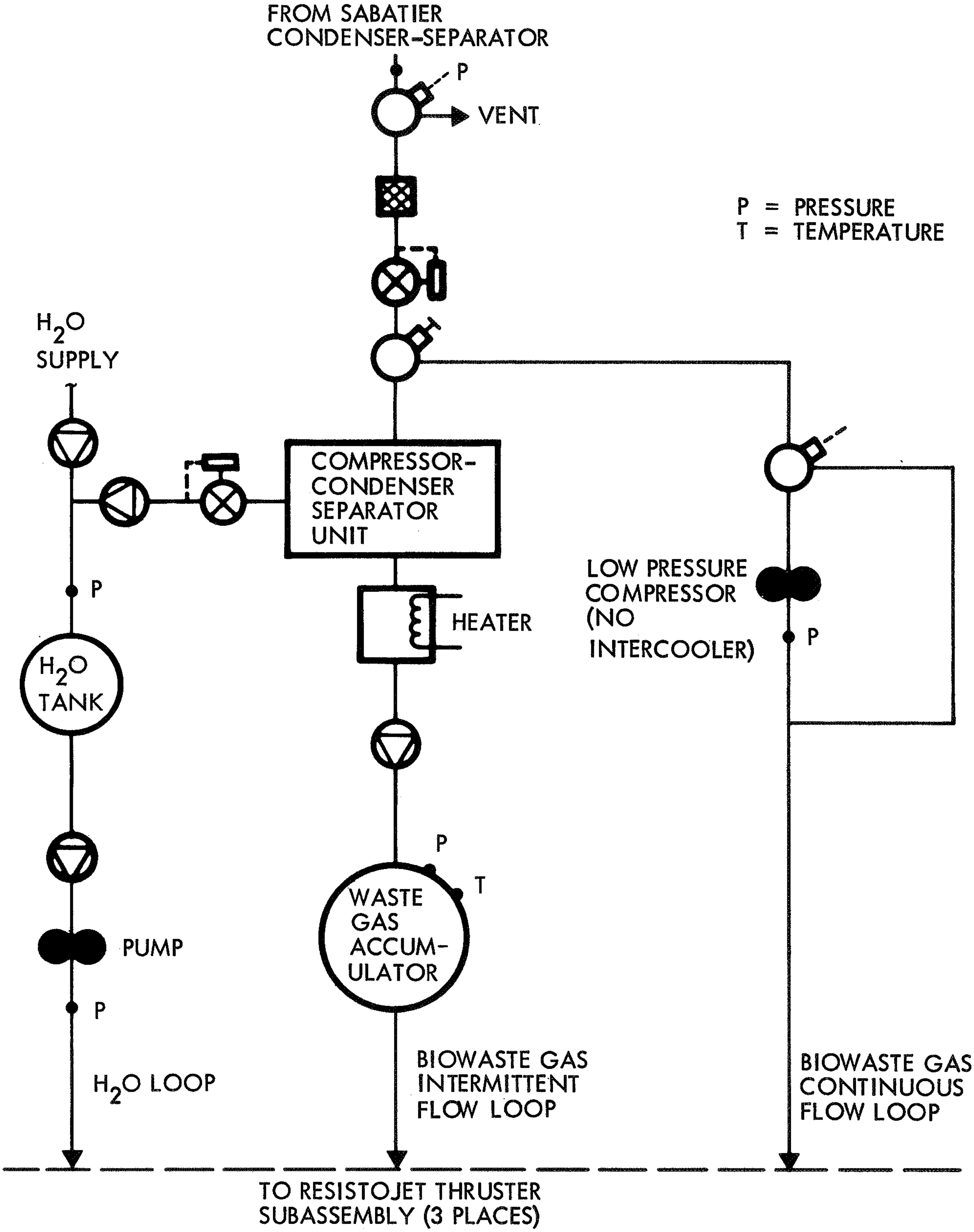


Figure 3-57. Resistojet Propellant Storage Subassembly

A maximum of three thrusters is adequate for the development test. The thrusters will be located in the four "corners" of the space station, and typical line lengths from the propellant storage subassembly are 10, 50, and 100 feet. The thruster subassembly schematic is shown in Figure 3-58. The manifold in the biowaste side is to dampen pressure fluctuations. A pressure damper is also required on the water side. A variable pressure regulator is shown for control of all three loops. An intermittent biowaste gas system in the space station would probably have a fixed pressure regulator since there is no significant advantage in variable thrust for the intermittent flow option. The development test should have the option, however, of testing all reasonable variations. The thruster also has variable temperature capability.

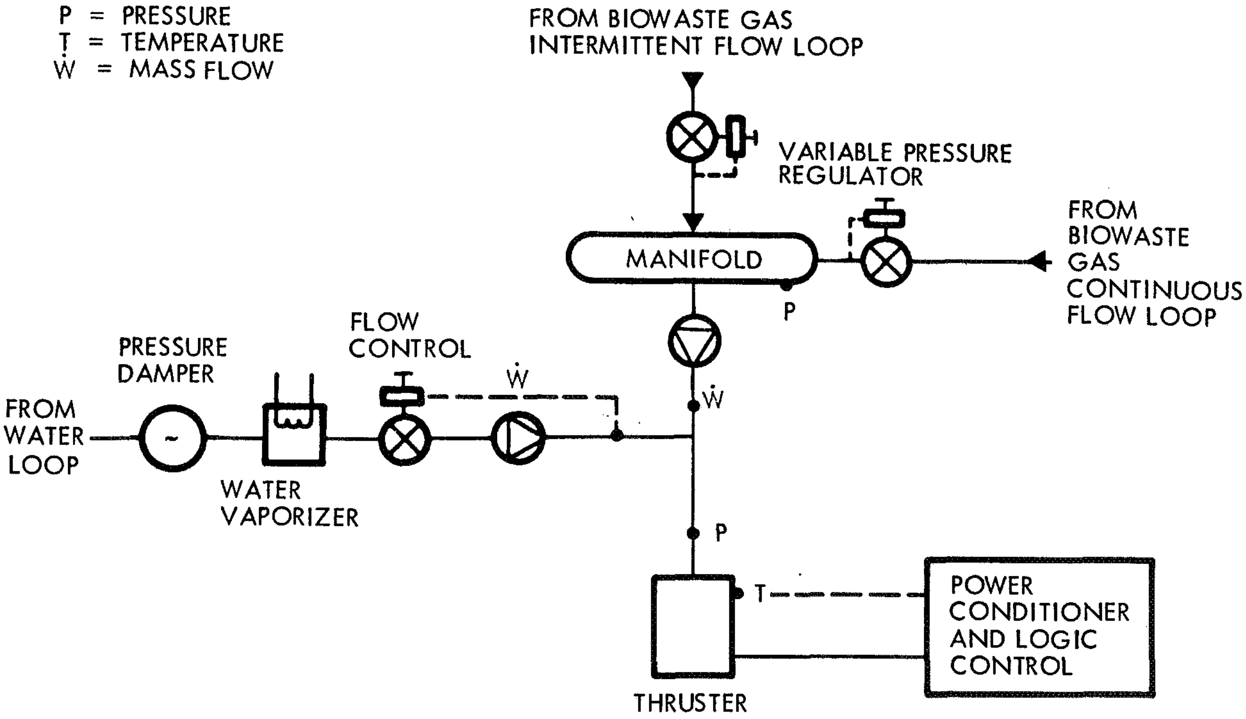


Figure 3-58. Resistojet Thruster Subassembly

IV. SPACE BASE

The Space Station Phase B Definition Study includes the conceptual design of a space base as a centralized earth-orbital facility for conducting a multidisciplinary research, development, and operations program.

Some of the stated requirements differentiate the space base from the precursor space station and dictate its unique design. Notably, the base is to be a large (nominally 60 men) assembly of general- and special-purpose modules. It must have utility during buildup to the nominal configuration and must be capable of growth beyond it. In further contrast to the station, the base will provide artificial-gravity and zero-gravity environments simultaneously and in separate volumes. Power is to be supplied by multiple nuclear reactors. A detailed description of the Phase A Space Base Definition can be found in Reference 25.

The Space Base Phase A Study proposed biowaste resistojets to supplement the medium-thrust RCS and significantly reduce resupply requirements. To identify any development requirements not covered by the space station biowaste resistojet development program, a more detailed definition of this resistojet system is provided in this section.

SPACE BASE RCS REQUIREMENTS

SPACE BASE CONFIGURATIONS AND FLIGHT MODE

The selected space base concept is shown in Figure 4-1 as it would operate in its normal flight mode. In the nominal configuration, the artificial-gravity section consists of the hub and four basic modules, which rotate in the direction of the orbital velocity vector. The axis of rotation of the artificial-gravity section (X-axis), which is the centerline of the zero-gravity section, is normal to the orbit plane.

Launch vehicle payload and program resource constraints and the orderly evolution of the space operations and scientific investigations (SOSI) program dictate that the space base grow through a series of configuration and capability plateaus. The buildup sequence is presented in Figures 4-2 through 4-6. The three major operational configurations envisioned are preceded by early assembly stages centered on a 12-man, solar-powered core module, of which the space station may be a prototype. The buildup proceeds in such a manner that this unit becomes an element of the local-vertical-oriented zero-g section of the base.

The 36-man initial configuration would be reached after four INT-21 launches. It is nuclear-powered, has four modules in zero-g and two in artificial-g sections, and is the first stage of buildup to provide both gravity environments simultaneously. Initial manning of this configuration may be only 24.

The fifth INT-21 launch would bring up two combined personnel quarters/SOSI modules, which would be assembled in artificial gravity to complete the 60-man nominal configuration. The SOSI and support facilities would be complete at this stage, and the crew size would be adequate to achieve 40-percent utilization by operating them on a one-shift basis. Each module of the artificial-g section contains two decks of crew and system support and two decks of SOSI equipment. The zero-g section consists of five modular elements, the nuclear power module, an inertially oriented SOSI module, the rotating hub plus two decks of subsystem equipment, a crew and subsystems module, and a SOSI module oriented to the local vertical.

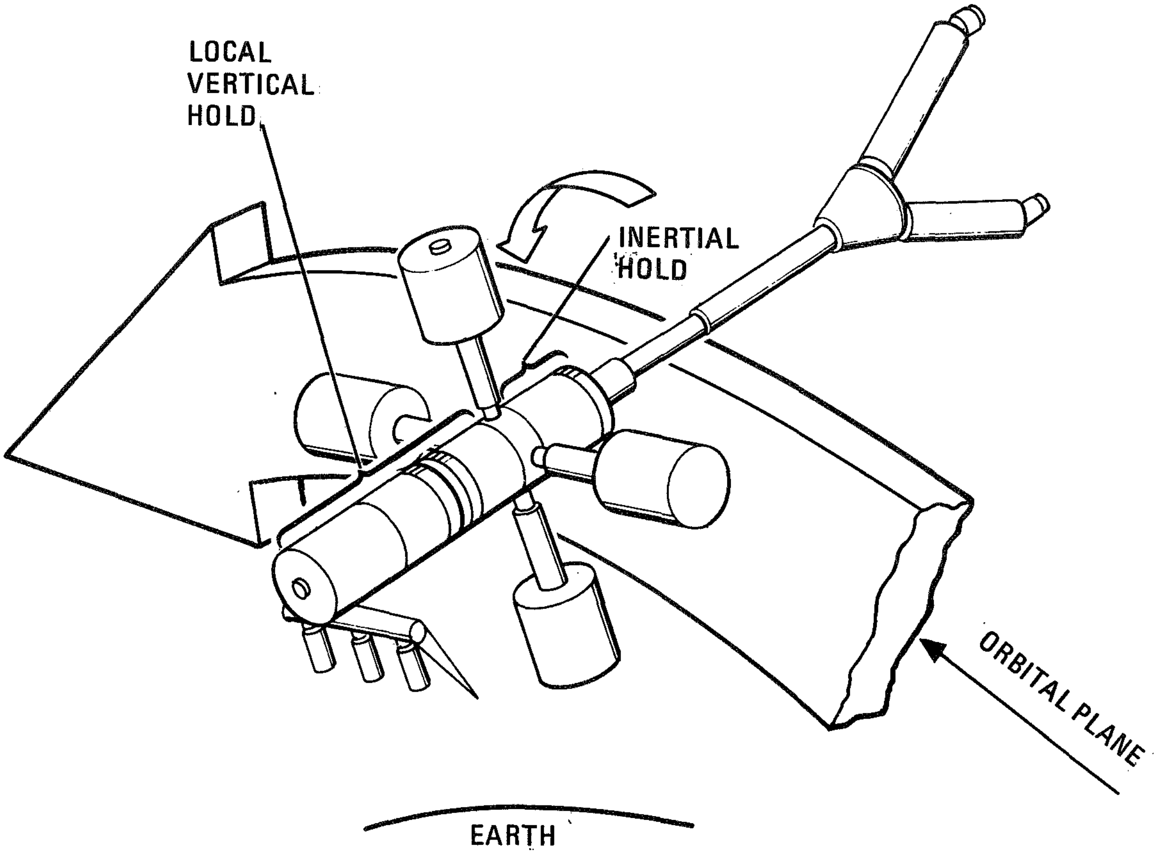


Figure 4-1. Space Base Flight Mode

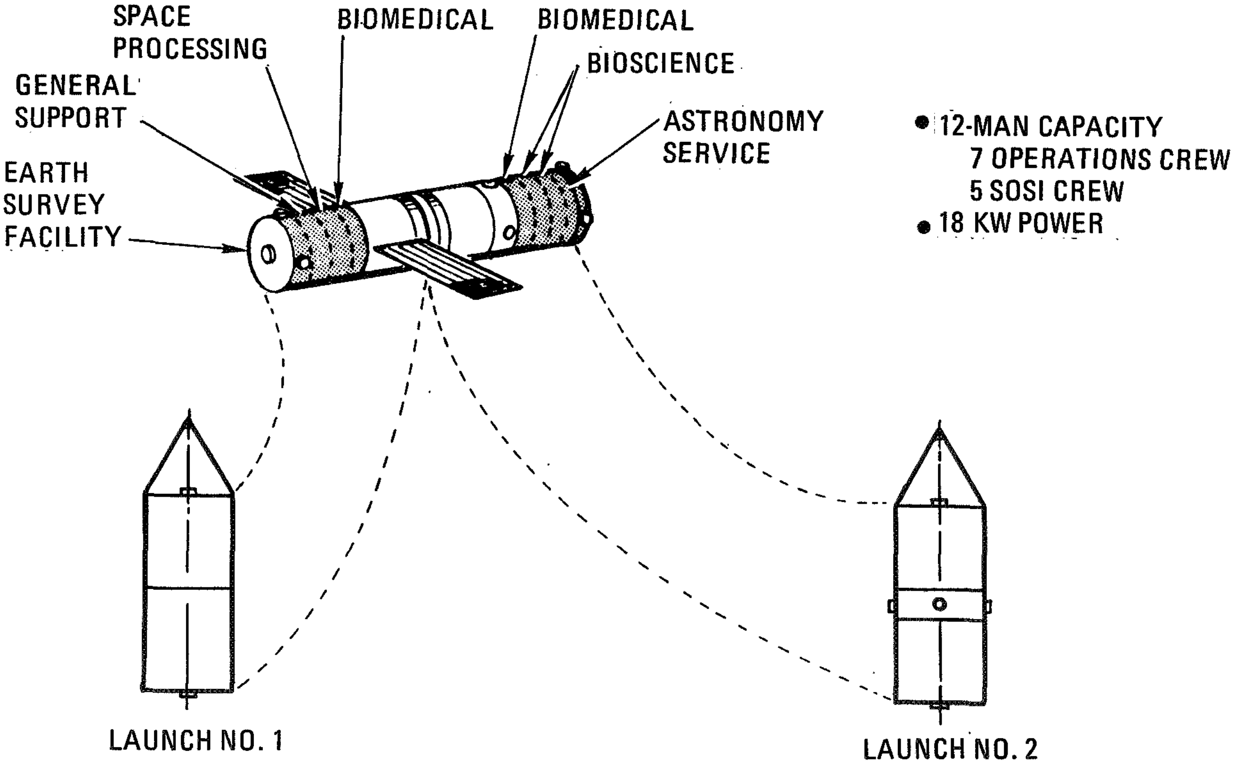


Figure 4-2. Space Base Buildup, Launches No. 1 and 2

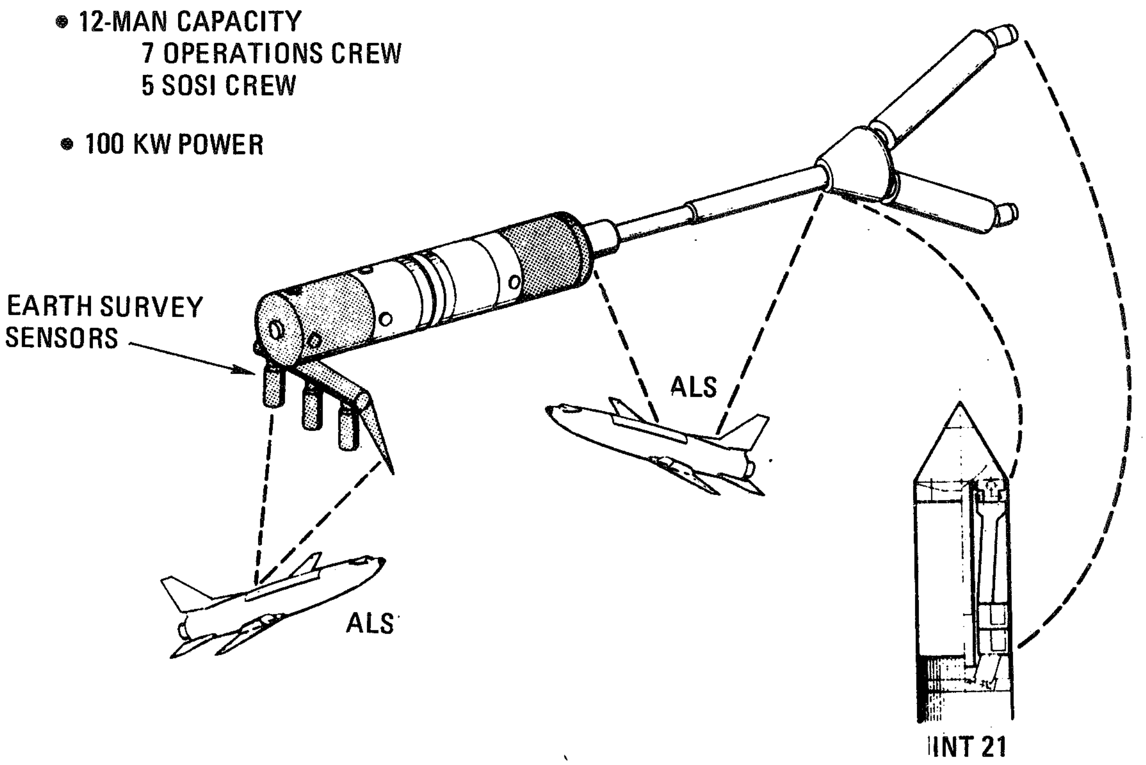


Figure 4-3. Space Base Buildup, Launch No. 3

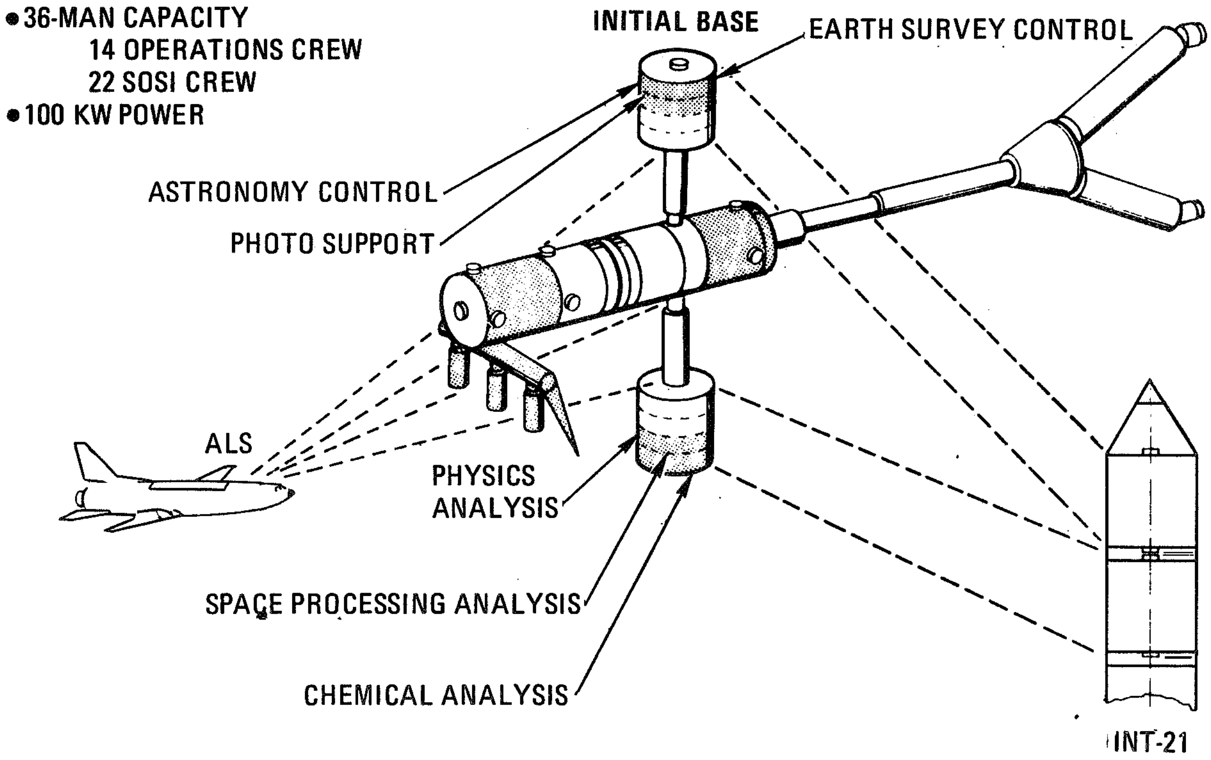


Figure 4-4. Space Base Buildup, Launch No. 4

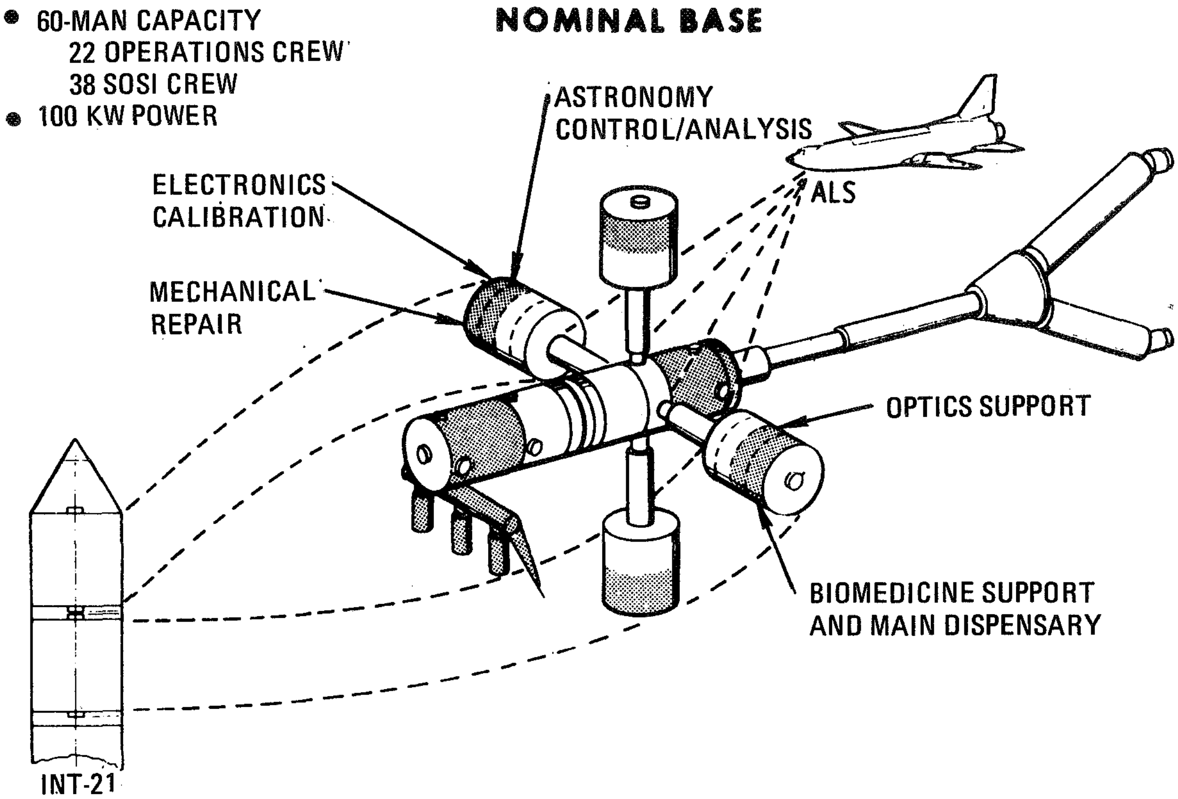


Figure 4-5. Space Base Buildup, Launch No. 5

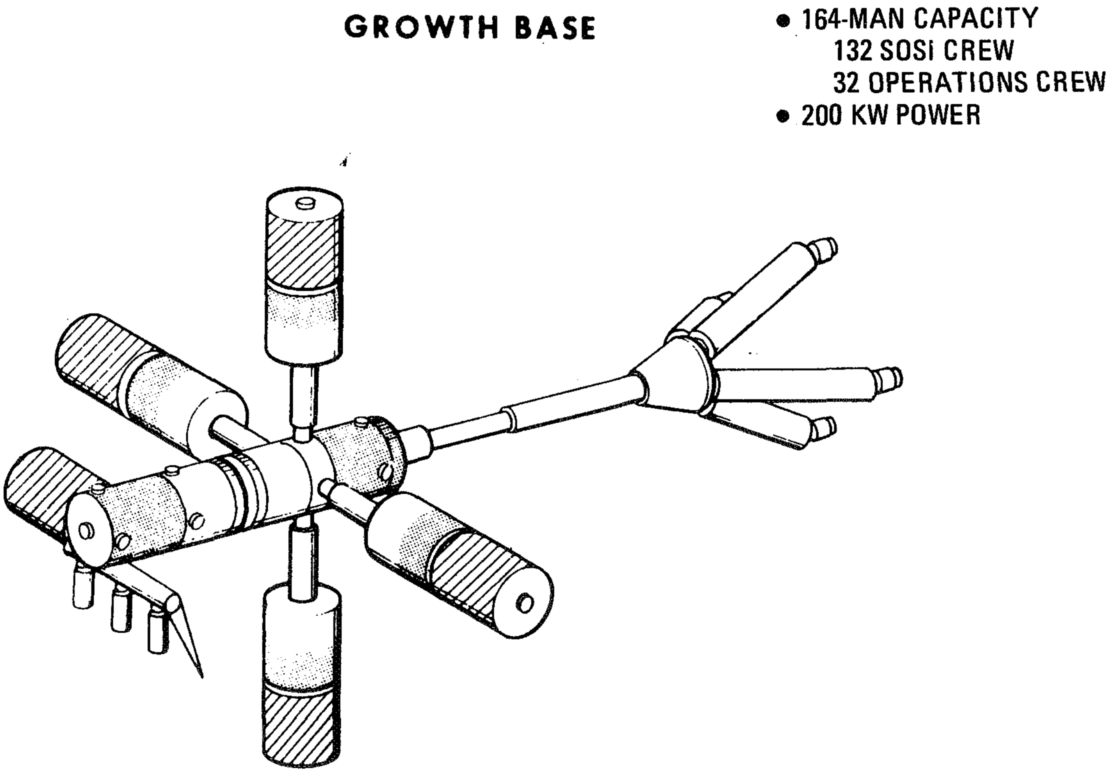


Figure 4-6. Growth Base

One end of the configuration contains the power module and one of the SOSI modules in an inertial hold mode, thereby providing a good base for low-gravity experiments and astronomy-type laboratories. On the other side of the rotating hub, the zero-g section would be in a local-vertical hold mode and would, therefore, rotate slowly at orbital rate.

Full utilization would be achieved in the growth configuration through multishift operation by the 164-man crew. When the growth plateau is reached, either the nuclear power modules would be replaced by larger units or additional reactors would be incorporated. The four additional artificial-g crew quarters modules require two more launches, for a total of seven. There exists the possibility of an intermediate step, after the first two additional artificial-g crew quarters modules are attached, which would require a 112-man crew. The crew, booms, and attached SOSI would be ferried to orbit by the shuttle during all stages of buildup.

REACTION CONTROL SUBSYSTEM

The reaction control subsystem selected in the Space Base Phase A conceptual definition (Reference 25) has three thrust levels. The RCS functions and jet locations are shown in Figure 4-7. Spin and despin of the artificial-gravity section is done by 100-pound bipropellant thrusters (N_2O_4/MMH). A low-thrust (0. 1 pound) biowaste resistojet system utilizes waste gases from the ECLSS to provide momentum vector control and orbit maintenance. Control of docking disturbances and some of the excess momentum vector control and orbit maintenance requirement is achieved by a medium-thrust (10 pound) system using oxygen and hydrogen in a gaseous bipropellant thruster. Oxygen and hydrogen, at a weight ratio of 8:1, are obtained from water electrolysis and supplemented with excess hydrogen from the ECLSS ammonia dissociator, so that the bipropellant thrusters operate at an O_2/H_2 weight ratio of 3:1. Reference 25 specifies an O_2/H_2 mixture ratio of 3. 65:1 and 25 pounds of thrust; however, subsequent selection of 3:1 and 10 pounds for the space station thrusters would drive the space base RCS to the same design, for common development and cost savings.

Nonperiodic torques that result in a CMG desaturation requirement could occur if modules were docked to the earth-referenced (local vertical) section of the space base. These torques would be about the longitudinal (X-axis) of the zero-gravity section and would have approximately the same magnitude as listed for the space station (Figures 3-8 and 3-9). These torques are smaller than the momentum vector control torques and can be handled concurrently with the momentum vector control function. Therefore, CMG desaturation is not listed separately.

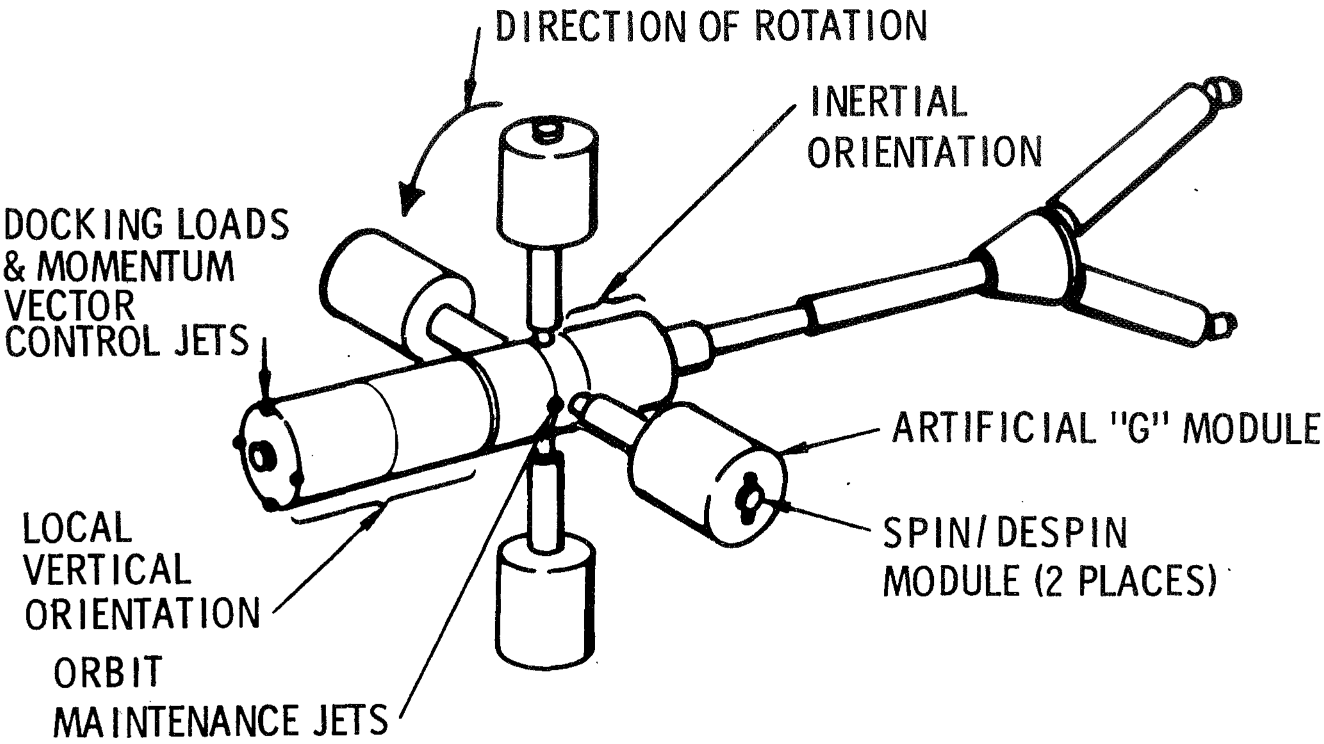


Figure 4-7. RCS Functions and Jet Locations

All of the space base functions have the same meanings as those discussed in the space station section. However, the momentum vector control is for a different purpose. The angular momentum generated by the artificial-gravity section would tend to maintain the space base in an inertial orientation (gyroscopic effect) as the orbit regresses. Since the desired orientation is with the artificial-gravity section rotational axis normal to the orbit plane, the angular momentum vector must be continually changed to match the orbit plane regression. The momentum vector control thrust vector (for the jet location shown) is coplanar with the orbit plane and always in the same direction relative to a coordinate system defined on the orbit plane, regardless of the space base position in the orbit plane.

The orbit maintenance and momentum vector control impulse requirements for the nominal space base configuration are given in Figures 4-8 through 4-10 as a function of altitude (200 to 300 nautical miles) and sunspot activity for a typical 11-year solar cycle. Momentum vector control (Figure 4-10) is a function of altitude only.

The spin/despin function is accomplished with an independent RCS, and the impulse required for control of docking transients is negligible. Therefore, only the orbit maintenance and momentum vector control functions are considered in the design of space base integrated ECLSS/RCS.

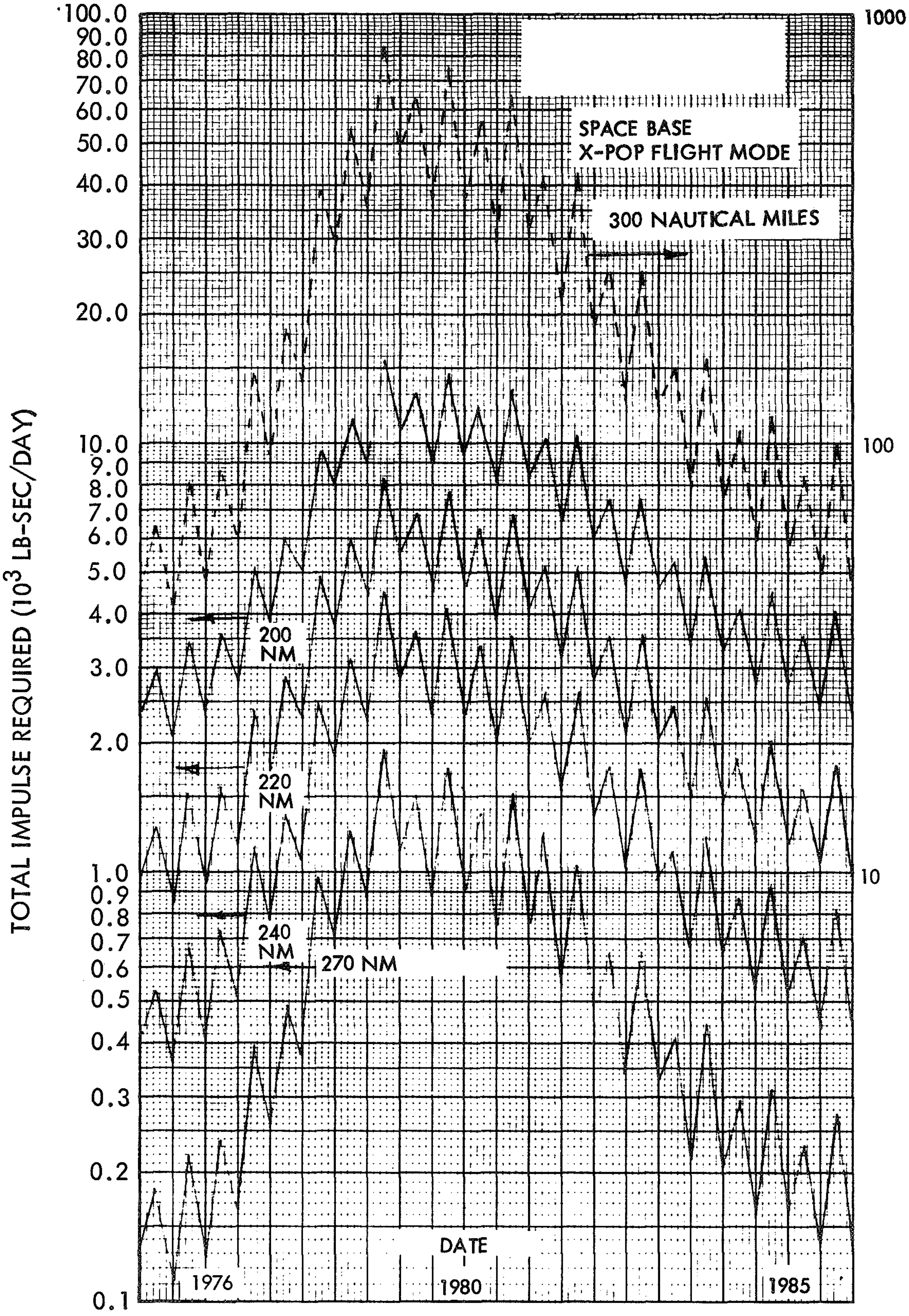


Figure 4-8. Orbit Maintenance Impulse, Nominal Atmosphere

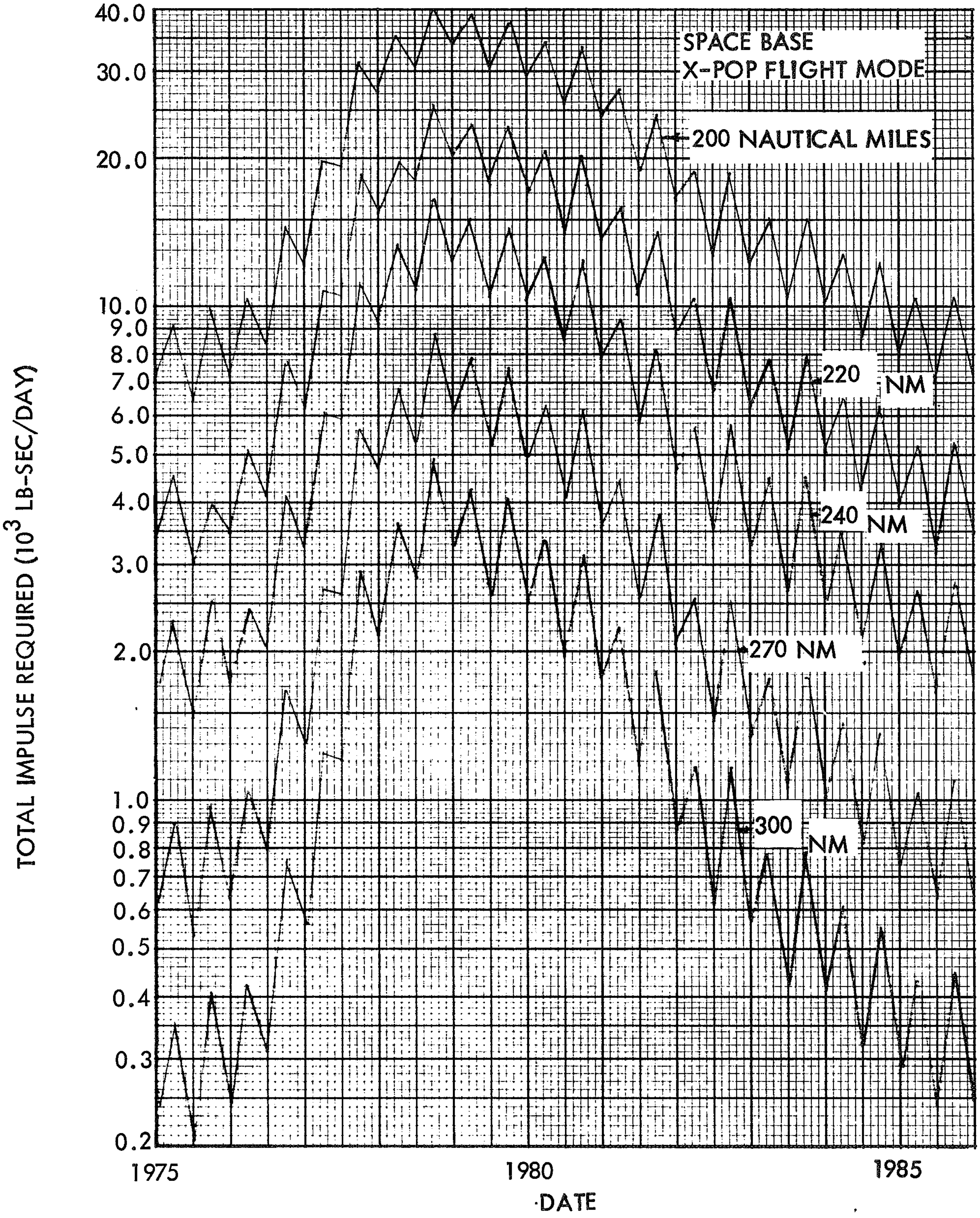


Figure 4-9. Orbit Maintenance Impulse, 2σ Atmosphere

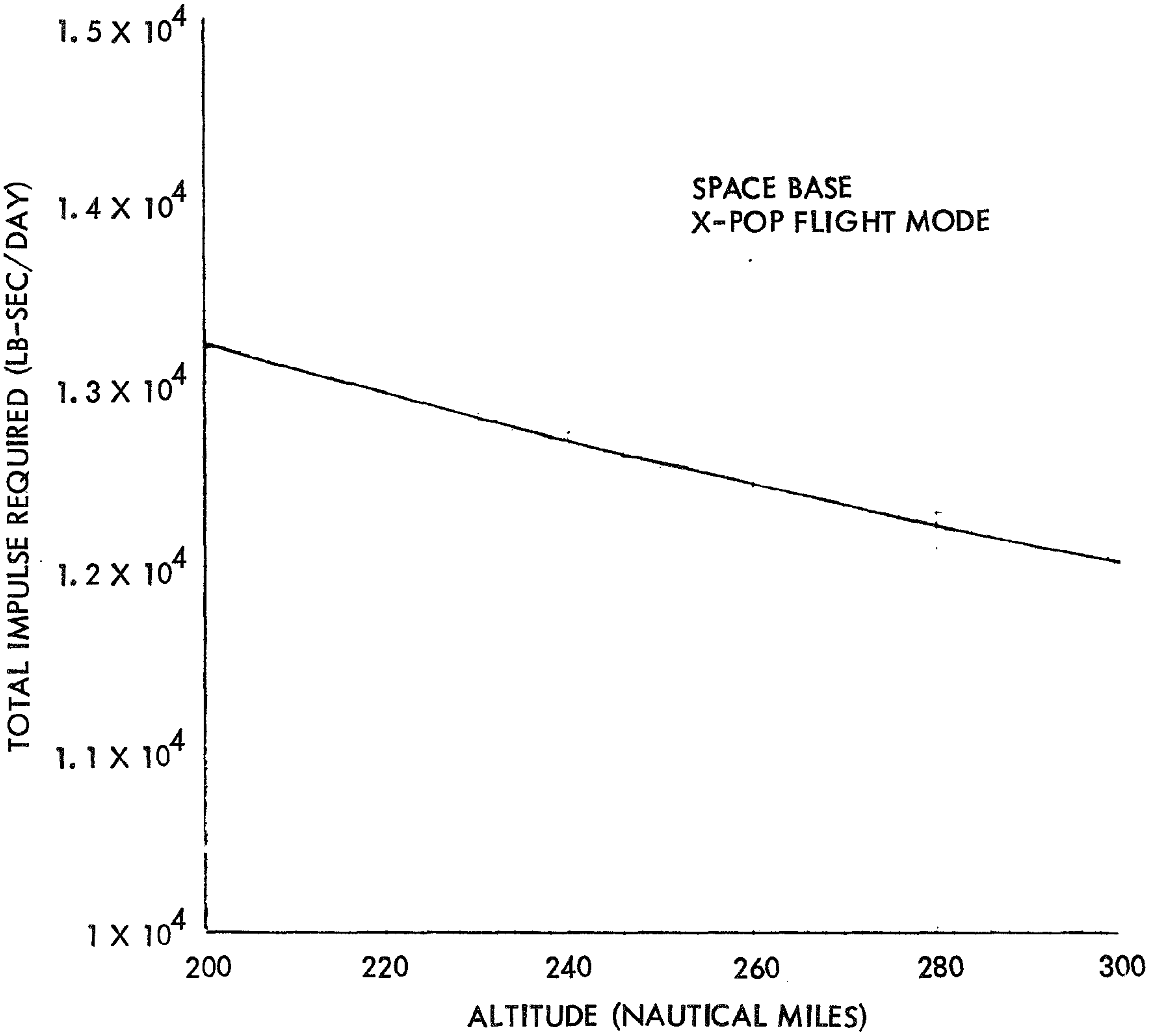


Figure 4-10. Momentum Vector Control

ECLSS WASTE FLUIDS FOR RCS PROPELLANT

The space base uses a modular buildup, with crew increments as follows:

Space Base Buildup Phase	Crew Size
Initial base	24
Initial base	36
Nominal base	50
Nominal base	60
Growth base	112
Supergrowth base	164

The space base configurations are shown in Figures 4-4 through 4-6.

The space base ECLSS incorporates central processing of metabolically produced CO_2 for oxygen recovery and resistojet propellant supply. The oxygen recovery concept incorporates molecular sieve for CO_2 removal, Sabatier for CO_2 hydrogenation, water electrolysis for O_2 and H_2 production, and ammonia dissociation for N_2 supply and additional H_2 to the Sabatier to allow processing of all the metabolically produced CO_2. These subassemblies are included in the air-scrubbing assembly (ASA). The ASA is located in the initial core module and in the hub module in the zero-gravity portion of the space base, as illustrated in Figure 4-11. Safety requirements preclude the transfer of H_2, CH_4, or NH_3 across the rotating portion of the hub to the artificial-gravity modules.

When additional 26-man living-quarter modules are added to each of the four artificial-gravity "arms," they are equipped with self-contained oxygen reclamation equipment (growth base and supergrowth base). The oxygen recovery concept for the growth-base 26-man modules incorporates membrane diffusion for CO_2 removal and solid electrolyte for O_2 recovery from CO_2. These units, located in the added modules, produce hydrogen as a waste gas. Since hydrogen cannot be transferred across the rotating hub, any utilization of this gas must occur in the artificial-gravity arm in which it is produced.

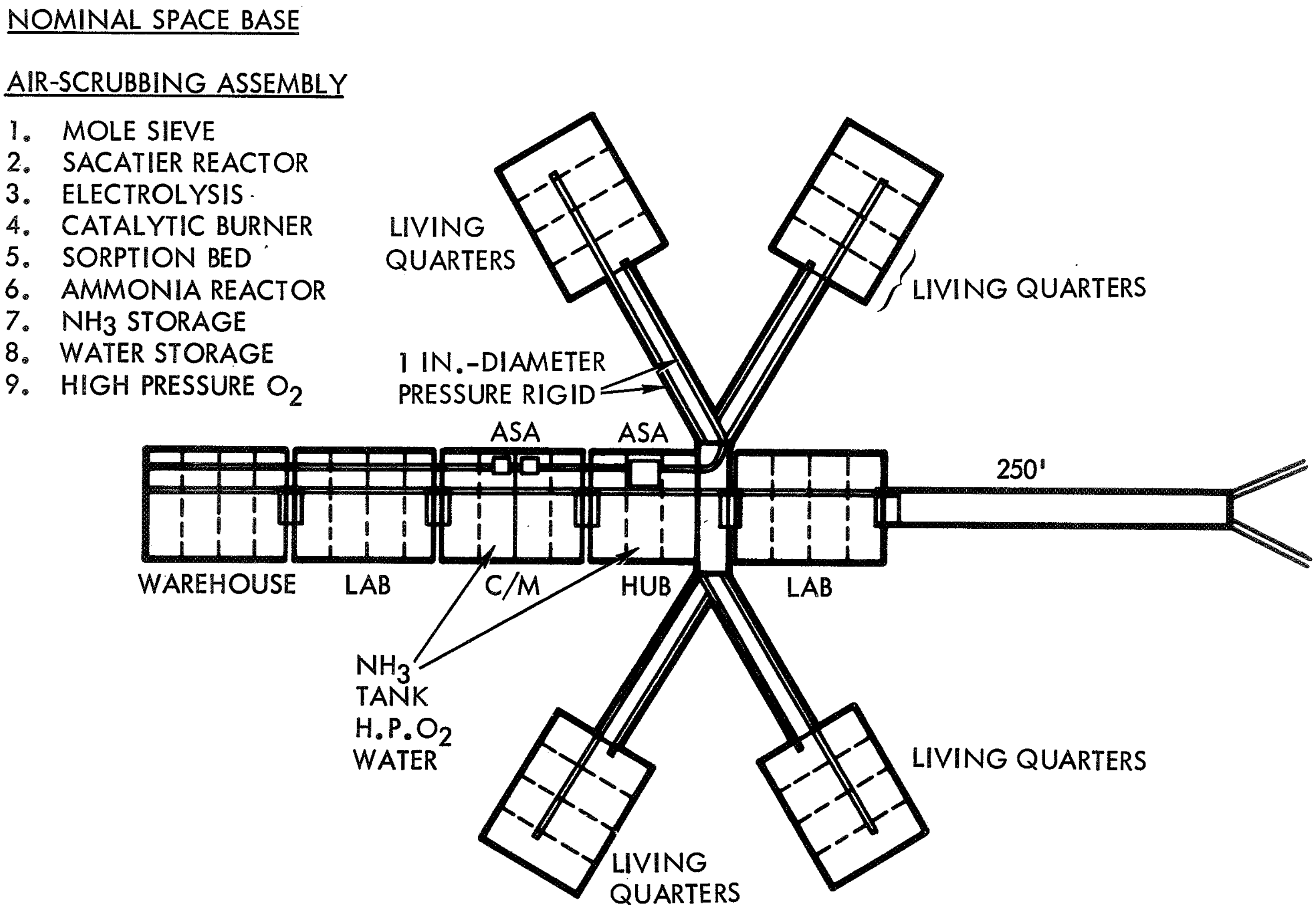


Figure 4-11. Equipment Location, Air-Scrubbing Assembly

WASTE GASES FROM AIR-SCRUBBING ASSEMBLY

The major difference between the space station and space base ECLSS, relative to ECLSS biowaste resistojet integration, is in the makeup of nitrogen for cabin atmosphere leakage. The presently defined space station resupplies cryogenic N_2 to make up for leakage. Leakage of the space base atmosphere to space is compensated for by water electrolysis for O_2 supply and ammonia (NH_3) dissociation for N_2 supply. The H_2 product from both water electrolysis and NH_3 dissociation is used to react the CO_2, and excess H_2 is available as RCS propellant.

Seal Leakage

The base leakage is assumed to be a function of the seal length associated with docking ports, ground-loading doors, etc. The estimated seal leakage is given in Table 4-1.

Toilet Vent

The base toilet concept incorporates vacuum-dumping of the air contained in the fecal collection tank and vacuum-drying of the feces. It is estimated that eight toilet vents per day are required for 12 men. Future preliminary designs of the toilet concept may indicate that the fecal tank should be pumped down prior to vent or that a fecal slurry concept may be required to avoid loss of cabin gas. However, baseline space base design incorporates a vacuum dump (same as the space station design). The vent quantities are listed in Table 4-2.

Table 4-1. Space Base Seal Leakage

Space Base Buildup Phase	O_2 Leak (lb/day)	N_2 Leak (lb/day)	Total Leak (lb/day)
Initial base	14.9	49.1	64
Nominal base	17.2	56.8	74
Growth base	19.6	64.4	84
Supergrowth base	21.9	72.1	94

Table 4-2. Toilet Vent Atmosphere Loss

Space Base Buildup Phase		O_2 Vent (lb/day)	N_2 Vent (lb/day)	Total Vent (lb/day)
Initial base	(24)	0.56	1.84	2.4
	(36)	0.84	2.76	3.6
Nominal base	(50)	1.17	3.83	5.0
	(60)	1.40	4.6	6.0
Growth base	(112)	2.61	8.59	11.2
Supergrowth base	(164)	3.82	12.58	16.4

Air Lock Operation

Space base air locks would be pumped from a pressure of 14.7 psia to 1.0 psia prior to venting to space. The 1.0-psia gas vent represents an impact to the H_2O electrolysis and NH_3 dissociation subassemblies. Air lock gas-loss estimates are summarized in Table 4-3.

Table 4-3. Air Lock Atmosphere Loss

Space Base Buildup Phase	O_2 Loss (lb/day)	N_2 Loss (lb/day)	Total Loss (lb/day)
Initial base	0.37	1.23	1.6
Nominal base	0.73	2.41	3.14
Growth base	1.44	4.75	6.2
Supergrowth base	1.50	4.94	6.44

Waste Gas Quantities

The quantity of waste gases produced by ASA are a function of the cabin atmosphere losses (Tables 4-1 through 4-3), crew size, CO_2 production rate (per man), and O_2 consumption rate (per man). Mass-balance diagrams for the initial, nominal, and supergrowth bases are given in Figures 4-12 through 4-14 for nominal crew sizes, metabolic rates, and the predicted leakage rates. Table 4-4 summarizes the waste gases available from ASA, including variations due to crew size and metabolic rates. The H_2 from the Sabatier reactor is mixed with the methane. The excess hydrogen (from ammonia dissociation) may be utilized separately or mixed with the Sabatier reactor effluent. As previously stated, hydrogen from the solid electrolyte is available only in the artificial-gravity module in which it is produced.

SPACE BASE WATER MANAGEMENT

The space base water management assembly is essentially the same as that for the space station (described in a previous section). This assembly incorporates a two-loop reclamation concept consisting of a vapor diffusion compression loop (potable water) and a reverse-osmosis loop (wash water). Brine from the reverse-osmosis recovery unit is directed to the vapor compression potable water recovery unit for further processing; therefore, the two loops are connected. The additions to the water management assembly are a laundry and an anal wash for the toilet.

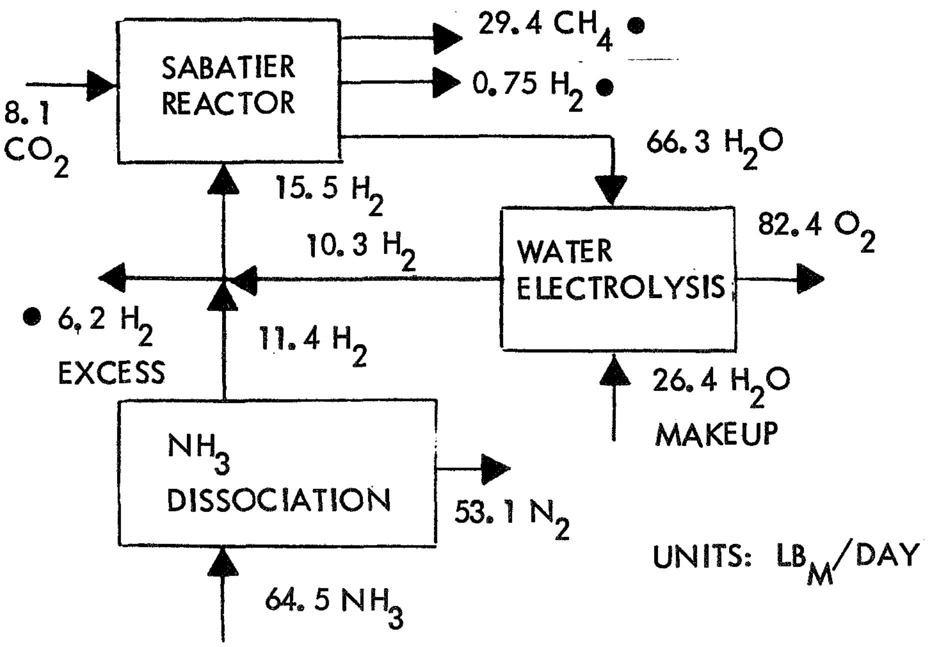


Figure 4-12. Mass Balance, Initial Base, 36 Men

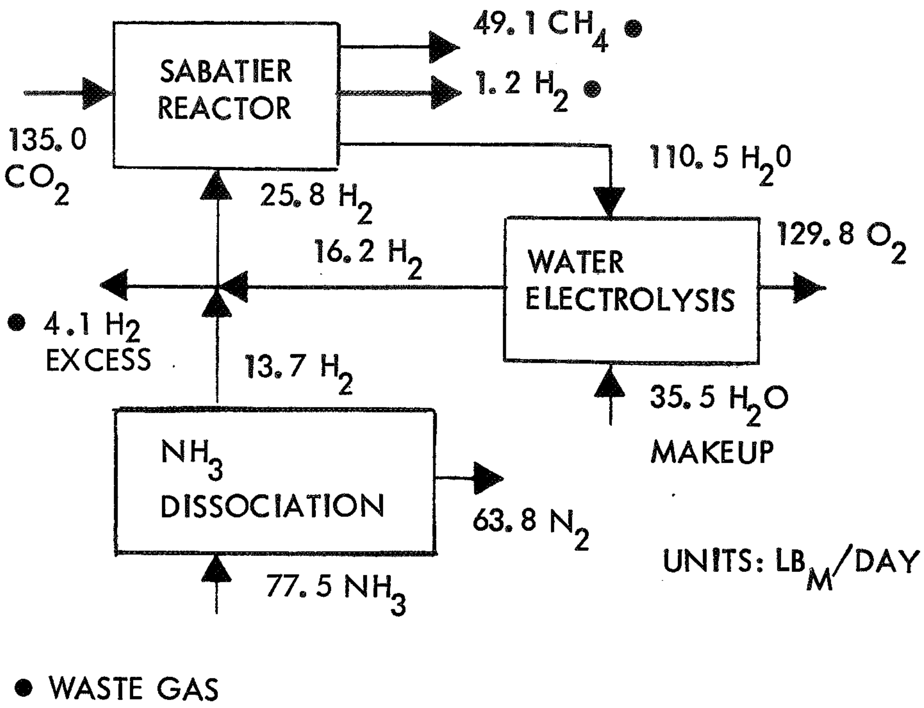


Figure 4-13. Mass Balance, Nominal Base, 60 Men

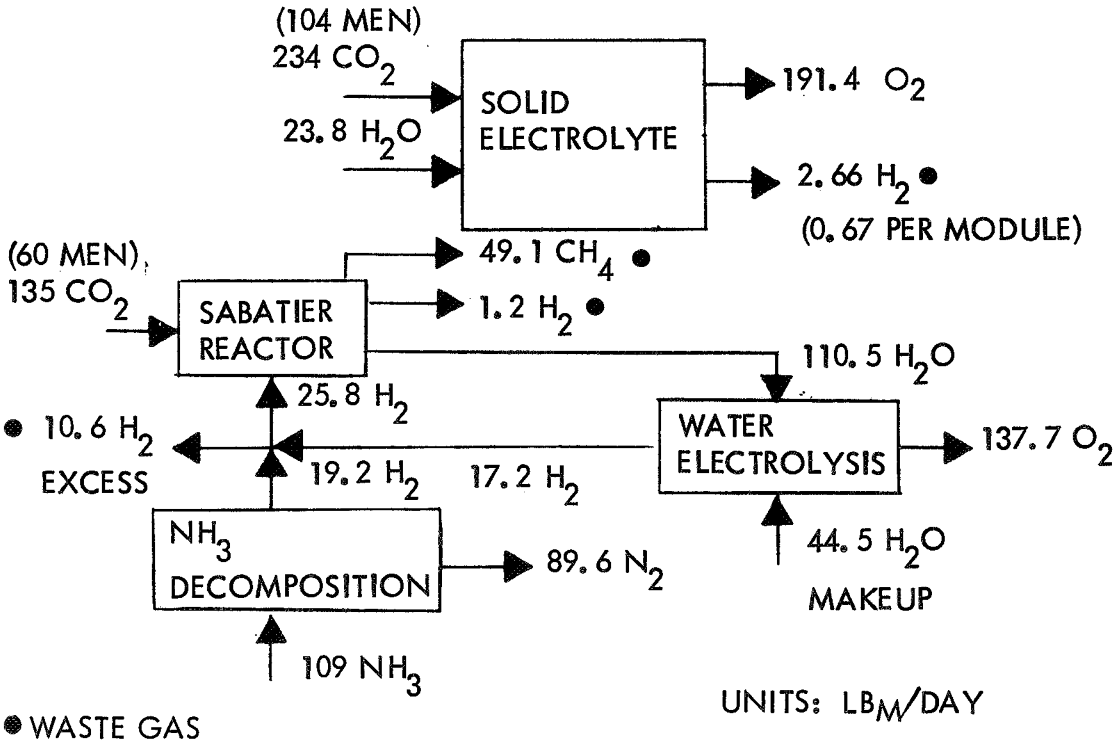


Figure 4-14. Mass Balance, Super Growth Base 164 Men

Table 4-4. Space Base Nominal Biowaste Gas Availability

Space Base Buildup Phase	Crew Size	CO_2 (lb/man-day)	Cabin Atmosphere Loss			Resistojet Fuel		
			Vehicle* Leakage (lb/day)	Toilet* Vent (lb/day)	Air Lock* 1-psia Vent (lb/day)	From Sabatier CH_4 (lb/day)	From Sabatier H_2 (lb/day)	System Excess H_2** (lb/day)
Initial	24	2.25	64	2.4	1.6	19.6	0.49	8.9
Initial	36	2.25	64	3.6	1.6	29.4	0.75	6.2
		1.92				25.1	0.60	7.4
		2.55				33.4	0.85	5.75
Nominal	50	2.25	74	5.0	3.1	40.9	1.0	5.9
Nominal	60	2.25	74	6.0	3.1	49.1	1.2	4.1
		1.92				41.9	1.0	6.14
		2.55				55.6	1.4	3.42
Growth	112	2.25	84	11.2	6.2	49.1	1.2	7.6 1.33$^+$
Supergrowth	164	2.25	94	16.4	6.4	49.1	1.2	10.6 2.66$^+$

*O_2 fraction = 0.233 at 3.1 psia
N_2 fraction = 0.767 at 11.6 psia
**Excess H_2 from NH_3
$^+H_2$ from solid electrolyte available in artificial-g modules

The space base water balance was not evaluated in detail in the Phase A conceptual study (reported in Reference 25). The shower requirements, urine production, and basic water use requirements for the base are similar to those for the station. The laundry increases the wash-water requirement by 4 pounds/man-day, while the anal wash increases the vapor compression loop by 3 pounds/man-day. An estimate of the excess water, assuming 98-percent efficiency of the vapor compression unit, is given in Table 4-5.

It should be noted that most of the excess water listed in Table 4-5 results from the variation in the quantity of oxygen required for metabolic purposes relative to the leakage requirement. As the leakage decreases, the water required for electrolyses decreases and becomes excess. The excess water reported in Table 4-5 corresponds to the nominal leakage values reported in Table 4-4. This excess could increase in time if the leakage decreases as holes become plugged by particles in the cabin atmosphere.

Table 4-5. Excess Potable Water

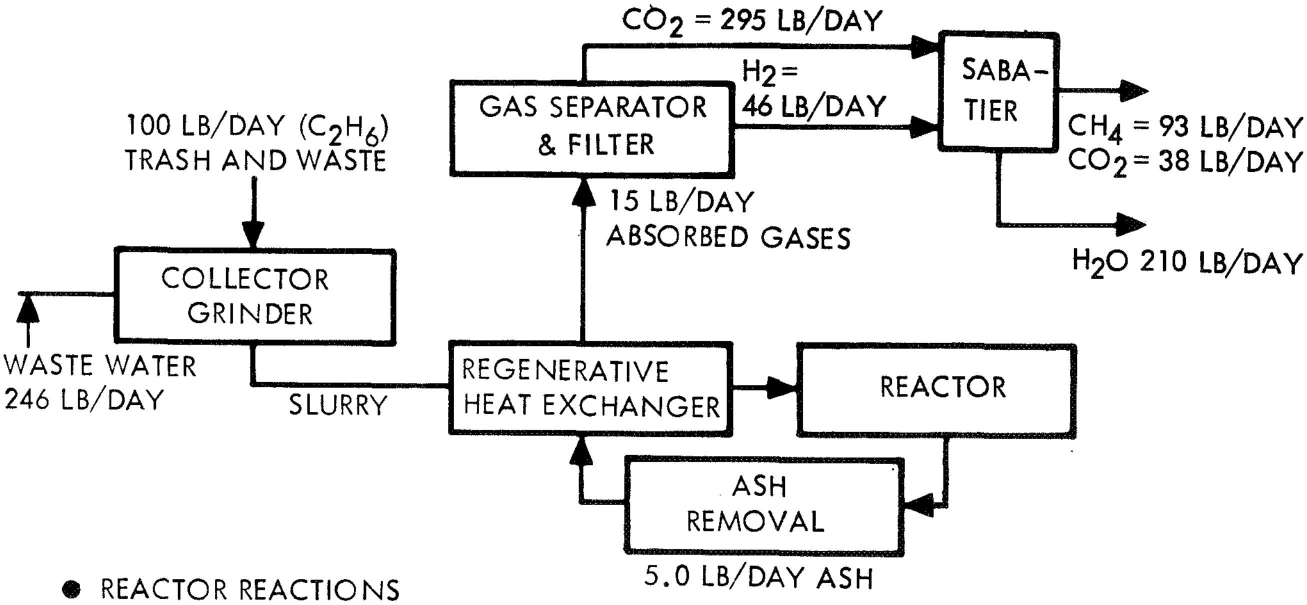
Buildup Phase (crew size)	Excess H_2O (lb/day)
36	3.4
60	14.1
112	40.4
164	67.0

ECLSS WASTE PROCESSING

The processing of trash on board the space base provides another potential ECLSS/RCS integration, through the utilization of waste gases generated by trash processing. During the course of the Space Base Phase A Study (Reference 25), several ECLSS waste processes were considered (thermal decomposition, destructive distillation, incineration, wet oxidation, and steam reformation). In general, the exhaust products of decomposition and destructive distillation can be expected to be heavy hydrocarbons that can condense on experiments and contaminate the exterior of the base. Although the incineration and oxidation processes produce clean by-products such as CO_2, CO, and water vapor, they result in relatively high resupply weight due to oxygen consumption. The steam reformation process, on the other hand, has by-products of CO_2 and H_2. When these by-products are combined in a Sabatier reactor, the products are water and CH_4, as in the reduction process. The steam reformation process has been used for many years by the petrochemical industry in the production of hydrogen from crude oil and coal (Reference 26). The feasibility of trash processing by steam reformation is now being investigated.

Of the trash processing concepts studied, steam reformation was the most attractive. However, the capability of returning the trash to earth via the shuttle and the development status of the steam reformation concept for this application preclude the selection of any trash processing method for the Space Base Phase A concept. Nevertheless, a tremendous potential exists for processing water, which is not normally recoverable, along with trash to obtain potable water and gases for propulsion.

A block diagram of the process that might be applied to a space base is shown in Figure 4-15. It starts with the grinding of processable trash and the addition of waste water to form slurry, which is pumped through



- REACTOR REACTIONS

1. $C_nH_{(2n+2)} + n\,H_2O \rightarrow n\,CO + (2n+1)\,H_2$
2. $CO + H_2O \rightarrow CO_2 + H_2$
3. $C_nH_{(2n+2)} + 2n\,H_2O \rightarrow n\,CO_2 + (3n+1)\,H_2$

Figure 4-15. Steam Reformation Trash Processing a regenerative heat exchanger to the reactor. At this point, the reductions shown occur at approximately 1000 F. The by-products are then passed through an ash filter, and the ash is separated. The product gases are passed through a gas separator/filter, where CO_2 and H_2 are separated and trace gases such as sulphur dioxide (SO_2) and NH_3 are absorbed. The CO_2 and H_2 are reacted in a Sabatier reactor, and CO_2, CH_4, and H_2O are formed.

The Space Base Phase A Study showed that a 50-man base would generate approximately 100 pounds of processable trash a day. Assuming that this trash is typified by C_2H_6, the chemical balance is as shown in Figure 4-15, based on the reactions shown. This balance results in a net water loss of 36 pounds per 100 pounds of trash. However, there is the possibility that 96 lb/day of experiment water, which is incompatible with the normal water recovery system, could be made available for trash processing. In addition, a wet fecal collection system could produce 150 lb/day of fecal water slurry.

These results suggest the potential for processing a fecal slurry and other contaminated waters to provide clean water and gases which would be sufficient to eliminate all propellant resupply requirements (both medium and low thrust). It must be emphasized, however, that the concept is still in the feasibility stage, as it is applied to trash-water processing in a space vehicle. There also may be significant differences between the trash-waste water availability and the chemical makeup of the trash assumed above and that which may actually exist.

REACTION CONTROL SUBSYSTEM OPERATION

The RCS selected in the Space Base Phase A conceptual definition has both medium- and low-thrust jets. The low-thrust system uses excess gases (CH_4 and H_2) in resistojets for momentum vector control and orbit maintenance requirements. Control of docking disturbances and any excess momentum vector control is achieved by a medium-thrust system using oxygen and hydrogen in a gaseous bipropellant thruster. Oxygen and hydrogen at a weight ratio of 8:1 are obtained from water electrolysis and supplemented with hydrogen from the environmental control and life support ammonia dissociater assembly, so that the bipropellant thrusters operate at an oxygen/hydrogen weight ratio of 3:1.

NOMINAL BASE RCS OPERATIONS

The mission operations study, reported in Reference 25, recommended that a 273-nm orbit inclined 55 degrees would best meet all experiment requirements. The space base is oriented with the rotating (artificial gravity) section in the orbit plane and the longitudinal axis of the zero-gravity section perpendicular to the orbit plane (Figure 4-1). In this flight mode, the impulse requirements for the 60-man nominal base are 12,300 lb-sec/day for momentum vector control (Figure 4-10) and 8300 lb-sec/day for orbit maintenance with a 2σ atmosphere for 1 October 1978 or 1780 lb-sec/day for orbit maintenance with a nominal atmosphere for 1 October 1978 (Figures 4-9 and 4-8, respectively).

The total impulse available from the waste gases listed in Table 4-4 (2.25 lb/man-day CO_2) for the 50- and 60-man nominal base RCS is shown in Figure 4-16 as a function of the fraction of excess H_2 (from NH_3 decomposition) used with the medium-thrust system. Maximum impulse (low- plus medium-thrust systems) for a given design occurs when all of the excess hydrogen is utilized in the bipropellant thrusters. If the orbit maintenance and momentum vector control are handled separately, the design impulse requirement is 20,600 lb-sec/day. This is well within the system design capability, but necessitates some water resupply and electrolysis operation for the medium-thrust makeup of the momentum vector control.

A more economical mode of operation is to combine the two functions in a manner similar to that used to combine the space station orbit maintenance/CMG desaturation.

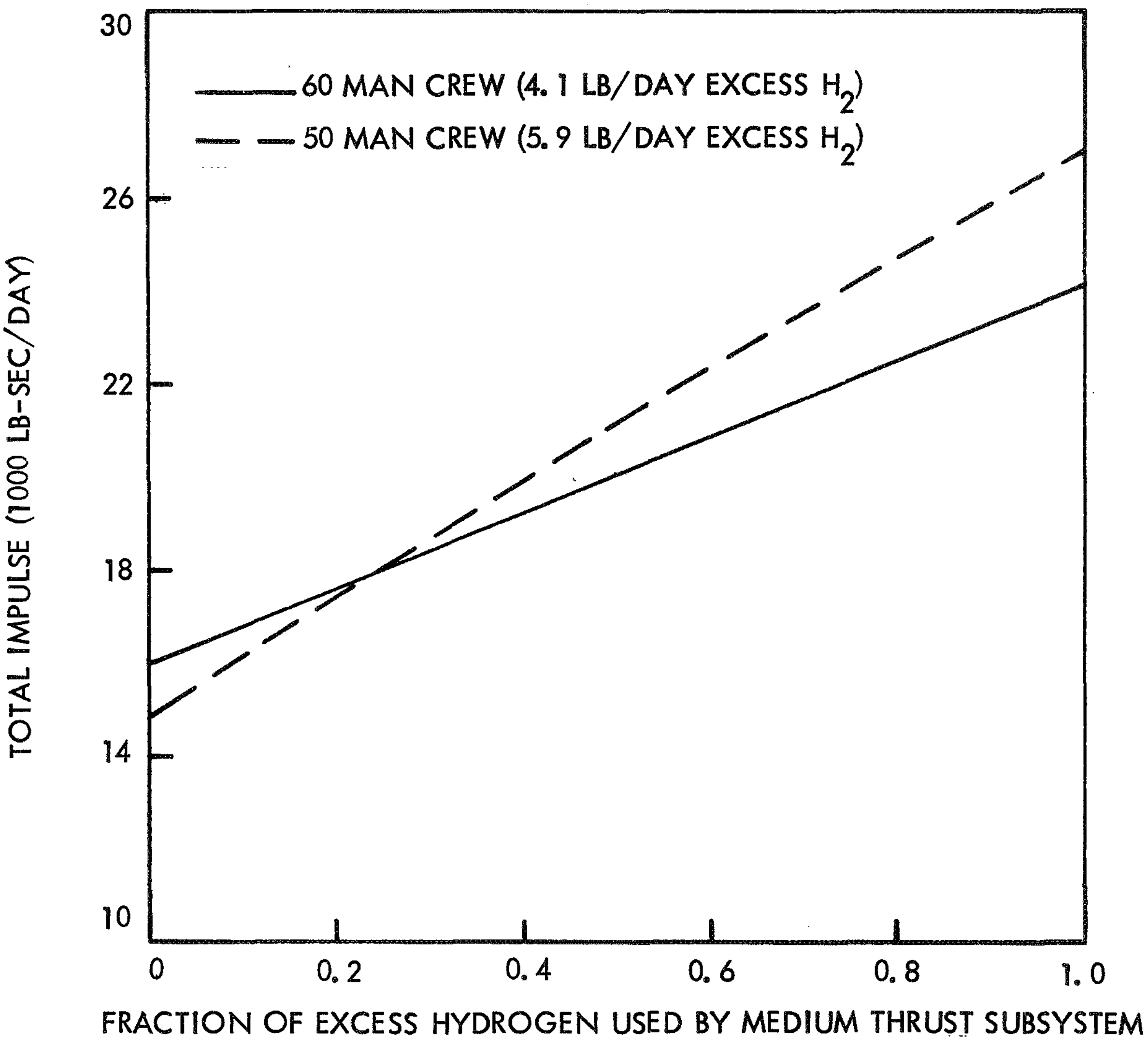


Figure 4-16. Space Base Impulse Capability

As stated previously, the momentum vector control thrust vector is always in the same direction relative to the orbit plane. Therefore, a set of thrusters located in an orthogonal arrangement on an earth-referenced module can be used effectively four times per orbit (Figure 4-17). Since the orbit-maintenance thrust must be in the direction of the velocity vector, combined momentum vector control and orbit-maintenance thrusting can be done only once per orbit. Obviously, it is necessary to delete the momentum vector control thrusting 180 degrees from the combined thrusting point.

The thrusting periods, particularly with the low-thrust resistojet, are relatively long (minutes), so that the space base sweeps a finite arc in the orbit plane relative to earth. The thrusters are located on the earth-referenced module so that the thrust vector turns through a corresponding angle. The thruster impulse (I_t) required to produce an effective impulse (I_{te}) for momentum vector control, therefore, is

$$I_t = I_{te}\,\theta/\sin\theta \qquad (4\text{-}1)$$

where θ, in radians, is equal to thrusting half.angle about the a point where the thrust vector coincides with the momentum vector control vector (Figure 4-17). During the combined thrusting mode, the orbit-maintenance impulse is equal to I_t, since the thrust vector is always in line with the velocity vector.

The thrust, F, required to supply the momentum vector control impulse is

$$F = \frac{3.636(10)^{-5}\,I_{te}}{n\sin\theta} \qquad (4\text{-}2)$$

where n is the number of equal thrusting periods per orbit and I_{te} is in units of lb-sec/day. This equation is independent of orbit altitude.

If three 0.1-pound thrusters are used three times per orbit, an angle θ, equal to 0.52 radians, is required (each thrusting period) to provide 12,300 lb-sec/day momentum vector control impulse. The actual impulse produced by the thrusters from Equation 4-1 is 12,870 lb-sec/day. A third of the thruster impulse (4290 lb-sec/day) is used for orbit maintenance. The remaining orbit-maintenance requirement, therefore, is 4010 lb-sec/day). It can be seen in Figure 4-16 that 16,000 lb-sec/day is available if all of the waste gases are used in the resistojet. Since 12,870 lb-sec/day is used for momentum vector control, only 3130 lb-sec/day is available for orbit maintenance (4010 lb-sec/day is required). An iteration would be required to determine the amount of thrusting required from the medium-thrust O_2-H_2 system to balance the requirements. The above analysis, however, indicates that utilization of the combined mode of operation can significantly reduce the amount of thrusting by the O_2/H_2 system, thereby reducing the resupply requirements.

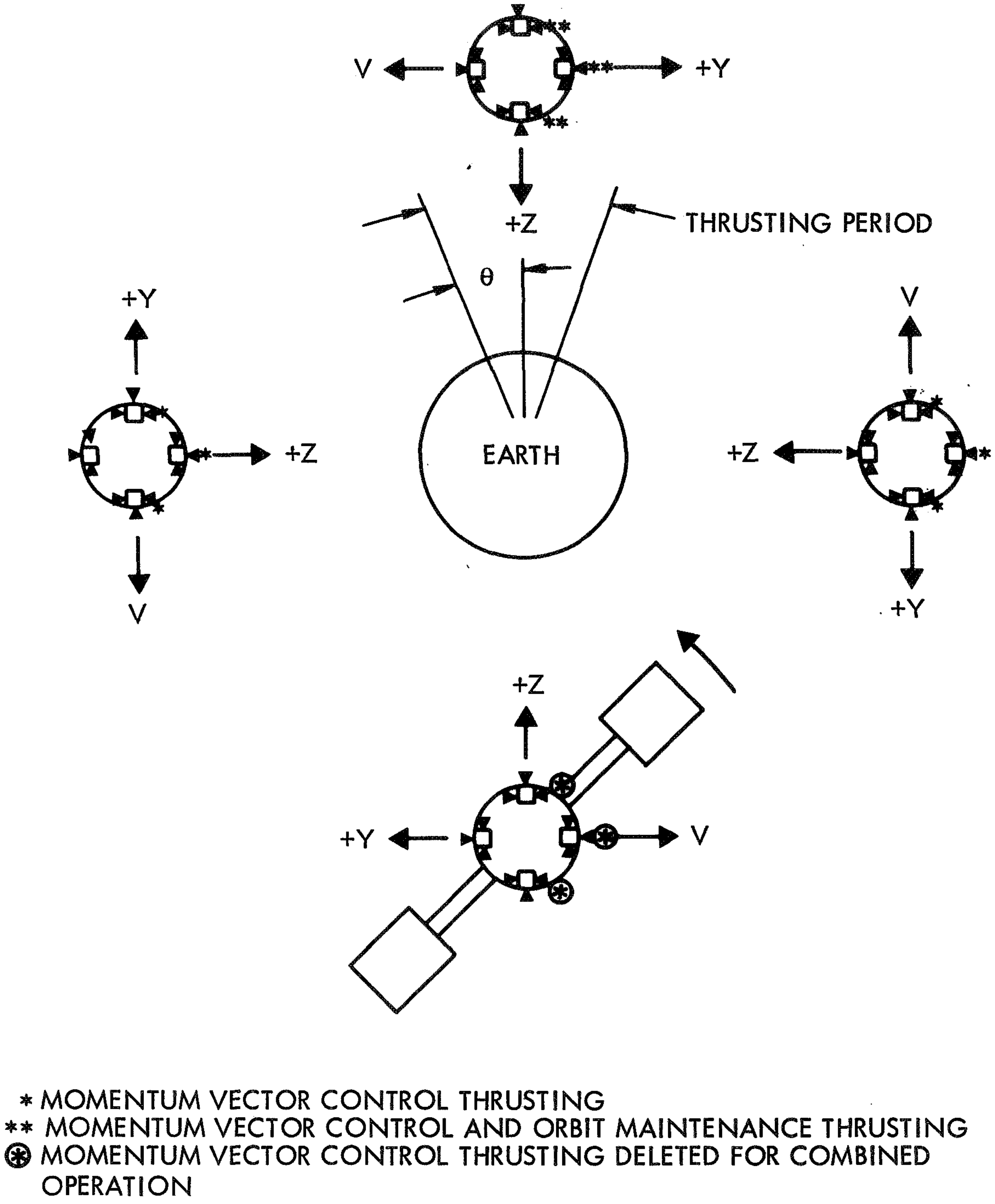


Figure 4-17. Thrusting for Momentum Vector Control and Orbit Maintenance

OFF-DESIGN OPERATIONS

Although the recommended orbit altitude is 273 nautical miles, the space base must have the capability of operating over the full range of 200 to 300 nautical miles. In addition, the various buildup phases result in different impulse requirements and quantity of waste gas available. The following sections describe the various possibilities and define variations in the RCS operational mode to meet the varying requirements. For those cases where the impulse requirement exceeds the normal RCS capability, supplemental propellant requirements are defined.

Off-Nominal Crew Size

For crew sizes less than nominal for a given space base configuration, there exists a situation unique to the NR space base integrated ECLSS/RCS subsystem concept. It can be seen in Table 4-4 that the amount of waste gases available to the RCS with a 50-man crew is less than that with 60 men, as might be expected. However, since the 50-man crew produces less CO_2 for reduction, less hydrogen is required by the Sabatier reactor, resulting in more excess hydrogen from ammonia dissociation (leakage is very nearly constant). The excess hydrogen, when used in the O_2/H_2 thrusters (supplemented by water electrolysis gases), is equivalent to 2680 lb-sec/lb of excess H_2. Therefore, the total impulse capability of the space base increases as the crew size decreases, as shown in Figure 4-16.

High-Density Atmosphere

For the $+2\sigma$ atmosphere at a 200-nm altitude, the 24,300 lb-sec impulse capability of the biowaste resistojets and O_2/H_2 thrusters is exceeded four years of the 11-year solar sunspot cycle. At this density, the orbit-maintenance impulse requirement is much larger than the momentum vector control impulse requirement. For this condition, the most economical operation of the momentum vector control thrusting is once per orbit, so that all of the impulse generated is also being used for orbit maintenance. Since the orbit-maintenance impulse is much larger than the momentum vector control impulse, the combined impulse requirement is identical to the orbit-maintenance requirements.

During the peak four-year period, at 200 nautical miles (Figure 4-9), the impulse above the 24,300 lb-sec/day RCS capability is 45.7×10^6 lb-sec. The peak quarterly average impulse is 37,000 lb-sec/day, or an excess requirement of 12,700 lb-sec/day, maximum.

The primary fluids being resupplied to the space base reaction control subsystem are water and ammonia. These fluids would be the logical candidates for supplemental propellant. It is assumed that the biowaste resistojet will be designed to operate at a gas temperature of at least 2700 R. Based on operation at 2700 R, the supplemental requirements for water and ammonia are as shown in Table 4-6.

The nominal 180-day resupply and storage capacity for ammonia (leakage makeup) is 14,000 pounds, and for water (RCS only) 1447 pounds (assuming 14.1 lb/day excess from ECLSS). With a slight change in the resupply schedule, ammonia could be used as supplemental propellant without impact on the on-board or cargo module tankage. Use of water, however, would require a significant change in the water resupply schedule or an increase in on-board storage and cargo module tankage. The added flexibility in resupply scheduling and savings due to lower resupply cost dictate the selection of ammonia as the supplemental propellant.

Initial Base RCS Capability

The RCS impulse requirements for the buildup phases have not been calculated. However, the momentum vector control is lower than that for the nominal base, because the angular momentum of initial base phases is produced by only two rotating arms rather than four. The orbit-maintenance requirements are only slightly less, because the difference in projected area is only in the effective projected area of the rotating section. Both buildup phases have more impulse capability than has the nominal base, as shown in Figure 4-18. As designed the RCS is, therefore, adequate for the buildup phase for the nominal mission. High-atmospheric design requirements would be met through the use of supplemental propellants, as described in the previous section.

Table 4-6. Supplemental Propellant Characteristics

Parameter	Ammonia	Water
I_{sp} at 2700 R	300	240
Total propellant required, lb	152,300	190,400
90-day requirement (max.), lb	3,810	4,763
Volume of 90-day requirement, ft^3	100	76
Average power, 90-day peak, kw	1.54	1.47
Total resupply cost at $100/lb, dollars	15.23×10^6	19.04×10^6

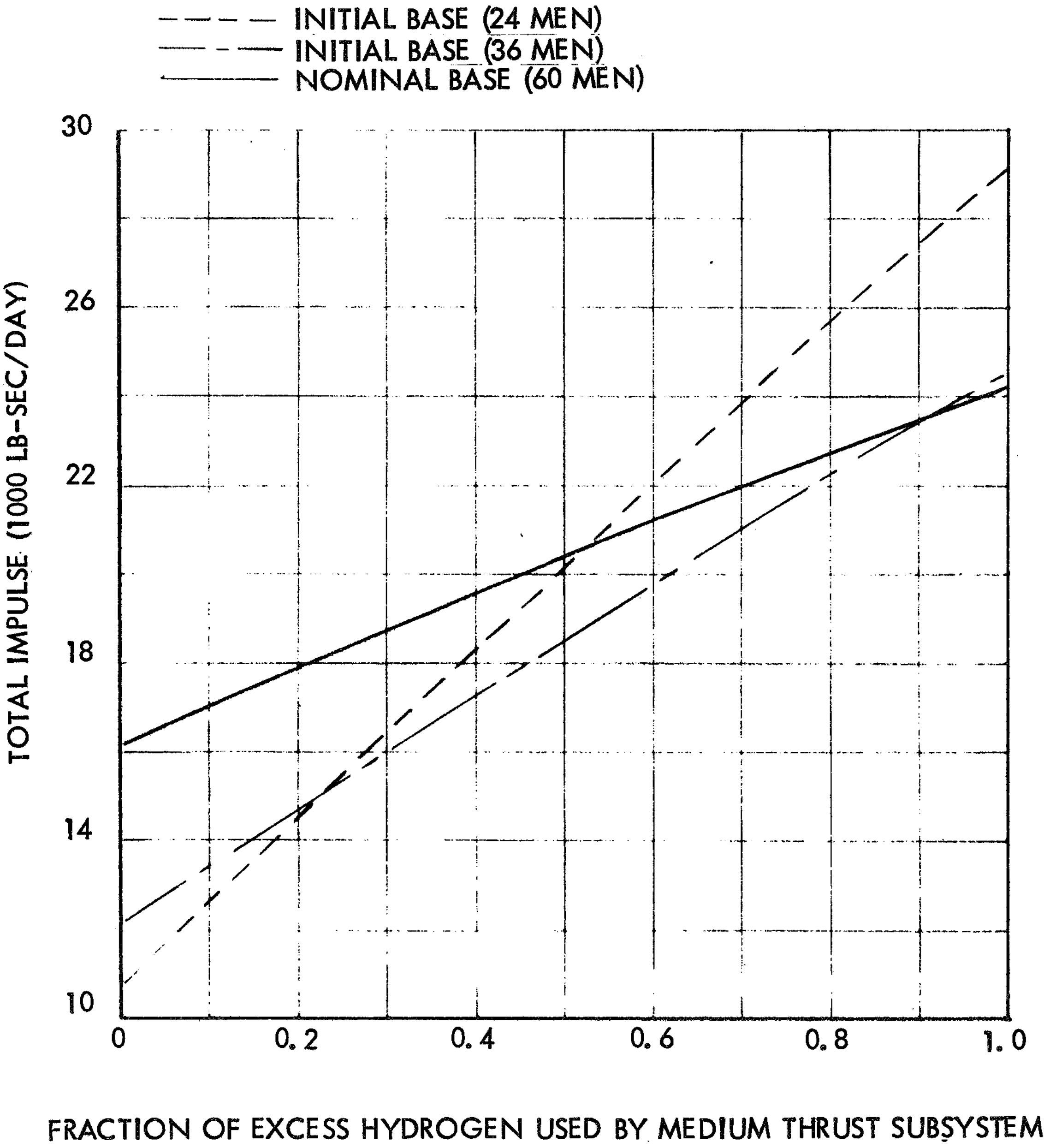


Figure 4-18. Initial and Nominal Space Base Impulse Capability

Growth Base RCS Capability

Mass properties for the growth version of the space base were not calculated in detail during the Space Base Phase A Study. Therefore, RCS requirements can be only approximated. During the Phase A study, it was estimated that the momentum vector control for the 164-man base would be a factor of 3.3 over that of the nominal base, and that the orbit-maintenance impulse requirement would increase by a factor of 1.2. Consequently, the momentum vector control impulse could require approximately 40,590 lb-sec/day with an orbit maintenance impulse requirement of 9960 or 2136 lb-sec/day for the 2σ and nominal atmospheres, respectively.

The metabolic CO_2 in the additional modules is reduced by the solid electrolyte concept, which produces H_2 only as a waste gas. This hydrogen is available only in the rotating arm in which it is produced, because safety requirements preclude the transfer of hydrogen across the rotating hub. The total quantity of hydrogen available (see Table 4-4) is 2.66 lb/day for four modules. This will provide 2040 lb-sec/day in a resistojet at 4000 R, or 7130 lb-sec/day if used in a bipropellant O_2/H_2 system similar to that of the nominal base. Neither of these is sufficient to meet the extra requirements.

From NH_3 dissociation for leakage, there is 10.6 lb/day H_2 available in the zero-gravity section of the growth base. This corresponds to 28,400 lb-sec/day when used in the bipropellant system. In addition to the resistojet capability of 13,200 lb-sec/day, this results in a total impulse capability in the zero-gravity section of 41,600 lb-sec/day. Assuming that the momentum vector control and orbit-maintenance functions are combined, as for the nominal base (three thrusting periods), at least 13,500 lb-sec/day would be available for orbit maintenance from 40,590 lb-sec/day of momentum vector control thrusting. Thus, the biowaste resistojet system in the growth base would be the same as that for the nominal base.

THRUSTER SIZE

For the design reference mission, 0.3 pound of thrust (three 0.1-pound thrusters operating concurrently) was shown to be adequate (in a previous section), with three thrusting periods per orbit for momentum vector control. However, for the 200-nm, 2σ atmosphere, only one thrusting period per orbit would be used for momentum vector control. This could result in a larger resistojet thrust requirement. It will be shown, however, that the maximum impulse requirement can be met with a reasonable number of 0.1-pound thrusters.

The $+2\sigma$ atmosphere at 200 nautical miles results in a maximum orbit-maintenance impulse requirement of 37,000 lb-sec/day. The momentum vector control impulse required at this altitude is

13,200 lb-sec/day. When the total impulse requirements reach or exceed the normal capability of the RCS (24,300 lb-sec/day), the O_2/H_2 thrusters are providing 11,000 lb-sec/day. Assuming that these O_2/H_2 thrusters are used in the combined mode of operation, resistojet orbit-maintenance and momentum vector control impulse requirements are reduced to 26,000 and 2200 lb-sec/day, respectively. Five 0.1-pound resistojets, oriented as shown in Figure 4-19, can provide this impulse, as follows. The three thrusters (F = 0.3 pound) at the end of the vehicle provide the momentum vector control by operation through the angle 2 θ (from Equation 4-2).

$$\theta = \arcsin\left(\frac{3.636\ (10)^{-5}\ I_{t_{mvc}}}{F}\right) = 0.27 \text{ radians} \tag{4.3}$$

The total impulse produced by the three thrusters for orbit maintenance (from Equation 4-1) is

$$I_{t_{om}} = I_{t_{mvc}} \frac{\theta}{\sin\theta} = 2230 \text{ lb-sec/day} \tag{4.4}$$

If the two resistojets that thrust through the center of gravity are operated at the same time, the total orbit-maintenance impulse obtained in this period of operation is 3720 lb-sec/day. The remaining orbit-maintenance impulse is obtained by thrusting with all five resistojets in two equal periods on opposite sides of the orbit and with a centerline perpendicular to the centerline of the momentum vector control thrusting period. The angle ϕ is equal to 1.62 radian. The duty cycle of the five thrusters is 60 percent.

MIXED VERSUS SEPARATE GAS USAGE

In the previous sections, it was assumed (unless otherwise stated) that the excess hydrogen that was not used in the O_2/H_2 thrusters would be mixed with the Sabatier reactor effluent, and used in the resistojet at 2000 R. Supplemental propellants are used in the resistojet separately from the gases produced on board and at a higher temperature (2700 R) to obtain better specific impulse.

Theoretically, the specific impulse of perfect gas mixtures relative to the individual gas specific impulse, at constant temperature is

$$I_s = \sqrt{X_1 I_{s1}^2 + X_2 I_{s2}^2} \tag{4-5}$$

where X_1 and X_2 are the respective weight ratios of the two gases. Defining W_1 and W_2 as the mass of the two gases, then

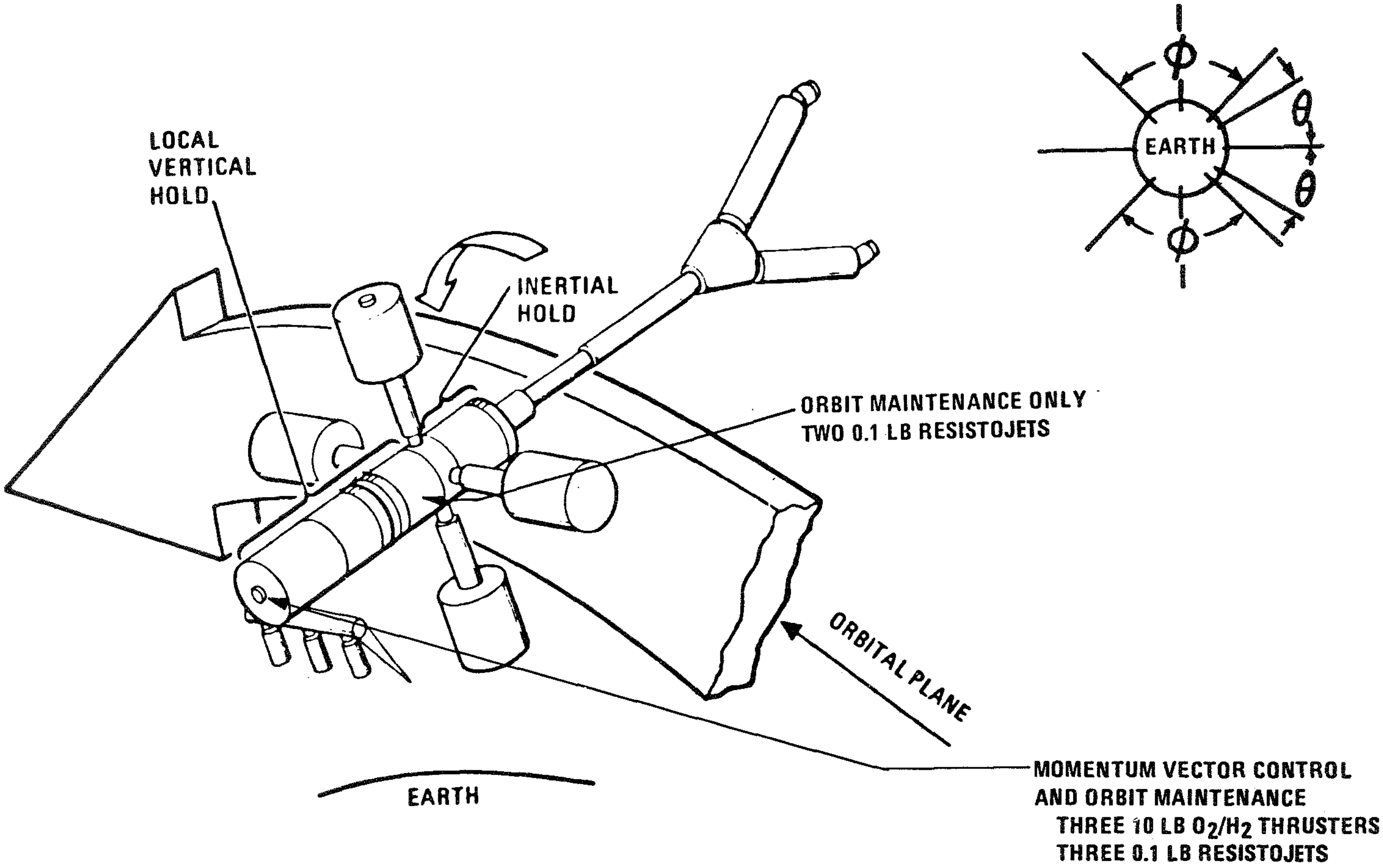


Figure 4-19. Combined Thrusting Mode

$$I_t = (W_1 + W_2)\, I_s \tag{4-6}$$

$$I_{t_1} = W_1\, I_{s1} \tag{4-7}$$

$$I_{t_2} = W_2\, I_{s2} \tag{4-8}$$

It can be shown that

$$I_t^2 - (I_{t1} + I_{t2})^2 = W_1 W_2 (I_{s1} - I_{s2})^2 \geq 0 \tag{4-9}$$

Therefore, at the same gas temperature, more impulse can be obtained by mixing the gases than by using them separately (the equality exists only in the trivial solution of $W_1 = 0$, $W_2 = 0$, or $I_{s1} = I_{s2}$).

However, since methane is limited to a lower temperature (2000 R) than that of the other gases and limits the mixture to the same temperature, a larger impulse may be obtained by using the other gas separately at the higher temperature. The relative gain of operating the second gas at a higher temperature can be shown by defining an impulse ratio, ϕ.

$$\phi = \frac{\text{impulse with second gas at higher temperature}}{\text{impulse of mixed gases at 2000 R}}$$

This parameter is plotted in Figure 4-20 as a function of the second gas temperature for mixtures representative of the space base and space station.

For the nominal space base (0.9 CH_4/0.1 H_2), it is obviously better to combine the excess hydrogen with the Sabatier effluent gases. The space base supplemental propellant (NH_3) has very nearly the same specific impulse as that of methane, and very little is gained by combining the two fluids. Since the ammonia is stored as a liquid and must be vaporized before entering the thruster, there is no simplification of the overall system to be obtained by combining the ammonia vapors with the biowaste gases. Therefore, the supplemental propellant for the space base will be used separately.

It was suggested in the space station section that the addition of significant quantities of water vapor to the Sabatier effluent may result in a higher temperature limit for the mixture before methane decomposition occurs. If test results verify this increased limit, it certainly would be desirable to combine the two propellants. Otherwise, the use of water in the space station resistojets has essentially the same result as does the use of supplemental ammonia usage in the space base.

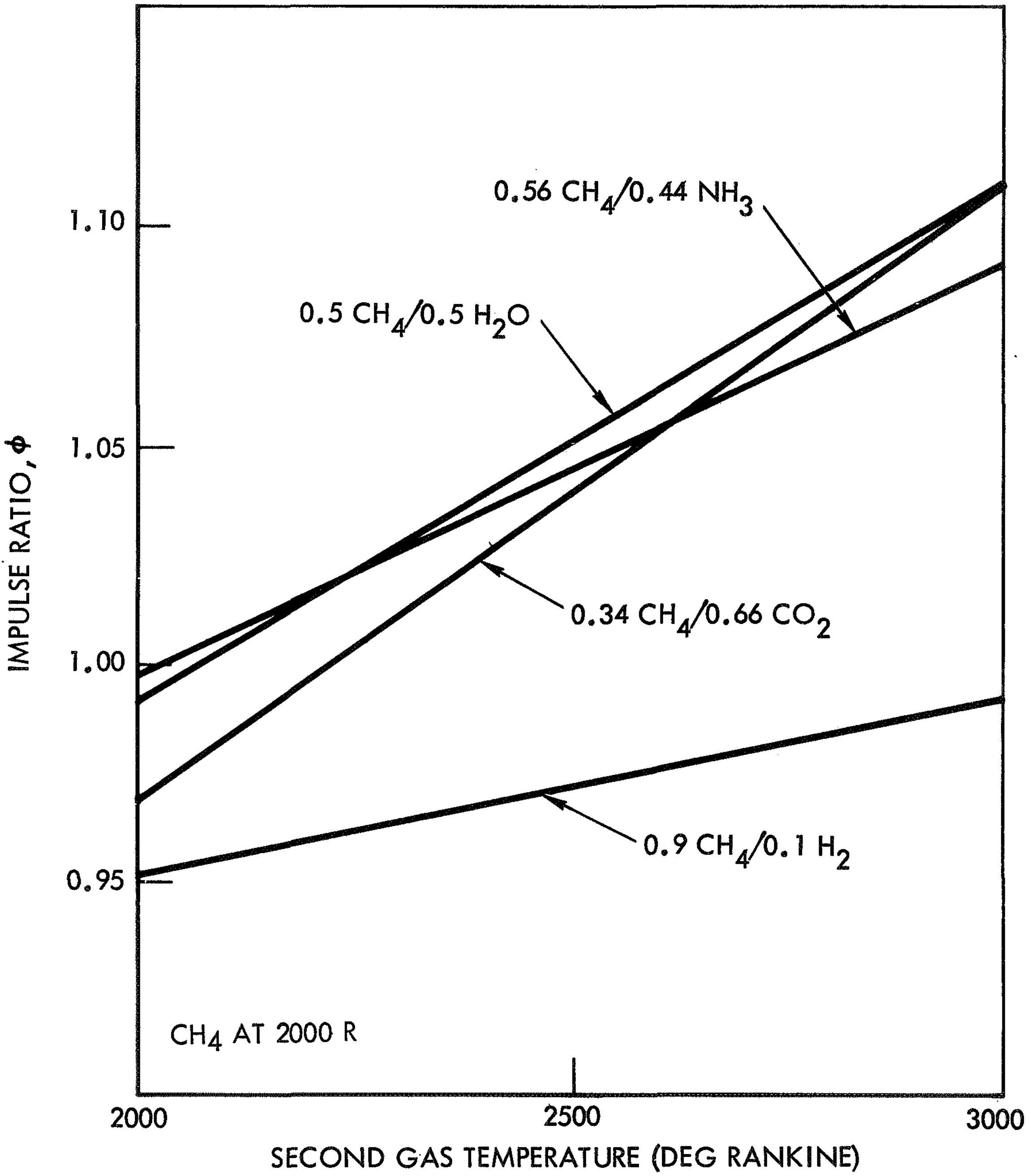


Figure 4-20. Impulse Ratio for Combined Gas Usage

As a matter of interest, the methane/carbon dioxide ratio obtained in the Sabatier effluent when the only hydrogen available to the Sabatier reactor is from water electrolysis is also shown. If all of the CO_2 is passed through the reactor, the reactor effluent is in the ratio shown. It is also possible to obtain the CO_2 for independent usage in the resistojet by removing, at a point upstream of the reactor, that quantity of CO_2 that will not react in the Sabatier reactor. This results in the duplication of compressors, regulators, accumulators, valves, etc. If subsequent NR space station studies result in a partial CO_2 reduction, the separate operation of CO_2 at a higher temperature would not be recommended. The additional impulse (7 to 8 percent) does not justify the complexity of a dual system.

BIOWASTE ACCUMULATORS

In the interest of commality and cost savings, the space base biowaste accumulators should be the same size as the space station accumulator. The additional flow rate for 60 men and the excess hydrogen mixture will necessitate the use of eight accumulators. Four of the accumulators will be located in the hub module near the ECLSS equipment and the resistojets in that section; the other four will be located near the four quads at the end of the local vertical section. All accumulators will be interconnected.

SPACE STATION/BASE COMMONALITY

The space station biowaste resistojet subsystem and the space base biowaste resistojet subsystem have many common features. Both vehicles use biowaste gases from a Sabatier reactor operating stoichiometrically, with a five-percent excess of hydrogen. Although a different total accumulator volume is necessary for the space base, due to higher impulse requirements (and biowaste availability), the additional volume will be obtained in the space base by use of more accumulators of the same size. The range of duty cycles required to meet all the space station requirements should provide sufficient variations in usage to simulate the space base usage, but on a smaller absolute level. There will be as much as 10 percent of hydrogen in the base biowaste gas mixture compared with 2.5 percent in the station mixture. The effect of the different gas properties should be tested.

The only other significant difference between the space station and space base biowaste resistojet systems, which might require a delta development for the space base, is in the choice of supplemental propellants. The space station used as a baseline for this study would use water as supplemental resistojet propellant, whereas the space base would use ammonia. The shuttle-launched space station presently under study at NR, however, may utilize hydrazine as a source of nitrogen for leakage makeup. If this were the case, the space base might also use hydrazine rather than ammonia for leakage makeup, and hydrazine would be the supplemental propellant in both cases.

V. SPACE STATION/BASE TECHNOLOGY REQUIREMENTS

Development of the integrated ECLSS—resistojet—CMG system for the space station and space base does not require technical breakthroughs. There is an adequate technical base to support an orderly development program. However, there are areas that require special emphasis.

From a technical viewpoint, the key problem in all space station/base subsystems is the lifetime requirements, particularly that of demonstrating the achievement of adequate component life. The small number of space stations (one or two) is a strong driver for the selection of standard hardware for subsystem assemblies. Use of standard hardware in the biowaste resistojet development program should add greatly to the data bank of component life and failure modes.

Technology or development issues are often assumed to pertain to the development of hardware for a specific requirement. This kind of work must be done, of course. In addition to hardware, however, the development of various operational modes for the integrated system is required. Although several operational modes have been considered in this study and recommendations made, the real effects on interfacing subsystems can be determined only from test results.

Three specific areas requiring additional development were identified as a result of this study. They are (1) the removal or control of water vapor from the Sabatier effluent; (2) additional thruster development for the use of hydrazine as a supplemental propellant; and (3) development of a unit to recover waste water from the solids dryer, fecal collection subassembly, and trash compactor.

WATER SEPARATION

Water vapors in the Sabatier effluent gases will condense when compressed to the accumulator storage pressures and cooled to ambient temperatures. Subsequent two-phase flow in the lines downstream of the accumulator could cause control problems or result in damage to regulators. Several concepts are presented in Section III for the removal of these water vapors or for maintaining the water in the vapor phase. More detailed studies and tests should be made to determine which concept should be used for the integrated ECLSS-resistojet development program.

HYDRAZINE THRUSTER

As a supplemental propellant, hydrazine is not presently considered a baseline concept for the space station/base biowaste resistojet. However, selection of hydrazine monopropellant thrusters for the medium-thrust requirements (a possibility in space stations under study) would make hydrazine a valid option as a supplemental propellant. If the hydrazine were passed through a gas generator at the biowaste thruster, significant specific impulse improvements would be obtained for a minimal power requirement (approximately 300 lb-sec/lb at 0.1 pound of thrust for 400 watts). Since the hydrazine is being used as a supplemental propellant, the impulse requirement must be high, and the power requirement for the resistojet is a premium.

The major technology issue of this concept is in the thruster valve design. If the gases from the hot-gas generator are introduced upstream of the valve, the valve (particularly the valve seat) must be designed to withstand relatively high temperatures (1100 to 2000 F). An alternative is to introduce the hot gases downstream of the waste gas control valve and provide a check valve to prevent the hot gases from reaching the waste gas valve, or provide some waste gas flow in conjunction with the hydrazine flow. A similar problem, but of lesser degree, with respect to the steam for water usage in the resistojet is under study at the Marquardt Corporation.

WASTE WATER RECOVERY

Approximately 10.7 lb/day of waste water has been identified as available from the ECLSS water and waste management assemblies. However, this water is presently vented to vacuum or contained in the solids dryer of the vapor compression subassembly. It will be necessary to design and develop the hardware required to recover this water for use in the resistojet.

REFERENCES

1. "Solar-Powered Space Station Preliminary Design," Space Station Program Phase B Definition, Volumes I through IX, North American Rockwell, Space Division, Report SD 70-159 (July 1970) MSC-00720.

2. "Executive Summary," Space Station Program Phase B Definition, North American Rockwell, Space Division, Report SD 70-153 (July 1970) MSC-00701.

3. Natural Environment Criteria for the NASA Space Station Program, Don K. Weidner, editor, Marshall Space Flight Center, Alabama NASA TM X-53865 (31 October 1969).

4. Bioastronautics Data Book, National Aeronautics and Space Administration, Washington, D.C., NASA Sp-3006, (1964).

5. "Space Station Crew Operations Definition," Space Station Program Phase B Definition, North American Rockwell Space Division, Report SD 70-156 (21 July 1970) MSC-00718.

6. Investigation of Integrated Carbon Dioxide Hydrogenation Systems, Phase III, The Garrett Corporation, AiResearch Division, Report SS-712-R (May 1962).

7. Investigation of Integrated Carbon Dioxide Hydrogenation Systems, Phase III, The Garrett Corporation, AiResearch Division, Report SS-863-R (16 January 1963).

8. Life Support System for Space Flight of Extended Time Periods, prepared by General Dynamics for the Langley Research Center, NASA CR-614, (November 1966).

9. "Final Report Sabatier Carbon Dioxide Reduction System," Douglas Space Cabin Simulator Purchase Order 7A-1273937K, The Garrett Corporation, AiResearch Division, Report 67-2686 (26 September 1967).

10. Evaluation of Desorbates from a Regenerative CO_2 Removal System Used in a 60-Day Manned Test, McDonnell Douglas Astronautics Company, Western Division, Report No. MDC-G1192 (October 1969), NASA CR-106214.

11. Jackson, J.K., and A. O. Pearson. A 90-Day Manned Test of an Advanced Regenerative Life Support System, McDonnell Douglas Astronautics Company, Western Division, Report No. MDAC-WD1234 (June 1970), presented to ASME Space Technology and Heat Transfer Conference, Los Angeles, California, 21-24 June 1970.

12. Plasma Reactor Development for Methane Decomposition to Acetylene and Hydrogen, The Boeing Company, NASA CR 66904 (May 1970).

13. Computerized Analytical Techniques for Design and Analysis of a Sabatier Reactor Subsystem, United Aircraft Corporation, Hamilton Standard Division, Contract NAS9-9844 Rough Draft Report, (May 1970).

14. Development of Regenerative CO_2 Removal System Design Techniques, The Garrett Corporation, AiResearch Division, Contract NAS1-8559, 15th and 16th Monthly Status Report. (March 1970)

15. Telecon 17 September 1970 between G. Schaedle, NR, and Larry Peyser of Fairchild Hiller.

16. Telecon 18 September 1970 between G. Schaedle, NR and Robert Wheaton of Whirlpool.

17. "Space Station Program Phase C/D Program Operations Plan," Space Station Program Phase B Definition, North American Rockwell, Space Division, Report SD 70-132 (July 1970) MSC-00705.

18. "Solar-Powered Space Station Definition," Volume II, Part 1, and Volume V, Space Station Program Phase B Definition, North American Rockwell, Space Division, Report SD 70-155-2-1 and S SD 70-155-5 (July 1970), MSC-00717.

19. "Thruster Study for Propulsion/RCS Subsystem," Space Station Program Phase "B" Definition Study, prepared by the Marquardt Corporation, under contract to North American Rockwell Corporation, Space Division, MIR No. 373, (30 April 1970).

20. Summary Report, Ten Millipound Resistojet Development, the Marquardt Corporation, Report S-861, (January 1968).

21. NASA CR-66601, "Definition of a Resistojet Control System for the Manned Orbital Research Laboratory," Final Report, Volume II, Resistojet Control System Analysis, Douglas Aircraft Company dated May 1968.

22. Tuve, G. L., and L. C. Domholdt. Engineering Experimentation, New York: McGraw-Hill Book Co. (1966).

23. Halbach, C.R., "Technology Development of a Biowaste Resistojet," Third Quarterly Report, prepared by the Marquardt Company under contract to the NASA Langley Research Center, TMC Report 25,310 (June 1970).

24. "Solar Powered Space Station Preliminary Performance Specification," Space Station Program Phase B Definition, North American Rockwell Space Division, Report SD70-510-1 (July 1970), MSC-00729.

25. "Space Base Definition," Volumes I-III, Space Station Phase B Definition, North American Rockwell, Space Division, Report SD70-160 (24 July 1970), MSC-00721.

26. Sixth World Petroleum Congress Proceedings, Section III, Frankfurt/Main, published by Verein Zur Forderung, Des 6 Welt-Erdol Gongresses, Hamburg (19-26 June 1963).

APPENDIX A

BIOWASTE SUPPLY MODEL

The Sabatier condenser effluent consists primarily of methane and hydrogen and secondarily of varying quantities of CO_2, N_2, H_2O, O_2 and airborne contaminants. The resistojet system is particularly adaptable to a wide range in the supply model, both in terms of gases present and mixture ratios. This property of resistojets makes the operation of a real system relatively simple and the ECLSS interface relatively non-critical in some respects. However, knowledge of the variation in the supply model is necessary to:

1. Verify the detailed resistojet performance
2. Evaluate the long life characteristics of the resistojet (condensation, corrosion, effects)
3. Verify that only safe gas mixtures are involved
4. Evaluate resistojet plume contamination on the vehicle and environment

This section of the report presents a description of the previous research and the variation in the biowaste model.

To establish the variation in the resistojet supply, the performance of the molecular sieve subassembly, the Sabatier reactor, and the Sabatier condenser was studied and the significant research test programs to date were surveyed. It was observed that several of the Sabatier effluent variations were due to specific design problems which can reasonably be improved for the station system. Consequently, the proposed design models do reflect performance extrapolation to a 1977 space station launch.

The sources of variation in the resistojet supply, exclusive of the crew, are identified in Figure A-1. Figure A-1 indicates that the primary sources causing variation in the biowaste supply are: (1) Sabatier reactor performance, (2) Sabatier condenser saturated water vapor, (3) adsorption of cabin gases in the molecular sieve, and (4) leakage of cabin gases into the ECLSS/resistojet system at locations which are below the cabin pressure. The factors which influence the primary sources are identified in Figure A-1.

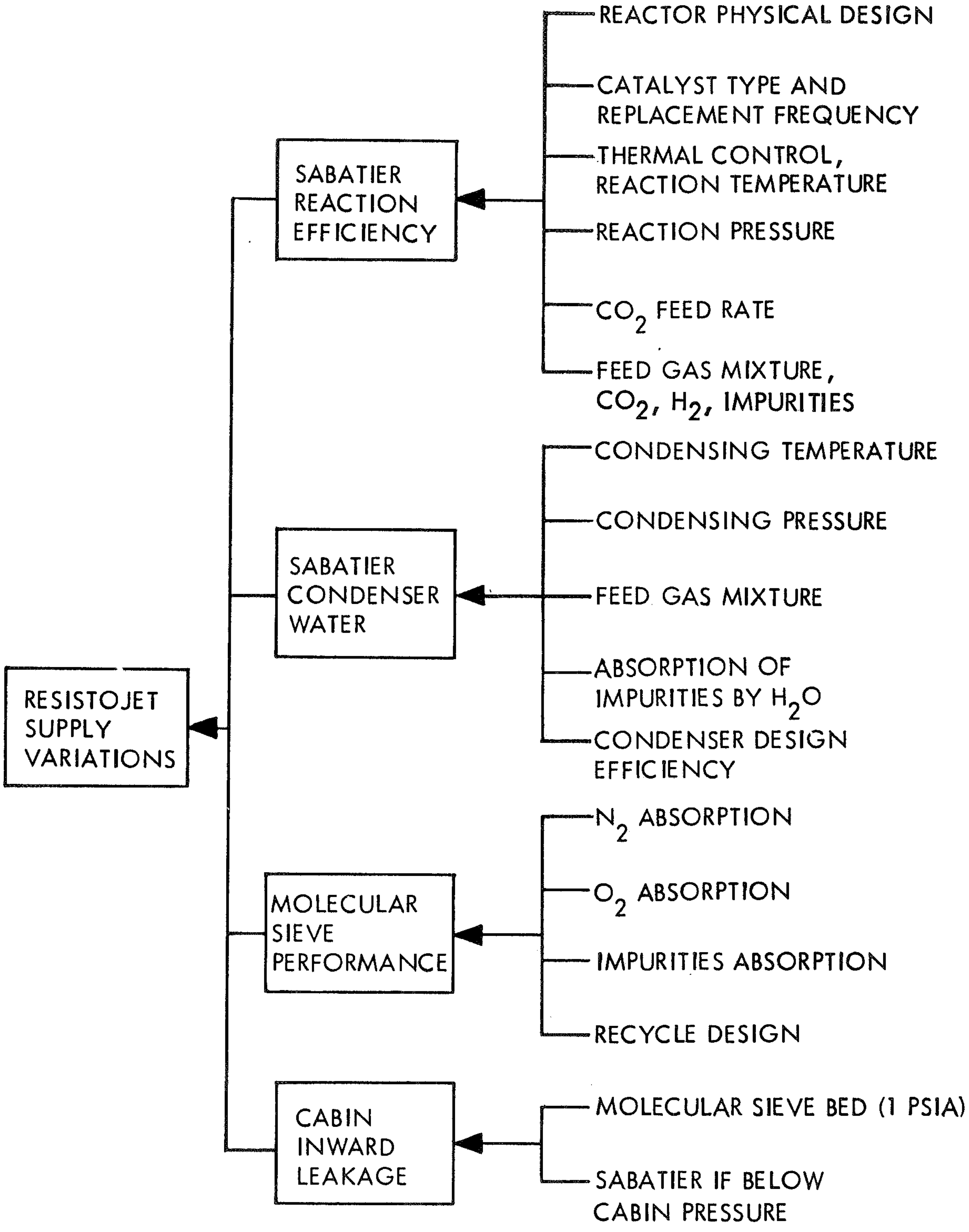


Figure A-1. Sources of Variation in the Resistojet Supply Exclusive of the Crew

The following significant research programs were surveyed as a basis for prediction of the biowaste supply.

1. North American Rockwell/AiResearch Sabatier research, 1961-1963.
2. Integrated Life Support System (ILSS) 28-Day Test, NASA Langley. General Dynamics, 1966-1967.
3. Manned 60-Day Test, NASA Langley/McDonnell Douglas, 1969.
4. Manned 90-Day Test, NASA Langley/McDonnell Douglas, 1970.
5. Boeing/NASA Langley Sabatier Research, 1970.
6. Hamilton Standard/NASA-MSC Sabatier Research, 1970.
7. AiResearch/NASA-MSC Molecular Sieve Research, 1970.

These programs are briefly surveyed in the next sections of this report, concluding with a section on recommended biowaste design models for the station.

NR SABATIER RESEARCH

In 1961, 1962, and 1963, NR performed hydrogenation studies as a part of a series of test programs directed toward thermal and atmospheric control systems for manned space flight being conducted under Contract AF 33(616)-8323, sponsored by the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. The studies were conducted at AiResearch under subcontract to NR. The significant documentation of this study is indicated as Reference 6 and Reference 7.

Research on four catalysts is presented in Reference 6; 67 percent nickel on kieselguhr, nickel on alumina, platinum on alumina, and thoria promoted nickel on zeolite. The nickel on kieselguhr was the preferred catalyst. Carbon dioxide conversion efficiencies of 90 and 95 percent were reported in Reference 6. The variation of CO_2 conversion efficiency for changes in reactor temperature, pressure, CO_2 flowrate and water in the feed gases, is presented in Figures A-2 through A-5. It is seen that temperature affects conversion efficiency significantly. Greater conversion occurs at lower temperatures (~300 F) (refer to Figure A-3), however, a higher temperature is required to initiate the reaction. Conversion efficiency increases as reaction pressure increases and decreases as CO_2 flowrate increases and as water in the inlet feed increaseses.

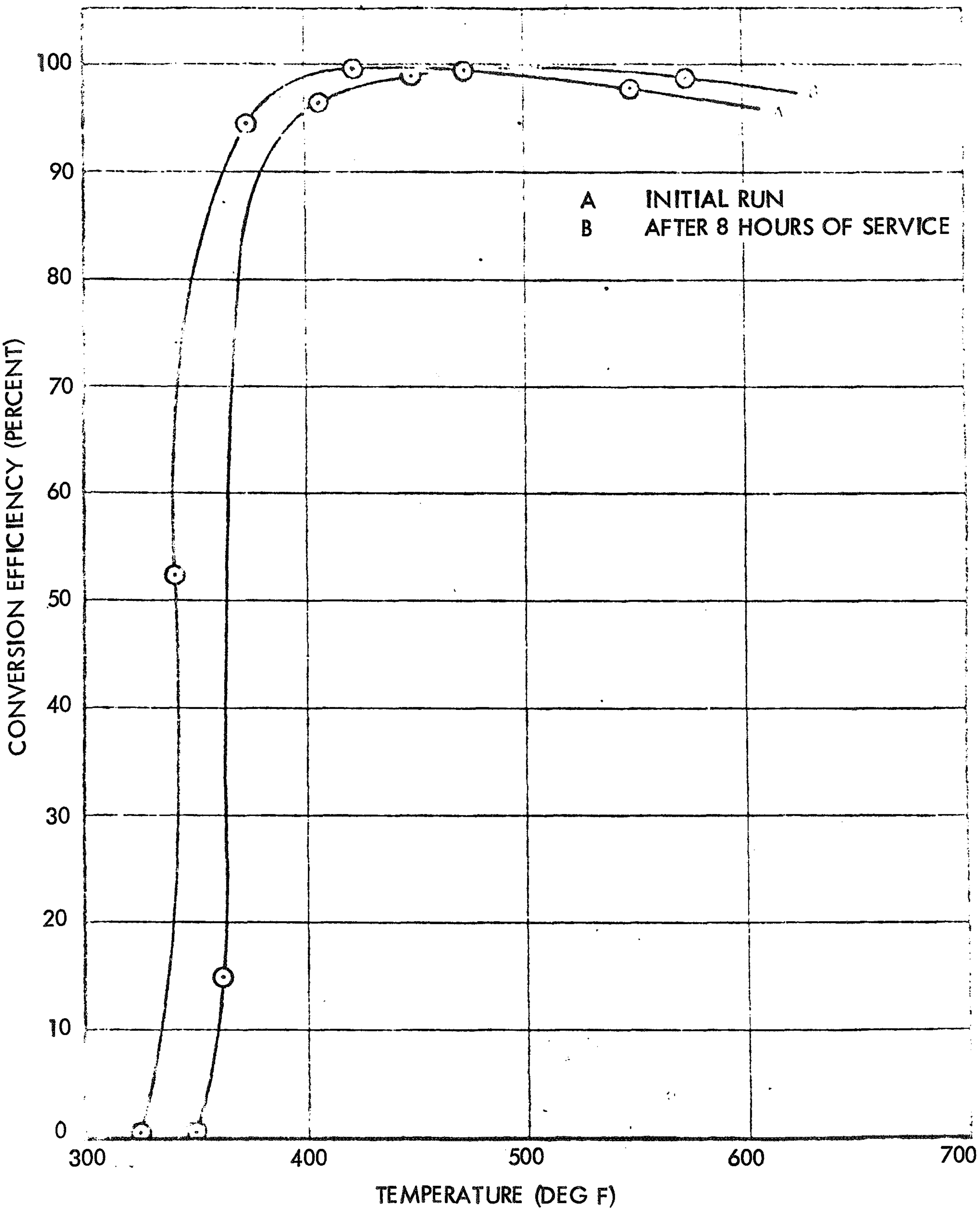


Figure A-2. Nickel on Kieselguhr Catalyst Performance

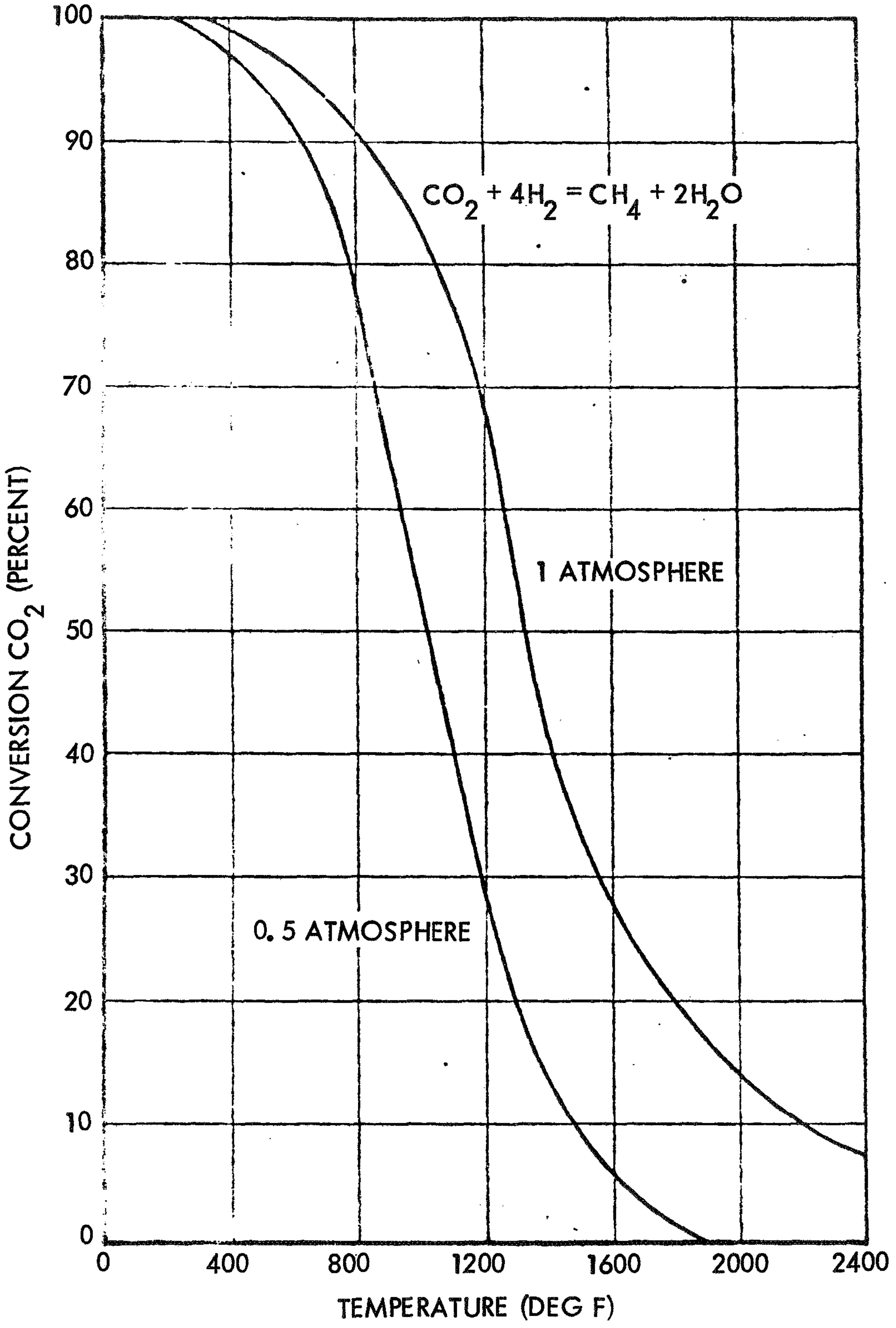


Figure A-3. Percent Theoretical Conversion Versus Temperature

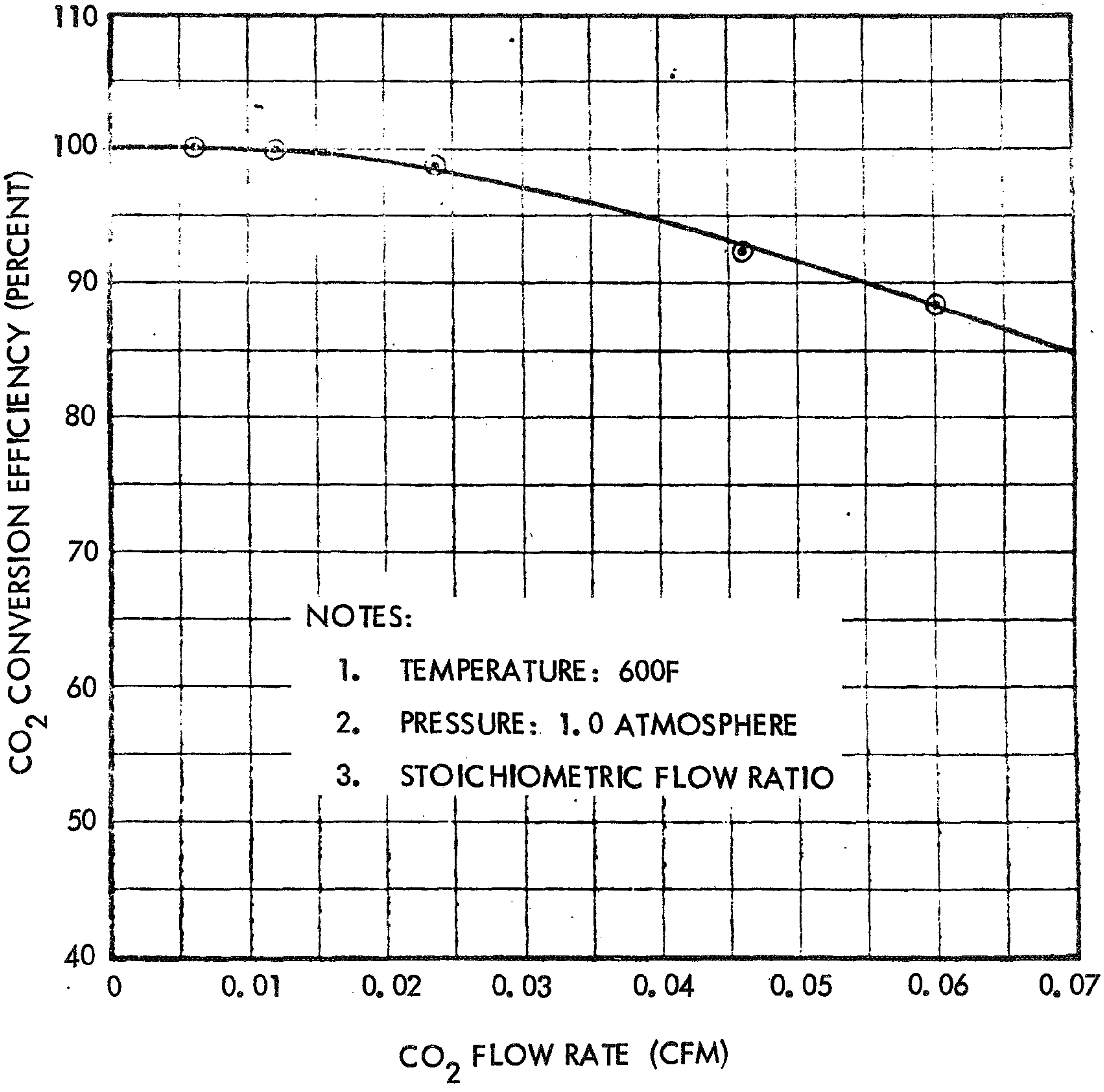


Figure A-4. Nickel on Kieselguhr Performance - Conversion Efficiency Versus Flow Rate

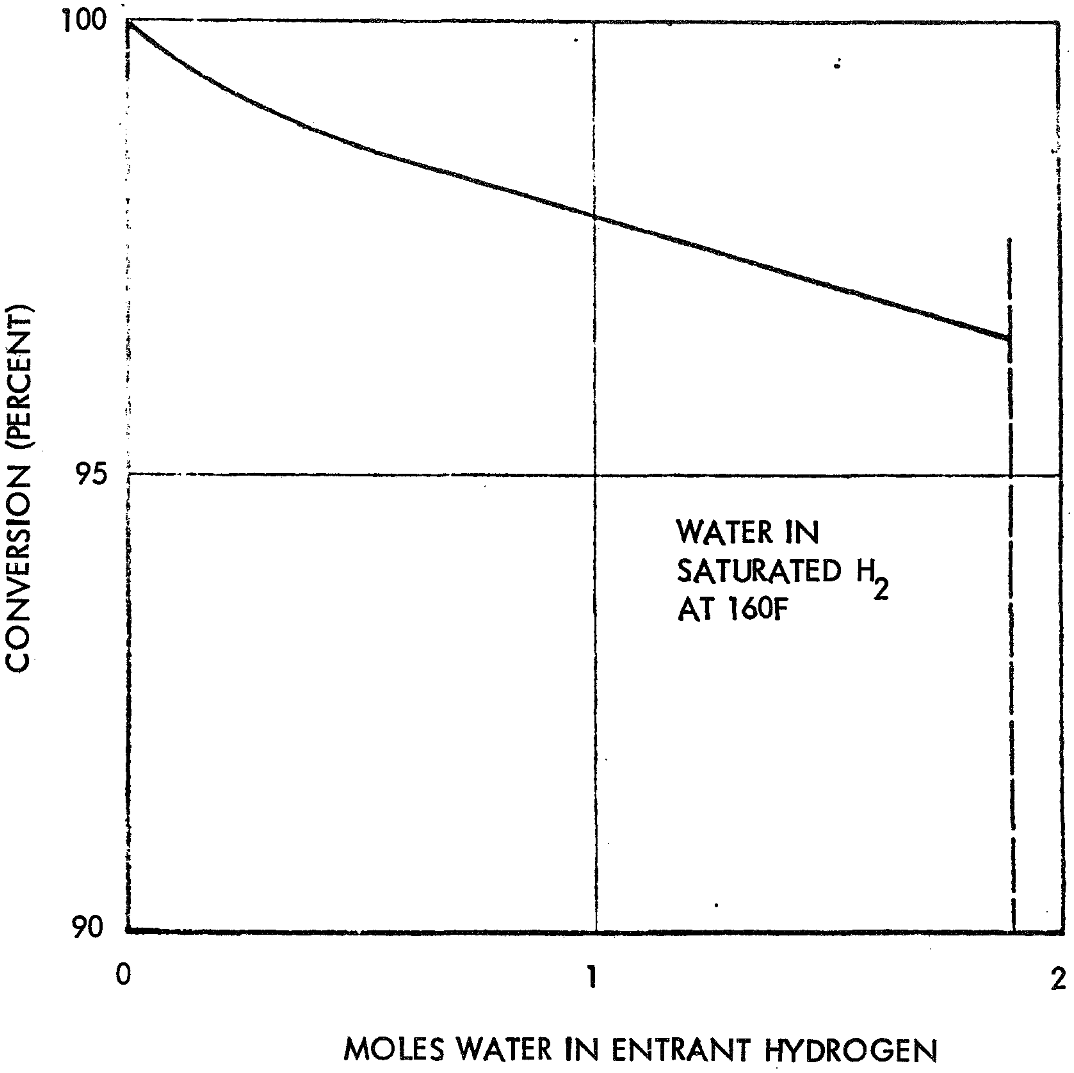


Figure A-5. Effect of Water on Sabatier Reaction

Conversion efficiency of 99 percent is reported in Reference 7 with stoichiometric hydrogen. No carbon monoxide was detected in any of the testing.

ILSS - 28-DAY TEST

An Integrated Life Support System (ILSS) test using a 4-man crew and a regenerative life support system was performed by General Dynamics and NASA-Langley (Reference 8). An analysis of the Sabatier acceptance test data prior to the actual 28-day test run (which is reported in Table 8.2-XVI of Reference 8) did not produce reasonable results. The data is summarized below.

Input:	CO_2	8.77 lb/day
	H_2	1.69 lb/day
Output:	H_2%	67.5 % by volume
	CO_2	4.5 % by volume
	CH_4	28.0 % by volume
	H_2O	4.88 lb/day condensed

If the measured condensed water is assumed correct the CO_2 conversion efficiency is:

$$\frac{44}{36} \times 4.88 \frac{\text{lb } H_2O}{\text{day}} = \frac{5.96\ CO_2 \text{ reacted}}{8.77\ CO_2 \text{ should react}} = 68\%$$

The source acceptance inspection tests reported in Reference 8 identified that Sabatier water production was 40 to 60 percent of the theoretical rate. Problems encountered included leakage of N_2 with 21 percent N_2 in the Sabatier vent line and a temporary failure in the precooler which allowed FC-75 coolant contamination of the system.

A typical gas analysis of the Sabatier system operating normally during the 28-day test was obtained from Mr. Lenwood Clark (NASA-Langley, telecon, August 17, 1970) which is listed below.

INPUT:

H_2	0.918 lb/day, 17 psia reactor
CO_2	7.58 (plus 1.82 vented before entering reactor)
N_2	0.163 (air leakage and bed absorbed)
O_2	
	8.661 total

OUTPUT:

CO_2	2.63 lb/day
N_2	0.163
H_2	0.017
CH_4	1.80
H_2O	0.074
CO	--
O_2	--

H_2O condensed: 3.98 lb/day

$$\text{Calculated efficiency: } \frac{4.95\ CO_2 \text{ did react}}{5.05\ CO_2 \text{ should react}} = 98 \text{ percent}$$

60-DAY TEST

A four-man, 60-day test of an advanced regenerative ECLSS, including Sabatier oxygen reclamation, was performed by McDonnell-Douglas under contract to NASA-Langley. The test incorporated a Sabatier reactor built by AiResearch (Reference 9). The results of the AiResearch testing indicated that the reactor operated at approximately 93 percent conversion efficiency with stoichiometric reactor inlet conditions, and at 96 percent when operating with inlet conditions that are 10 percent H_2 rich. The reactor was tested at pressures from 7 to 25 psia. The condenser temperature was 45 F.

An evaluation of desorbates from the molecular sieve used in the 60-day test was performed for NASA-Langley as reported in Reference 10. The airborne organic contaminants were measured and it was determined that approximately 7.7 ppm per day were being absorbed by the CO_2 removal system (based on a 4100 ft^3 cabin); 3.52 ppm in the silica gel; and 4.15 ppm in the zeolite molecular sieve bed. The contaminants in the silica gel bed are not diverted to the Sabatier reactor. The contaminants in the zeolite bed pass through the reactor. The water soluble contaminants are removed with water condensate at the condenser further reducing the impurities in the resistojet propellant. Table A-1 identifies contaminants desorbed from the molecular sieve. A total of 44.5 mg of contaminants was absorbed in each 45-minute cycle. An approximate extrapolation of this data point to the space station indicates 2 grams of contaminants per day in the resistojet supply.

Table A-1. Quantitative Analysis of Individual Contaminants From Two Sorbents

Column	1	2	3	4	5	6
	mg/kg(1)		mg/total sorbents(2)		ppm/600 ft^3 air	
Organic Contaminant	45-Min Molecular Sieve	45-Min Silica Gel	12-lb Molecular Sieve	9-lb Silica Gel	600 ft^3/45 min Molecular Sieve	600 ft^3/45 min Silica Gel
Acetone	1.87	2.75	10.2	11.3	0.256	0.283
Benzene	0.009	0.045	0.048	0.183	0.00089	0.00341
Carbon tetrachloride	---	1.49	---	6.1	---	0.0575
Chloroform	0.135	---	0.735	---	0.00895	---
1.2-dichloroethane	0.228	0.164	1.24	0.669	0.0182	0.00987
Dichloromethane	3.87	4.57	21.1	18.7	0.362	0.320
Hexane	0.615	0.913	3.36	3.73	0.0565	0.063
Isobutane	0.438	1.38	2.39	5.64	0.0598	0.141
Methyl ethyl ketone	0.111	0.071	0.605	0.29	0.0121	0.00587
Toluene	0.418	1.31	2.28	5.37	0.0359	0.0849
1.1.1-trichloroethane	0.235	0.336	1.28	1.38	0.0140	0.0150
Trichloroethylene	---	0.500	---	2.04	---	0.0226
O-Xylene	0.237	0.274	1.29	1.12	0.0177	0.0153
Totals	8.166	13.803	44.528	56.522	0.84204	1.02145

(1) mg of contaminants per kg of each sorbent
(2) Total sorbents consisted of 12-lb molecular sieve and 9-lb silica gel

90-DAY TEST

A four-man, 90-day test (completed in September 1970) of a regenerative ECLSS was performed by McDonnell-Douglas under contract to NASA-Langley. The test incorporated a Sabatier reactor built by AiResearch, a condenser built by Langley, and a solid amine CO_2 removal system. A molecular sieve CO_2 removal system was utilized the last two weeks of the test. The Sabatier unit was air cooled and was operated at 9 psia initially and increased later to 11 psia to obtain increased efficiency when leak-proof integrity had been verified. Cabin test pressure was 10 psia. The Sabatier condenser temperature was 40 F.

A nominal Sabatier gas analysis for operation with the solid amine system was obtained from Mr. Otto Trout (NASA-Langley, telecon, August 19, 1970) and is listed below.

INPUT: CO_2 8.4 lb/day
H_2 1.2

CONDENSER		% by vol.	% by wt.	lbs/day
OUTPUT:	CO_2	37.5	0.6168	3.306
	H_2	0.7	0.0005	0.0027
	CH_4	58.2	0.3480	1.865
	N_2	2.9	0.0303	0.162
	O_2	0.1	0.0011	0.006
	H_2O	00.5	0.00336	0.018
				5.36 lb/day
		Water condensate	=	4.24 lb/day

The weight flowrate in the condenser effluent was calculated by a mass balance on the input and output carbon which resulted in a total gas flowrate of 5.36 lb/day. The water condensate was calculated as the difference between the input weight flow and the effluent gas flow. The CO_2 conversion efficiency is calculated as shown below.

$$\left.\begin{array}{r} 8.4 - 3.3 = 5.1\ CO_2 \text{ did react} \\ \\ \frac{44}{8} \times 1.2 \text{ lb } H_2/\text{day} = 6.6\ CO_2 \text{ should react} \end{array}\right\} = 77\%$$

The theoretical water production based on the CO_2 reaction is 4.17 lb/day which is in reasonable agreement with the calculated 4.24 water production.

Some problems experienced during the program included Freon 113 contamination due to a leakage failure and a failure of the KOH electrolysis system resulting in a small H_2, O_2 fire. To avoid any buildup of O_2 in the CO_2 accumulator or H_2 accumulator, the CO_2 is passed through charcoal and the H_2 passes through "deoxo" units to remove O_2 for safety reasons. Installation of these filters thus limits O_2 in the Sabatier and biowaste supply.

Nominal oxygen recovery system performance for the 90-day test from Reference 11 identifies a Sabatier efficiency of 90 percent. A Sabatier gas analysis for the period of time after switchover to the molecular sieve could not be obtained in time to include in this report. The data should be of particular interest with regard to potentially adsorbed N_2, O_2 and contaminants.

BOEING/LANGLEY RESEARCH

A significant research program was conducted by Boeing for NASA-Langley to design and test a hydrogen plasma reactor for decomposition of methane to acetylene (C_2H_2) and hydrogen and to design and test a Sabatier reactor (Reference 12). A CO_2 conversion efficiency of 99.89 percent was obtained using 30-percent hydrogen excess and a ruthenium and alumina catalyst. In addition, previous Boeing tests with similar reactors indicated CO_2 conversion efficiencies of 99.5 percent or higher at 30-percent hydrogen excess.

The performance of a 4-man Sabatier reactor as a function of H_2 feed is given in Figure A-6. Conversion efficiency was 96.5 percent at stoichiometric H_2 and increased rapidly to approximately 99 percent for 5-percent H_2 excess. Increasing the CO_2 flowrate to that corresponding to a 9-man reactor decreased the conversion efficiency to approximately 90 percent at 10-percent excess H_2 as shown in Figure A-7. Modifying the insulation design of the 4-man reactor improved the conversion efficiency to approximately 96 percent at 10-percent excess H_2. Per communication with

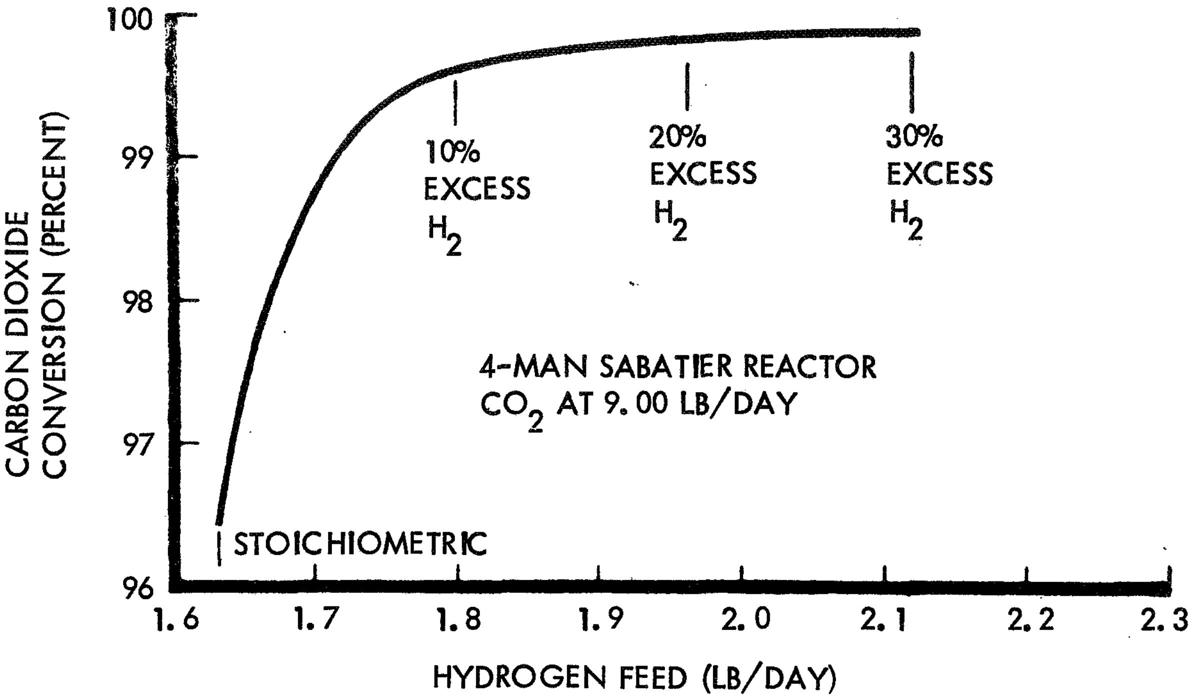


Figure A-6. Sabatier Reactor Performance - Four-Man System

Mr. R. K. Ames, at Boeing, September 14, 1970, it was verified that operating a Sabatier reactor at less than its design CO_2 flowrate should result in a negligible increase in efficiency. Consequently, operating a station 12-man Sabatier for a 6-man CO_2 flowrate should not cause an observable difference in CO_2 conversion efficiency.

HAMILTON STANDARD/MSC RESEARCH

Hamilton Standard, under contract NAS9-9844 to NASA-MSC, built a 12-man size Sabatier reactor and performed testing and research for the purpose of developing a comprehensive analytical model (Reference 13). The final report of this contract has not been released as of this date; however, the gas analysis listed below and process efficiency was obtained from Mr. A. Brouillet (Hamilton Standard, telecon, September 15, 1970).

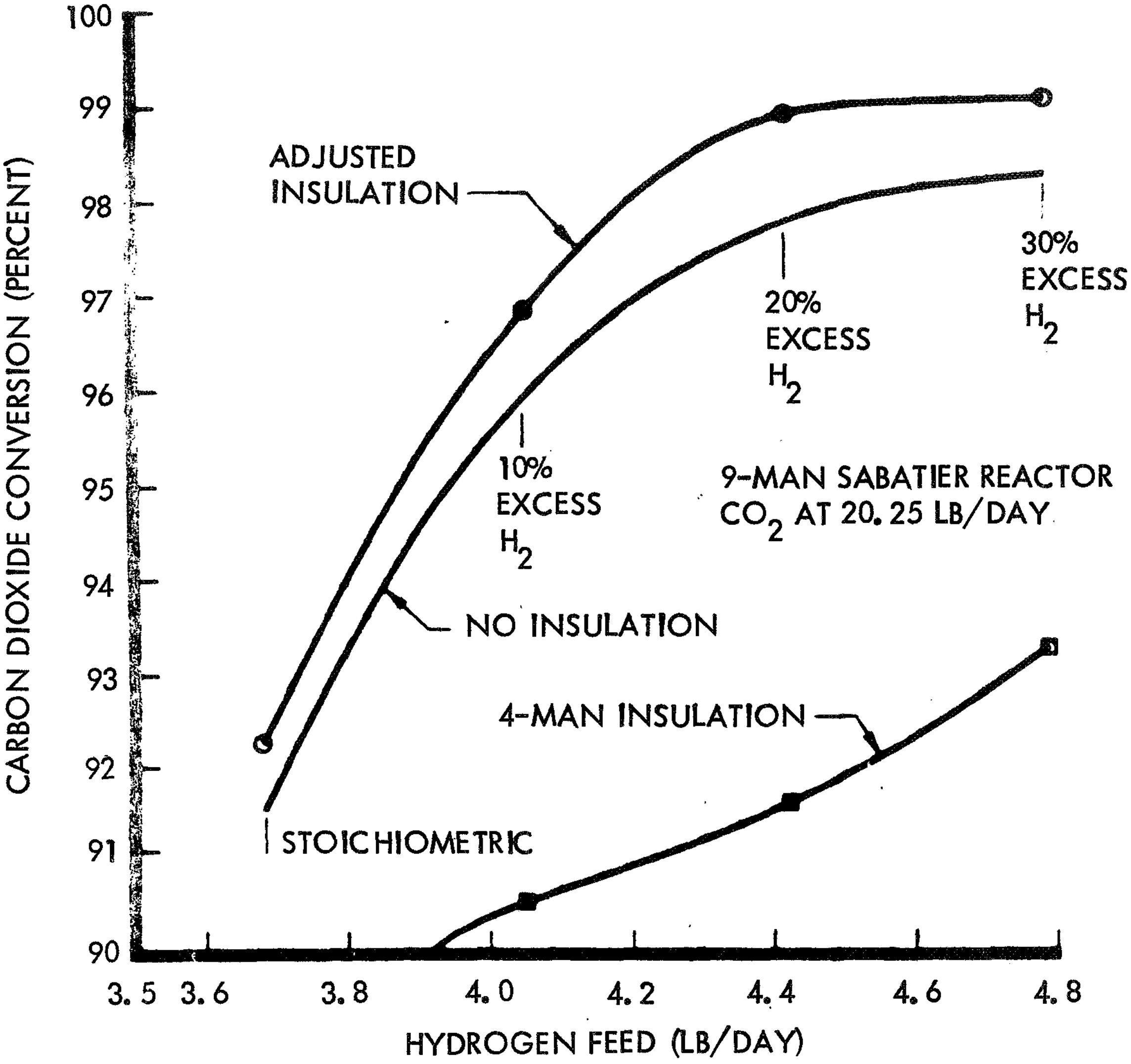


Figure A-7. Sabatier Reactor Performance - Nine-Man System

CASE 1: 18-19% H_2 Excess	CASE 2: STOICHIOMETRIC H_2
INPUT: H_2 0.83 mole fraction CO_2 0.17	INPUT: H_2 0.805 CO_2 0.195
OUTPUT: CO_2 0.0032 H_2 0.204 CH_4 0.269 H_2O 0.525	OUTPUT: CO_2 0.031 H_2 0.117 CH_4 0.300 H_2O 0.552
Efficiency: 98.8%	Efficiency: 91%

The program purpose was to develop modeling relations.

The Sabatier unit was not optimized for space station performance. The relation developed for the conversion efficiency of CO_2 for H_2 rich cases was:

$$\eta = \frac{r}{1 + r}$$

where

η = CO_2 conversion efficiency

$$r = \frac{CH_4 \text{ mole fraction}}{CO_2 \text{ mole fraction}}$$

The relation developed for the conversion efficiency of H_2 for CO_2 rich cases was:

$$\eta = \frac{4r}{1+4r}$$

where

$$r = \frac{CH_4 \text{ mole fraction}}{H_2 \text{ mole fraction}}$$

AIRESEARCH MOLECULAR SIEVE DESIGN STUDY

AiResearch Manufacturing Company is currently involved in molecular sieve design studies. Figure A-8 is abstracted from the 15th monthly status report (Reference 14) and identifies N_2 adsorbed on Linde 5A molecular sieve as a function of the inlet N_2 partial pressure. The space station N_2 pressure is 11.6 psia or 600 mm Hg and the molecular sieve bed-weight is approximately 35 pounds. Based on Figure A-8, the station will adsorb 0.28 lb N_2 per cycle resulting in 4.2 lb/day of N_2 adsorbed by the zeolite.

The zeolite bed is pumped down from the cabin pressure of 14.7 psia to 1 psia total pressure. During this phase, the gas volume trapped in the zeolite canister and most of the adsorbed N_2 is recycled to the inlet to the active molecular sieve rather than desorbed directly to the CO_2 accumulator. This recycling phase of desorption is done to improve the purity of CO_2 to the Sabatier reactor. Assuming the gas in the zeolite bed at 1 psia has the same O_2, N_2 mixtures as air, the N_2 partial pressure would be 0.79 psia or 41 mm Hg. From Figure A-8, the N_2 adsorbed is 0.4 lb/100 lb of zeolite or 0.14 lb N_2 for a 35-lb station bed. Considering 15 cycles of the molecular sieve per day, 2.1 lb N_2/day would be desorbed to the CO_2 accumulator.

The adsorption of oxygen on Linde 5A zeolite as a function of the inlet O_2 partial pressure is shown in Figure A-9, which was abstracted from the 16th monthly status report (Reference 14). The space station O_2 pressure is 3.1 psia or 160 mm Hg. Based on a 35-pound molecular sieve bed-weight and the data of Figure A-9, the station will adsorb approximately 0.05 lb of O_2 per cycle resulting in 0.7 lb/day of O_2 adsorbed by the zeolite. When the canister is pumped to 1 psia it is estimated that 0.007 lb of O_2 will be adsorbed in a 35-lb bed resulting in 0.1 lb/day O_2 desorbed to the CO_2 accumulator. Charcoal filters will probably be required in the CO_2 accumulator feed line due to safety requirements to avoid H_2 and O_2 being in contact. Consequently, the resistojet supply will not receive this oxygen.

It should be noted that the adsorption curves of Figures A-8 and A-9 cannot be applied separately. Coadsorption curves for CO_2, O_2, and N_2 are required for an accurate evaluation. However, inasmuch as the O_2 is not adsorbed to a significant extent (approximate magnitude $27CO_2$: $6N_2$:$1O_2$) the coadsorption curve of Figure A-8 for CO_2 and N_2 should be reasonably applicable to the station.

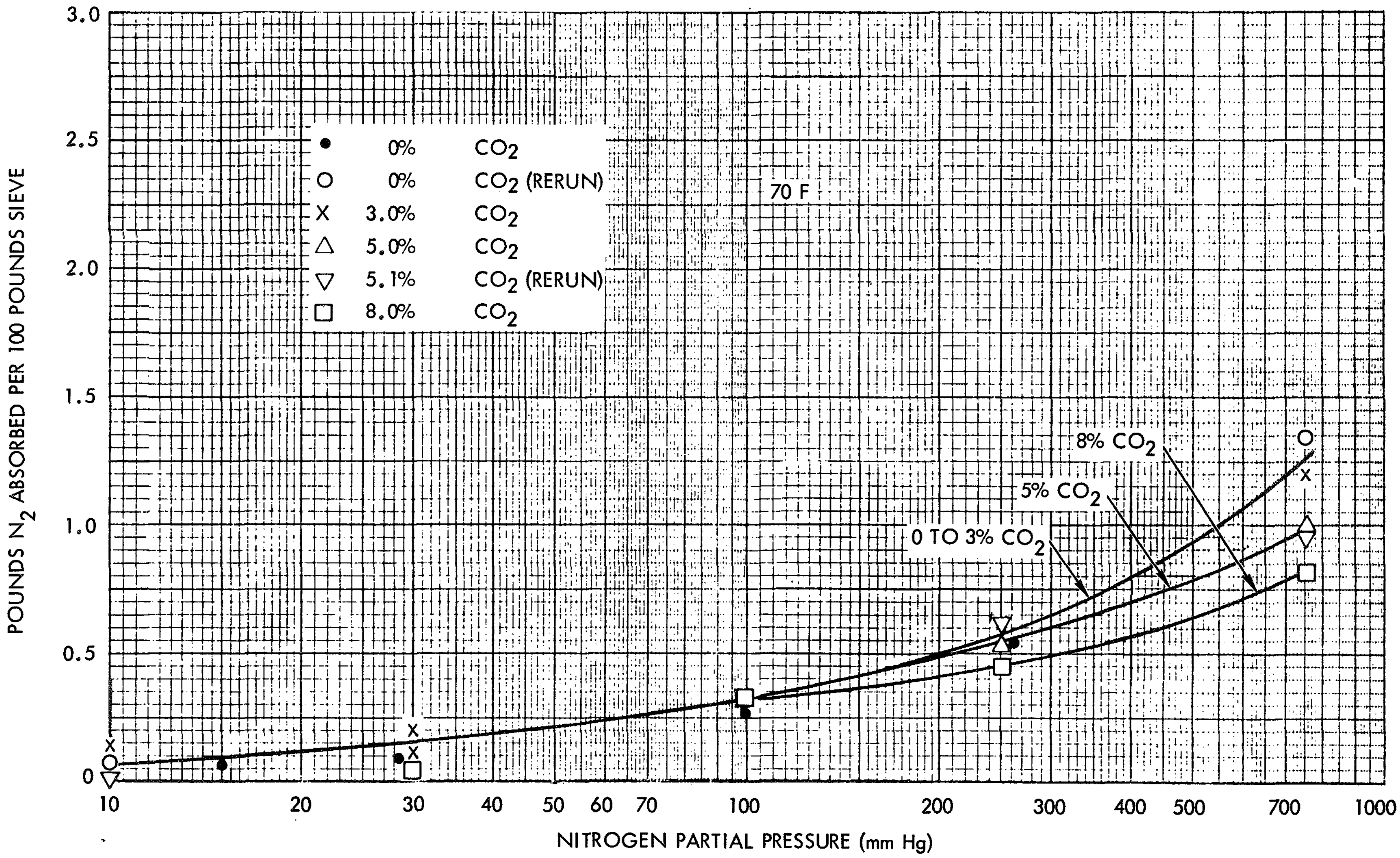


Figure A-8. Coadsorption of Nitrogen and Carbon Dioxide on Molecular Sieve (Linde) 5A

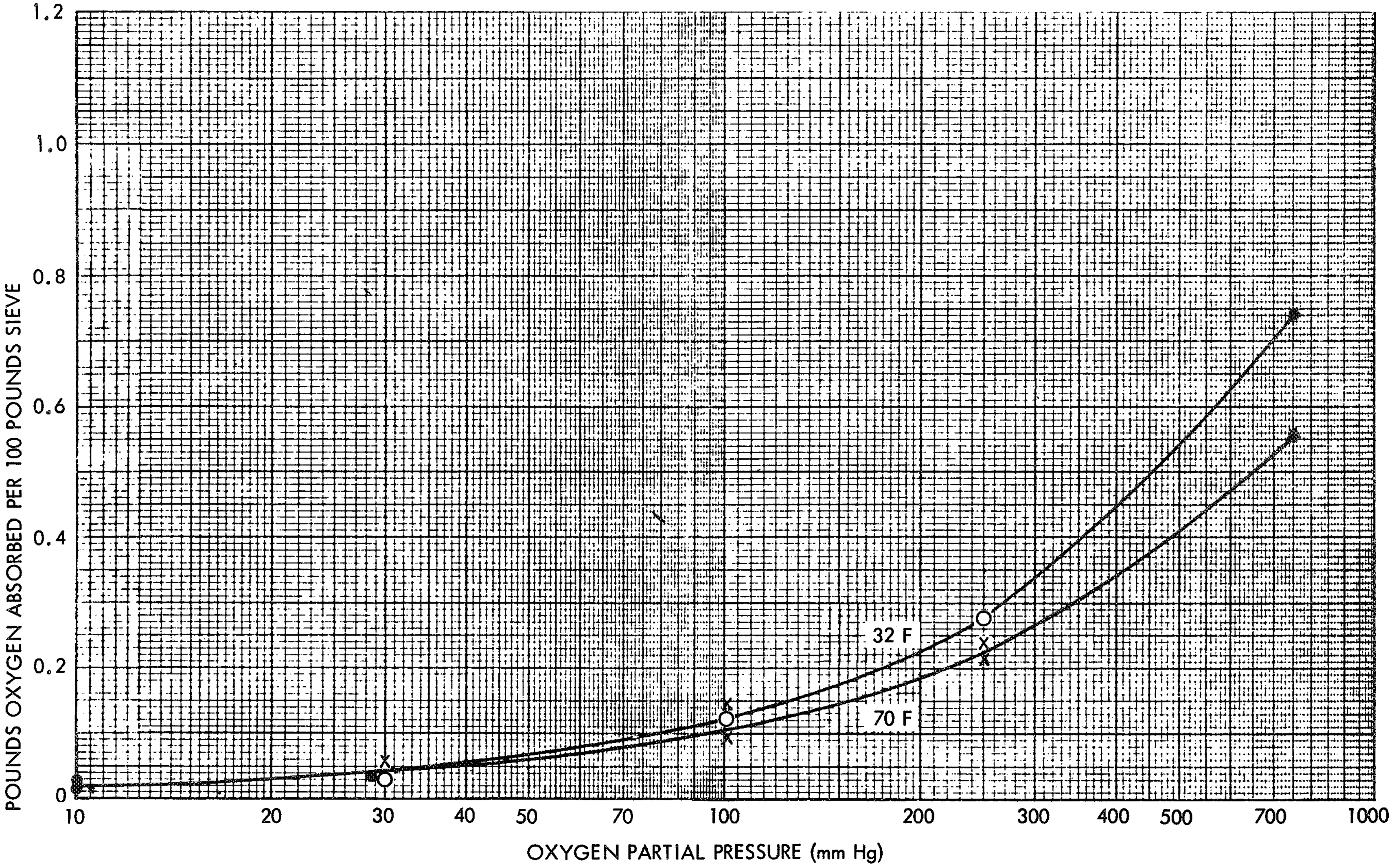


Figure A-9. Adsorption of Oxygen on Molecular Sieve (Linde) 5A

SABATIER CONDENSER WATER

The water-vapor effluent from the Sabatier condenser is primarily a function of the condensing temperature and pressure. However, for a given pressure, different gas mixtures cause changes in the quantity of water vapor. A computer program was generated to perform these calculations. The integral form of Clapeyron's equation for the saturation pressure of water utilized in the calculation is given below.

$$P_{H_2O} = 0.08854 \text{ EXP}\left[\frac{777.5}{85.58}\left(1348.4\frac{T-492}{492T} - 0.554\ln\frac{T}{492}\right)\right]$$

The weight of water in the effluent is

$$W_{H_2O} = \frac{P_{H_2O} \times R_{gas} \times W_{gas}}{85.58\,(P_{Total} - P_{H_2O})}$$

where:

P_{H_2O} = water vapor partial pressure

P_{total} = condenser total pressure

W_{gas} = weight of dry gas in condenser

R_{gas} = gas constant for dry gas mixture

$$R_{gas} = \sum X_i R_i$$

where:

X_i = weight fraction of dry gas, i^{th} component

R_i = gas constant of i^{th} component

For variation in the condenser temperature from 40 F to 70 F and pressure from 10 psia to 20 psia the water vapor in the biowaste supply varies from 0.1 to 0.6 lb/day.

CONCLUSIONS

The Sabatier condenser outlet on the station will consist of CH_4, H_2, CO_2, N_2, O_2 and trace contaminants. A review of Sabatier research identified no CO, C, or C_2H_2. A summary review of the expected variation in the biowaste model is listed in Table A-2. The nominal design model presented in Table A-2 is expected to represent nominal continuous performance of the Sabatier subassembly. The nomenclature "minimum performance model" is intended to represent a lower CO_2 conversion efficiency and an increased amount of impurities in the biowaste supply. The maximum performance model is intended to represent a higher CO_2 conversion efficiency and a minimum amount of impurities in the Sabatier effluent. The range of H_2 in the biowaste supply is related to the CO_2 and CH_4 and larger variation in H_2 can occur as described later. Typical trace contaminants in the biowaste supply were identified in Table A-1.

Nominal Long-Duration Model

The nominal Sabatier performance condition is defined as 99 percent CO_2 conversion at 5-percent excess H_2 over stoichiometric conditions. The 99-percent conversion efficiency is an estimate for the station Sabatier hardware and is extrapolated primarily from the results of Boeing (Reference 12), AiResearch (Reference 7) and the Space Station Phase B Program (Reference 1). The water in the biowaste supply is based on a 54 F condenser outlet saturation temperature at 15 psia which is the design condition reported in Reference 1. The N_2 in the biowaste supply is estimated primarily from the N_2 adsorption on zeolite for the station molecular sieve based on work by AiResearch (Reference 14). The 90-day test results also partially substantiate this conclusion about N_2. The O_2 in the biowaste supply assumes a station system configuration similar to the 90-day test program (Reference 11) in which O_2 filters are placed on the inlet CO_2 and H_2 supplies. The zeolite beds will adsorb some O_2 (Reference 14), however, filters will limit the O_2 in the biowaste supply.

The trace contaminants in the biowaste supply are estimated from Reference 10 as described in the previous section of this report on the 60-day test.

The nominal model is calculated as follows:

$$CO_2 + 4H_2 \rightarrow 2H_2O + CH_4$$

Table A-2. Space Station Biowaste Supply Models

(12-Man Crew, Nominal Metabolic Rate)

Biowaste Gas	Nominal Model			Minimum Performance Model		Maximum Performance Model	
	Lb/Day	Weight Fraction	Mole Fraction	Lb/Day	Weight Fraction	Lb/Day	Weight Fraction
Methane, CH_4	9.720	0.8445	0.7519	8.840	0.5258	9.770	0.8779
Hydrogen, H_2	0.294	0.0255	0.1816	0.490	0.0292	0.600	0.0539
Carbon dioxide, CO_2	0.270	0.0234	0.0076	2.700	0.1606	0.150	0.0135
Water, H_2O*	0.200	0.0174	0.0137	0.680	0.0404	0.102	0.0092
Nitrogen, N_2	1.000	0.0868	0.0441	4.000	0.2379	0.500	0.0449
Oxygen, O_2	0.020	0.0017	0.0008	0.100	0.0059	0.005	0.0004
Trace contamination	0.005	0.0004	0.0002	0.005	0.0003	0.000	0.0000
TOTAL	11.509			16.815		11.127	

*Saturation at 70 F and 10 psia for minimum performance model and 40 F and 20 psia for maximum performance model and 54 F and 15 psia for the nominal model.

CO_2 input = 27.0 lb/day (12-man crew)

CO_2 reacted = 27.0 x 0.99 = 26.73 lb/day

CO_2 output = 0.27 lb/day

H_2 input $= \frac{8}{44} \times 27 \times (1.05) = 5.154$ lb/day

H_2 reacted $= \frac{8}{44} \times 26.73 = 4.860$

H_2 output = 0.294 lb/day

CH_4 output $= \frac{16}{44} \times 26.73 = 9.720$ lb/day

H_2O output $= \frac{36}{44} \times 26.73 = 21.87$ lb/day

$$N_2 \text{ adsorbed in zeolite bed} = \frac{0.4 \text{ lb } N_2}{100 \text{ lb bed}} \times 35 \text{ lb bed}$$

$$\times\ 15 \frac{\text{cycles}}{\text{day}} = 2.1 \frac{\text{lb}}{\text{day}}$$

Referring to Figure A-8 it is noticed that data scatter at 30 to 40 mm Hg could justify using 1/2 of the value of the drawn curve

2.1 lb/day x 1/2 = 1.05 lb/day

Oxygen in the Sabatier effluent was reported in the 90-day test as 0.006 lb/day.

Scaling to the station on the basis of CO_2 process rate:

$$\frac{27.0}{8.4} \times 0.006 = 0.0193 \text{ lb/day } O_2$$

$$\text{Trace contaminants} = \frac{2 \text{ grams/day}}{453 \text{ gm/lb}} = 0.0044 \text{ lb/day}$$

Variation in the Biowaste Supply

Carbon Dioxide, Hydrogen, Methane

The CO_2 conversion efficiency may vary to a minimum of 90 percent and a maximum of about 99.5 percent (estimated from the literature review included in this report). The H_2 supply for the NR space station could vary from stoichiometric to 10-percent rich. The variation in the product CH_4 is predicted from the reaction equation utilizing the variation in efficiency stated above. For a H_2 input of 5-percent over stoichiometric, there would be 0.734 lb H_2/day at a 90-percent conversion efficiency and 0.274 lb H_2/day at a 99.5-percent conversion efficiency.

Water

The water in the biowaste supply will vary due to the condensing temperature and pressure and the composition of gases in the condenser. The condensing temperature may vary from 40 F to 70 F. The condensing pressure for the station may vary from 10 psia to 20 psia. The gas composition will vary as described in this section. The variation in the water is listed below for several cases.

Variation in Biowaste Water

Gas Composition	Pressure (psia)	Temperature (F)	Biowaste Water
Nominal model	10	70	0.5412
	10	40	0.08778
Min performance	10	70	0.6511
	20	40	0.1056
Max performance	10	70	0.6322
	20	40	0.1024

Nitrogen

The N_2 in the biowaste supply due to adsorption in the zeolite may vary from 0.5 to 4.0 lb/day (based on Figure A-8). The molecular sieve desorption operation is a two-phase operation. In the first desorbing phase, atmospheric gas filling the void volume in the zeolite canister is cycled to the active adsorbing bed and the canister pressure is reduced to one psia.

This low pressure causes partial desorption of air and CO_2 which is recycled with the void gas volume. This ullage and adsorbed air recycling is done to ensure delivery of high-purity CO_2. Air and contaminants will be delivered to the Sabatier subassembly depending on the completeness of this recycling phase. The second phase of desorbing diverts the compressor discharge to the CO_2 accumulator and heat is applied to the zeolite to aid desorption.

Nitrogen can also enter the system by means of inward leakage from the cabin through plumbing fittings and connections where the molecular sieve, Sabatier, or resistojet subsystems are at pressures lower than the cabin. The zeolite bed and the line leading to the compressor is at 1 psia and as such is candidate for leakage. If N_2 leaked into the system equivalent to the cabin partial pressure more than 10 lb/day could result. It is assumed that large leakage rates of N_2 would be considered a failure and repaired and consequently, for purposes of the biowaste model, the N_2 predicted from adsorption in the zeolite should "bound" the N_2 variation.

Oxygen

The O_2 in the biowaste supply will vary from approximately 0.005 to 0.10 lb/day based on Reference 14. The quantity of O_2 in the Sabatier inlet will be limited by application of filters for safety reasons.

Trace Contaminants

The trace contaminants require further study to define meaningful variations. Temporary larger quantities of contaminants may exist as a result of failures.