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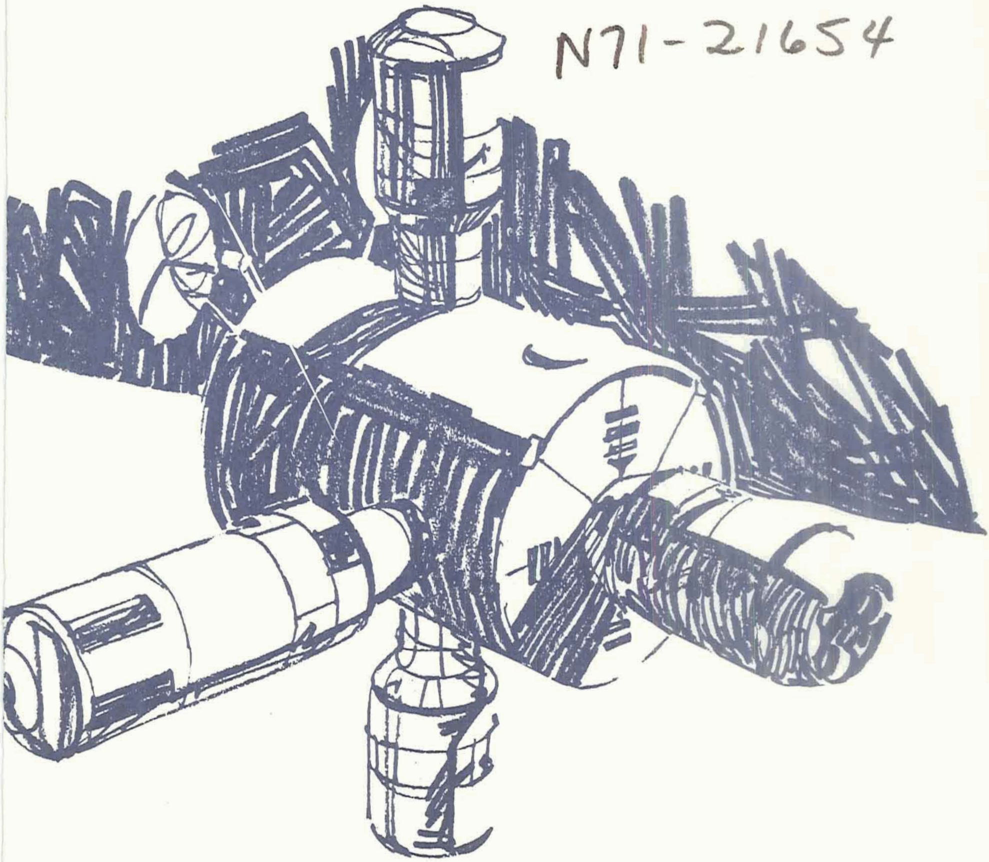

RESISTOJET SYSTEMS STUDIES DIRECTED TO THE SPACE STATION/SPACE BASE

SUMMARY REPORT

CONTRACT NAS1-10127

MCDONNELL DOUGLAS CORPORATION

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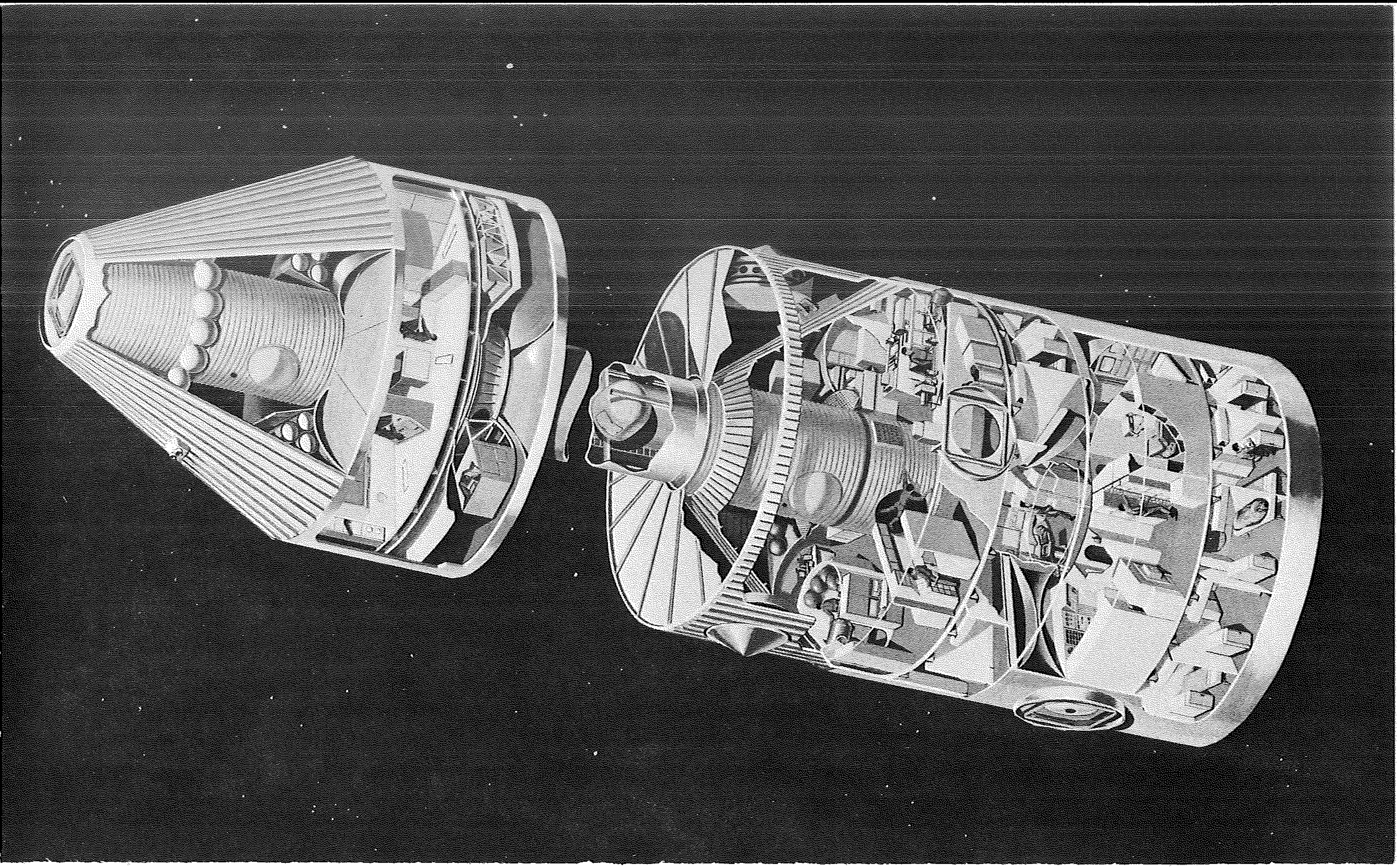

PREFACE

This final report is submitted by McDonnell Douglas Astronautics Company to the National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia, as required by Contract NAS1-10127, Resistojet Systems Studies Directed to the Space Station/Base. The work was conducted under the technical direction of Mr. Earl VanLandingham of the Space Technology Division of Langley Research Center.

The study results are documented in a two-volume final report and a summary report:

I Station/Base Biowaste Resistojet System Design

II Biowaste Resistojet System Development Program

Summary Report

This document summarizes the significant results. Volume I contains the preliminary definition of the resistojet system and the supporting system analysis. Volume II presents the details of the system development program, including system technology identification; a test plan covering components, assemblies, subsystems, and the integrated system; and a resistojet thrustor specification.

Requests for further information concerning this report will be welcomed by the following McDonnell Douglas personnel:

- D. E. Charhut
  Assistant Chief Program Engineer
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- R. V. Greco
  Study Director
  Resistojet Systems Studies

ABSTRACT

The two volumes of this report cover the in-depth evaluation required to develop and demonstrate a prototype biowaste resistojet system and to provide direction for future resistojet system development and qualification programs. The Space Station and Space Base resistojet system definitions generated under NASA Contract NAS8-25140, Space Station Phase B Definition Study, were used as a basis for this program.

This study reviewed, expanded, and finalized the orbit-keeping and control moment gyro (CMG) desaturation requirements for the primary vehicle orientations and applicable altitude ranges. The environmental control/life support (EC/LS) biowaste outputs and the effects of food wetness and cabin leakage on these outputs were evaluated to define the biowaste propellants and the quantities available. The biowaste resistojet performance and power goals, using propellants singly and in combination, were assessed for both contemporary and advanced concepts. The applicable resupplied propellants were compared to identify the supplemental propellant for excessive CMG desaturation requirements, maximum solar density years, and off-nominal crew size. These analyses yielded the data necessary to define the biowaste resistojet system and the thrust level, duty cycle, and operating modes necessary to effectively and efficiently furnish the required propulsive functions and dispose of otherwise useless biowastes.

The resulting system definition includes separate collection and storage of excess EC/LS CO_2 and CH_4. Water (resupplied or from EC/LS excess) was selected as the supplemental propellant. Resistojet thrust level was established at 0.111 N (25 mlb). The thrustors are used in a high-duty-cycle mode (25 to 80 percent). Four modules containing four thrustors each are equally spaced at each end of the Space Station for all-orientation capability. Power distribution and control were selected to permit operation of the resistojets at power levels appropriate for the impulse demands and propellant availability conditions, which vary significantly over the life of the Space Station.

The resistojet system was then evaluated on the assembly and component levels. Candidate methods and techniques for propellant collection and

storage and for power distribution and control were analyzed. A detailed definition of the Space Station resistojet system resulted from these analyses and from consideration of provisions for commonality, evolution, and growth to the Space Base. Similar requirement definition and system design efforts were performed for the Space Base, but to a lesser depth. The detailed system definition was used to identify the required biowaste thrustor and system technology development efforts, and to prepare a resistojet thrustor specification.

Resistojet heat exchanger materials, biowaste resistojet development, water vaporizer development, biowaste compressor development, and system test were identified as areas requiring additional effort. These efforts were incorporated into a system development program that identifies the design, development, and test efforts that are needed at the component, system, and integrated system levels to upgrade system technology status in time to benefit the Space Station Program.

ACKNOWLEDGEMENTS

Technical support in the establishment of resistojet performance goals during this study was furnished under subcontract by Advanced Rocket Technology, of Irvine, California. The Marquardt Corporation, of Van Nuys, California, and TRW Systems, Inc., of Redondo Beach, California, made valuable contributions on a noncontractual basis.

Acknowledgement is also extended to the individuals at MDAC-West who contributed significantly to the results of this study. These persons and their areas of contribution were:

J.T. Abe	Propulsion
J.R. Bliss	Propulsion
J.L. Fowler	Stabilization and Control
W.G. Nelson and I.L. Schaffer	Environmental Control/Life Support
D.L. Wright	Power Distribution and Control
D.L. Endicott	Propellant Collection and Storage
K.E. Meadows	Reliability and Maintainability
L.O. Schulte	Space Station

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UNITS OF MEASUREMENT

Units, abbreviations, and prefixes used in this report correspond to the International System of Units (SI) as prescribed by the Eleventh General Conference on Weights and Measures and presented in NASA Report SP-7012. The basic SI units for length, mass, and time are the meter, kilogram, and second, respectively. Throughout the report, the English equivalents (feet, pounds, and seconds) are presented for convenience.

The SI units, abbreviations, and prefixes most frequently used in this report are summarized below:

	Basic Units	
Length	Meter	m
Mass	Kilogram	kg
Time	Second	sec
Electric current	Ampere	A
Temperature	Degree Kelvin	°K
	Supplementary Units	
Plane angle	Radian	rad
	Derived Units	
Area	Square meter	m^2
Volume	Cubic meter	m^3
Frequency	Hertz	Hz
Density	Kilogram per cubic meter	kg/m^3
Velocity	Meter per second	m/sec
Angular velocity	Radian per second	rad/sec
Acceleration	Meter per second squared	m/sec^2
Angular acceleration	Radian per second squared	rad/sec^2

Force	Newton	N
Pressure	Newton per square meter	N/m^2
Kinematic viscosity	Square meter per second	m^2/sec
Dynamic viscosity	Newton-second per square meter	$N\text{-}sec/m^2$
Work, energy, quantity of heat	Joule	J
Power	Watt	W
Electric charge	Coulomb	C
Voltage, potential difference; electromotive force	Volt	V
Electric field strength	Volt per meter	V/m
Electric resistance	Ohm	Ω
Electric capacitance	Farad	F
Magnetic flux	Weber	Wb
Inductance	Henry	H
Magnetic flux density	Tesla	T
Magnetic field strength	Ampere per meter	A/m
Magnetomotive force	Ampere	A

Prefixes

Factor by which unit is multiplied	Prefix	Symbol
10^6	Mega	M
10^3	Kilo	k
10^{-2}	Centi	c
10^{-3}	Milli	m
10^{-6}	Micro	μ

Section 1
INTRODUCTION

Long-duration manned space flight to perform sophisticated Earth-oriented and inertially stabilized experiments imposes increasingly stringent requirements on stabilization and attitude control (S/AC) systems and propulsion and reaction control systems (P/RCS's). The NASA Space Station Program selected control moment gyros (CMG's) for primary control, and a biowaste resistojet system was chosen for simultaneous orbit-keeping and CMG desaturation.

Selection of the biowaste resistojet system was the result of complex system and integrated system tradeoffs using program and vehicle requirements, program guidelines and constraints, and the conventional cost, weight, power, volume, and crew time criteria. The vehicle requirements affecting biowaste resistojet system selection were:

- To provide near-zero gravity. Manufacturing and bioscience experiments require long periods of vehicle operation at 10^{-5} g or less.

- To minimize external contamination. Earth resource and solar astronomy experiments are extremely sensitive to particulate and molecular species, and also to deposition of propulsive exhaust products on optical surfaces.

- To provide for compatibility and adaptability to future missions and experiments. Although the nominal Space Station altitude and inclination (456 km, or 246 nmi, and 55 deg) are established, capability is required over the altitude range of 371 to 556 km (200 to 300 nmi) and inclinations from polar to equatorial. Future growth to the Space Base and operation in synchronous orbit are also desired with minimum modification. Further, it is desired that the Space Station be compatible with the requirements of as-yet-undefined experiments.

As a result of these vehicle requirements, the following system requirements were established:

- CMG sizing requires that desaturation be performed frequently (about once per orbit).
- Orbit-keeping using high thrust can be deferred to occasions when it will not interfere with near-zero-gravity experiments, or low thrust can be used nearly continuously.
- Provisions must be made for disposal of excess biowastes, which may be either periodically or continuously expelled overboard in a directed manner, or may be collected for return to Earth.
- Propulsion systems selected must have capability for growth to expanded missions.

Based on these requirements, system and system-integration tradeoffs were performed. The conclusions were:

- A biowaste resistojet system can efficiently and effectively provide both CMG desaturation and orbit-keeping using biowaste gases. Biowaste availability on both the Space Station and Space Base is such that the baseline system has excess capability and therefore could provide the required growth without system change.
- CMG desaturation by magnetic torquers or a low-thrust chemical system, orbit-keeping with a high-thrust chemical system, and EC/LS system capability to collect, store, and expel biowaste gases meet the vehicle and system requirements. Chemical propulsion system growth for future missions would require additional impulse capability.
- CMG desaturation and orbit-keeping with a low-thrust chemical system necessitate considerable development effort due to the extremely long engine firing durations required.
- EC/LS collection and storage of biowastes for return to Earth imposes significant design penalties.
- EC/LS collection, storage, and expulsion in a directed manner result in equipment similar to (but simpler than) the biowaste resistojet system.

These conclusions resulted in the selection of the biowaste resistojet system as being the most responsive to vehicle gravity-level and contamination requirements, providing reduced resupply weight, and disposing of otherwise useless biowastes. However, the required in-depth evaluation required for system development was not within the scope of the Space Station Program. It was the intent and objective of the study documented in this report to provide the in-depth evaluation required to develop and demonstrate a prototype biowaste resistojet system, and to provide direction for future resistojet system development and qualification programs.

The scope of the study included three principal efforts:

- Definition of design requirements, operational characteristics, system configuration, and system interfaces for the Space Station and Space Base
- Determination of the commonality and development effort required for use of the Space Station system on the Space Base.
- Identification of necessary resistojet thrustor and system development technology

The system requirements for the study were generated using the NASA Space Station Program baseline vehicles as models. The expanded capability Space Station (Figure 1) is 10 m (33 ft) in diameter and 33.9 m (111 ft) long at launch. It has six habitable decks containing general and crew facilities, and is powered by two 12.5-kwe isotope/Brayton systems. The Station will be manned by a crew of 12 and will have a useful life of 10 years with crew rotation and resupply occurring at 90-day intervals. The Space Base (Figure 2) uses Space Station modules with slight modifications and is assembled in five launches. The Base has 12 artificial-gravity and 12 zero-gravity decks, and can house a crew of 48. The two artificial-gravity spokes are counter-rotated so that net angular momentum is zero. Power is obtained from two nuclear reactors, each rated at 50 kwe.

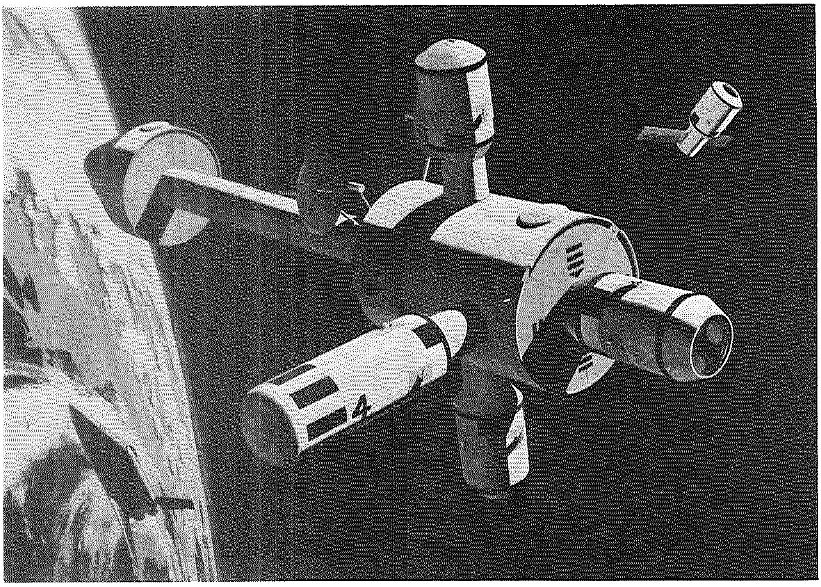

Figure 1. Expanded Capability Space Station

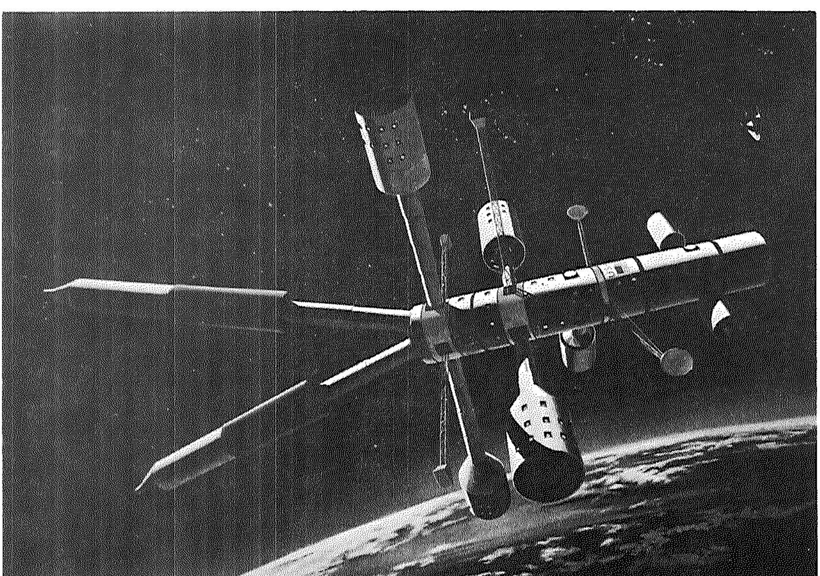

Figure 2. Space Base

Section 2
SYSTEM DESCRIPTION

The design model of the MDAC Space Station resistojet system uses EC/LS-produced biowaste gases (CO_2 and CH_4) as propellants. The gases are used separately, and water is employed as a propellant supplement. The system minimizes resupply requirements, furnishes a useful method of biowaste disposal, minimizes contamination, and permits near-zero acceleration.

The resistojets have a thrust level of 0.111 N (0.025 lb) and are operated in a high-duty-cycle mode (25 to 80 percent) for Space Station orbit-keeping and CMG desaturation. The thrustors are mounted in modules. Four modules are located at each end of the Space Station, and the gas storage tanks are housed in the pressurizable forward compartment. Figure 3 shows the general arrangement.

The major components of the system are compression pumps, heat exchangers, accumulators, propellant tankage, thrustors, and the necessary valves and swtiches for control and checkout. The system weighs 259 kg (570 lb), occupies a volume of 2.78 m^3 (100 ft^3), and requires 100 to 400 W of electrical power.

R45A-1

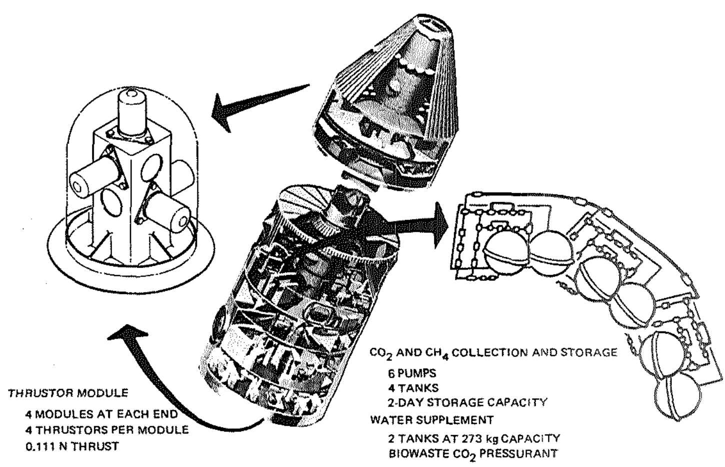

Figure 3. Resistojet System Installation

The biowaste gases may be used, stored, or supplemented with water at all times. This arrangement assures the operational independence of the EC/LS subsystem and the resistojet system while meeting requirements for propellant usage and thrustor duty cycle. At any given time, propellant usage can be determined solely by impulse requirements and operational constraints, and need not be dictated by EC/LS production rate.

The combination of variations in solar activity and in the number of modules attached to the Space Station results in an impulse range of 1,335 to 11,150 N-sec/day (300 to 2,500 lb-sec/day) for a 456-km (246-nmi) orbit. Since the biowaste gases will produce 3,120 to 15,000 N-sec/day (700 to 3,370 lb-sec/day), maximum flexibility is clearly desirable. The capability for this range of impulse is obtained by proper selection of resistojet operating power level. The power distribution and control electronics are located beneath and adjacent to the thrustor modules.

The resistojet thrustor used as a model for the study is the evacuated, concentric, tubular device under development by the Marquardt Company. This concept (Figure 4) consists basically of two functional parts: a resistance-heated gas heat exchanger and a nozzle for accelerating the resultant high-temperature gas to produce thrust. The electrical circuit is through the outer case, nozzle, and inner heating elements. A strut connector serves as the electrical connection between the two main heating elements while allowing gas to flow through the thrustor.

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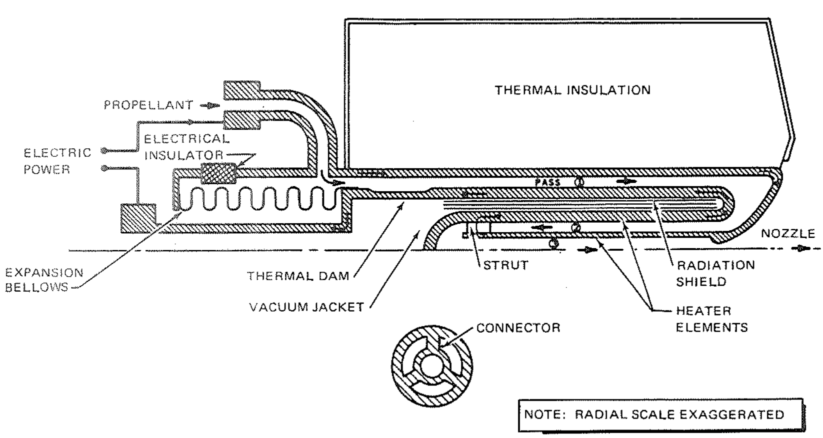

Figure 4. Evacuated Concentric Tube Resistojet Concept

MAJOR ASSEMBLIES

The biowaste resistojet system consists of five primary assemblies: collection and storage, water supplement, flow control, thrustor, and power distribution and control. The relationships among these assemblies and the interfaces with other subsystems are shown schematically in Figure 5.

Collection and Storage Assembly

The collection and storage assembly collects, pumps, and stores the gaseous biowaste outputs from the EC/LS subsystem. Accumulation and storage of the gases is necessary to smooth out EC/LS transients, collect gases when dumping is undesirable, and provide propellant during EC/LS maintenance or when crew size varies from the nominal. However, since the Sabatier outlet pressure is only 1.035×10^5 N/m^2 (15 psia), compression pumping is required for storage in reasonable volumes. The individual gases (CO_2 and CH_4) are compressed to 2.07×10^6 N/m^2 (300 psia) and are stored in accumulators with diameters of 0.76 m (2.5 ft). Four accumulators are used to provide the reliability of dual tanks for each gas.

Figure 6 shows the system and control interface between the EC/LS subsystem and the resistojet collection and storage assembly.

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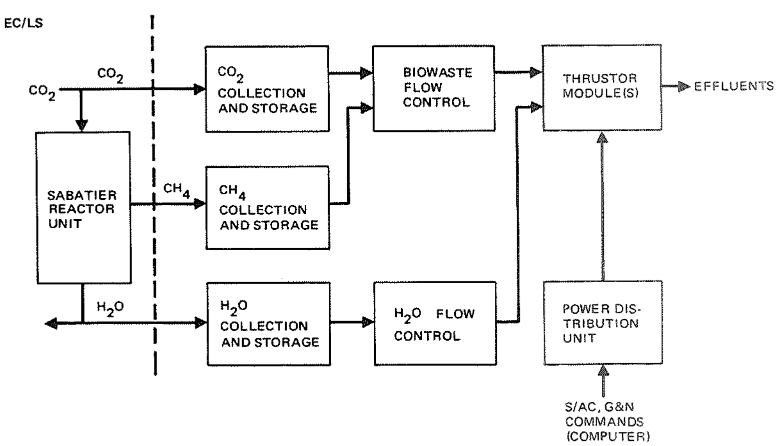


Figure 5. Functional Schematic of Resistojet System

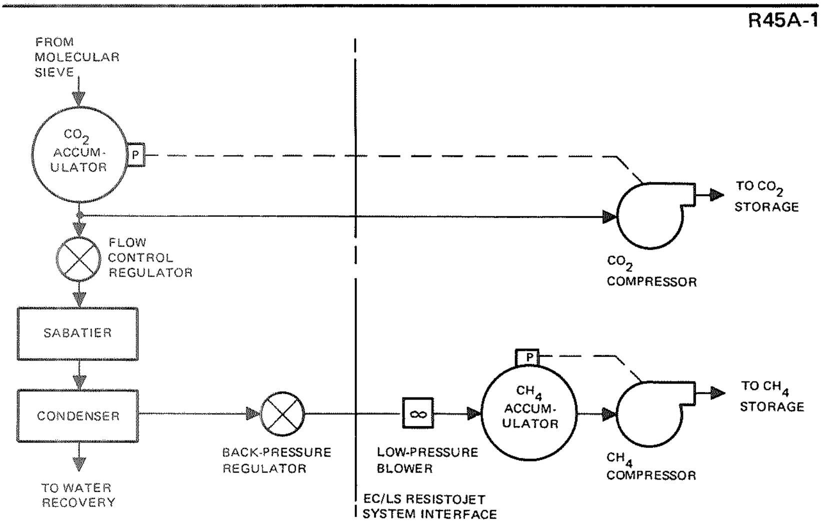


Figure 6. Schematic of Interface Between EC/LS and Resistojet Systems

Water Supplement Assembly

During most of the Space Station's life, the impulse requirements can be easily met with the biowaste gases. When demand exceeds supply, heating of the CO_2 to 1,600°K (2,800°R) will produce additional impulse. For larger impulse increases, a supplemental propellant must be used. [The CH_4 cannot be heated above 1,000°K (1,800°R) or it may dissociate, forming carbon and causing severe deterioration of thrustor performance.] Water was selected for the supplemental propellant because it is easy to resupply, because it is readily compatible with the thrustors, and because excess EC/LS water is readily available.

The water supplement assembly stores the water used for additional impulse during years of peak solar activity. Two tanks are employed for maximum reliability, and crossfeed provisions add flexibility. The tanks include positive expulsion devices. The readily available biowaste CO_2 serves as the pressurant for expulsion.

Flow Control Assembly

The flow control assembly, which regulates and controls propellant flow, is one of the key assemblies in automatic checkout, fault isolation, and maintenance. Its primary function is to furnish a constant supply pressure to the resistojets. All regulators and valves in the assembly are accessible and removable.

Thrustor Assembly

The thrustor assembly consists of eight modules (four at each end of the Space Station) with a total of thirty-two thrustors. It also includes module isolation valves for use during maintenance or repair, and a vaporizer to superheat water prior to injection into the thrustors.

The number and location of the resistojets allow operation in any likely orientation (horizontal, perpendicular to orbit plane, inertial, or attitude trim) with little or no penalty. In addition, this arrangement includes complete redundancy in all operating modes, which permits repairs to be scheduled at convenient times.

Power Distribution and Control Assembly

Thrustor operation is initiated by commands from the power distribution and control assembly. These commands, which are based on data generated by the Space Station guidance, navigation, and control (GNC) subsystem, simultaneously open thrustor valves, set power level, and control the resistojet heater element. The power level fixes heater current, and thus chamber temperature, which determines flow rate and specific impulse.

The power distribution and control assembly has two major functions: providing controlled (variable) power for the thrustor heater and supplying the operating power for propellant storage control and flow control. Variable power for the thrustors is required to match propellant usage to EC/LS biowaste generation, maximize thrustor life, and minimize power consumption. Power level is determined by system operational software, which utilizes GNC gimbal angle and accelerometer data and resistojet system operational status data.

Power distribution and control for the thrustor heaters uses power drawn from the 115-volt ac, three-phase, 1,200-Hz Space Station bus. Conditioning units and step-down transformers supply the power for the thrustor heaters. Distribution and control elements for propellant storage control and flow control operate from both the 115-volt ac, three-phase bus and the 28-volt dc bus. The CH_4 and CO_2 compression pumps use the three-phase ac source.

MAJOR TRADES

Although the Space Station Phase B study identified the resistojet system concept and its principal assemblies, several additional trade studies were needed to implement the selected concepts in the design shown in Figure 2-2 of Volume I. These major trade studies included supplemental propellant selection, water vaporizer location, propellant usage modes, compressor concept selection, and power conditioning mechanization.

Supplemental Propellant Selection

The combination of multiple attached experiment modules, various orientations, and low altitudes, together with variable solar activity, may result in impulse requirements exceeding the biowaste capability. Supplemental propellant is required to ensure proper Space Station operation and to provide adequate operational flexibility. The principal candidate methods for providing this added impulse are use of water or ammonia as supplemental propellant in the low-thrust system, and provision of additional propellant capacity in the high-thrust system.

The results of the trade study show that either the water or the high-thrust approach could be used, but that ammonia creates excessive design and operational penalties. Water was selected as the better alternative because it furnishes a useful means of disposing of excess EC/LS water and because it meets the Space Station acceleration level requirements without imposing operational constraints.

Water Vaporizer Location

Use of the concentric tube resistojet depicted in Figure 4 requires that propellants be injected as gases, not liquids. Therefore, some form of pre-injection vaporization (or liquid flow control) is required for the supplementary propellant. Portions of the feed system must therefore be compatible with steam. The nominal resistojet chamber pressure is between 2.76×10^5 and 3.45×10^5 N/m^2 (40 to 50 psia). After allowing for pressure drops, thermal losses, and a reasonable superheat margin, the feed system and valve must be capable of handling steam at 450°K (810°R).

Candidate approaches ranged from a centralized system vaporizer to an integral vaporizer incorporated into a resistojet. The centralized vaporizer was discarded due to the complexity, weight, and other adverse factors involved in providing a steam-fed system. The remaining candidate approaches and the criteria employed for their evaluation are shown in Figure 7.

The vaporizer approach selected consists of one common vaporizer per thrustor module and a common valve for thrustor inlet flow control of CO_2, CH_4, and steam. The design implications, development tasks, and thrustor sequencing for this approach are shown in Figure 8. This approach is the most desirable because it minimizes weight, volume, and interfaces, and because it involves less trapped water and simpler sequencing than separate vaporizer concepts. However, it does require a valve capable of withstanding steam at 450°K (810°R), lines sufficiently insulated to minimize thermal losses, and preheating of the feed lines.

Propellant Usage Mode

Variable propellant availability, potential methane dissociation, and the wide range of impulse requirements, all coupled with nearly uniform gas generation, make flow control mechanization considerably more difficult than for more conventional propulsion systems. The most serious of these factors is the methane dissociation potential, which dictates mixture ratio control if the propellants are mixed. System flexibility is maximized, system maintenance is simplified, and propellant management is facilitated when there is only one propellant feed line per thrustor module; however, analysis showed that no benefit could be derived for the Space Station from propellant mixing, and that optimum performance is obtained by separate use of each propellant.

The selected flow control design concept is shown in Figure 2-2 of Volume II. This concept uses a regulator to control and maintain feed system and resistojet inlet pressure at 3.45×10^6 N/m^2 (50 psia). Maintaining a constant inlet pressure results in a nearly constant resistojet thrust level, regardless of resistojet chamber temperature (performance level), with the resistojet nozzle throat determining propellant flow rate.

Compressor Concept Selection

The requirement to compress the EC/LS gases for efficient storage was established as part of the baseline resistojet system design concept. However,

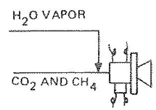
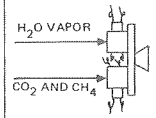
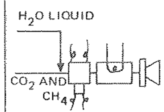
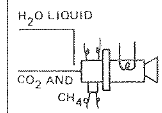
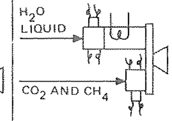
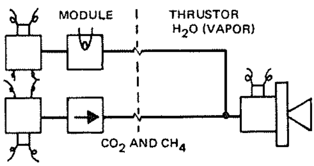
CRITERIA		CANDIDATE 1 COMMON VAPORIZER COMMON VALVE	CANDIDATE 2 COMMON VAPORIZER COMMON VALVE	CANDIDATE 3 SEPARATE VAPORIZER COMMON VALVE	CANDIDATE 4 INTEGRATED VAPORIZER COMMON VALVE	CANDIDATE 5 SEPARATE VAPORIZER SEPARATE VALVES
THRUSTOR SCHEMATIC						
WIRES ACROSS THRUSTOR - MODULE INTERFACE		VALVE (1)–6 RESISTOJET–7 13	VALVES (2)–10 RESISTOJET–7 17	VALVE (1)–6 RESISTOJET–7 16 VAPORIZER–3	VALVE (1)–6 RESISTOJET–7 13 VAPORIZER–0	VALVES (2)–10 RESISTOJET–7 20 VAPORIZER–3
MECHANICAL INTERFACE		ONE LINE, TWO MEDIA CO_2 AND CH_4 STEAM	TWO LINES, TWO MEDIA CO_2 AND CH_4 STEAM	ONE LINE, TWO MEDIA CO_2 AND CH_4 WATER	ONE LINE, TWO MEDIA CO_2 AND CH_4 WATER	TWO LINES, TWO MEDIA CO_2 AND CH_4 WATER
DESIGN	MODULE WEIGHT	2.35 kg	2.65 kg	2.8 kg	2.3 kg	3.1 kg
	COMPONENT VOLUME	$1.7 \times 10^{-3} m^3$	$1.75 \times 10^{-3} m^3$	$1.9 \times 10^{-3} m^3$	$1.7 \times 10^{-3} m^3$	$1.95 \times 10^{-3} m^3$
	INLET VALVE	450°K MEDIA TEMPERATURE–LIQUID AND GAS FLOW THROUGH SAME PATH	450°K MEDIA TEMPERATURE–SEPARATE MEDIA FLOW	LIQUID AND GAS FLOW THROUGH SAME PATH	LIQUID AND GAS FLOW THROUGH SAME PATH	SEPARATE MEDIA FLOW
	VAPORIZER	COMMON FOR MODULE	COMMON FOR MODULE	FOUR PER MODULE	FOUR PER MODULE	FOUR PER MODULE
	INSULATION	KEEP FEED LINES AT 450°K DURING FLOW	SAME AS CANDIDATE 1–WATER ONLY	KEEP WATER FROM FREEZING	SAME AS CANDIDATE 3	SAME AS CANDIDATE 3
DEVELOPMENT		START TRANSIENT (ALL PROPELLANTS) • VAPORIZER CAPACITY • CONDENSATE SEQUENCING AND TIMING	START TRANSIENT (H_2O ONLY) SAME AS CANDIDATE 1	START TRANSIENT (ALL PROPELLANTS) • VAPORIZER CAPACITY • TRAPPED LIQUID SEQUENCING AND TIMING	SAME AS CANDIDATE 3	START TRANSIENT (H_2O ONLY) SAME AS CANDIDATE 3
OVERALL EVALUATION		SELECTED CONCEPT				BACKUP CONCEPT

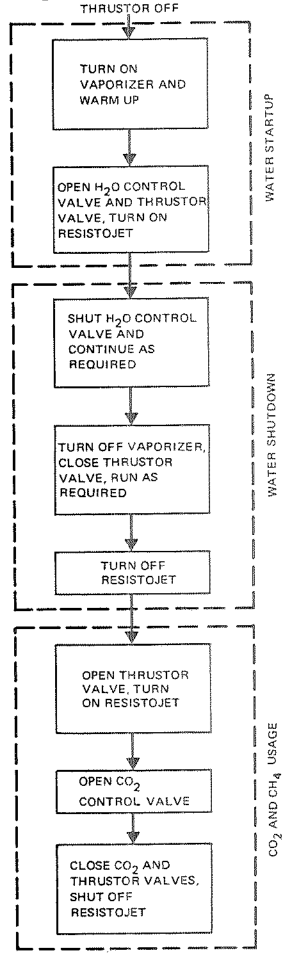
Figure 7. Vaporizer Selection Summary

COMMON VAPORIZER, COMMON VALVE



THRUSTOR USAGE
(SEE SEQUENCE DIAGRAM)

THRUSTOR SEQUENCE DIAGRAM
H_2O FOLLOWED BY CO_2 OR CH_4



DESIGN IMPLICATIONS

- VAPORIZER CAN HANDLE STARTUP (TWO THRUSTORS)
- VAPORIZER OPERATION THERMOSTATICALLY CONTROLLED
- VALVE-MEDIA COMPATIBILITY
- LINE HEATERS FOR START TRANSIENT (H_2O)

DEVELOPMENT TASKS (SYSTEM)

- VAPORIZER WARMUP TIME
- TIMING BETWEEN OPERATIONS
- SEQUENCE VERIFICATION
- MAGNITUDE OF CONDENSATE PROBLEM, INCLUDING ENTRAINMENT FROM ADJACENT THRUSTORS

  AMOUNT

  EFFECT

NOTE:

MAY BE NECESSARY TO INCORPORATE INDIVIDUAL CHECK VALVES AND/OR CLEAR ALL LINES AFTER USE

Figure 8. Vaporizer Concept Design Factors

EC/LS differences between the CO_2 and CH_4 interface characteristics require sophisticated mechanization. In summary, these differences are:

Gas	Pressure	Availability
CO_2	2.15 to 2.8 X 10^5 N/m^2 (31 to 42 psia)	Intermittent – controlled from EC/LS accumulator
CH_4	1.07 X 10^5 N/m^2 (15.5 psia)	Continuous – no EC/LS accumulator

Three important design factors were considered in selecting a collection concept: CO_2-CH_4 commonality, practicality of flow capacity concept, and cooling (compression heat). Basically, it is difficult to scale pumps to these flow rates, provide a 20:1 compression ratio without multiple stages or cooling, and produce the commonality needed to minimize development cost and simplify maintenance and spares requirements.

The selected design concept achieves these results by including a blower (2.7:1 compression ratio) and accumulator in the CH_4 line. The blower is operated continuously to keep the accumulator filled. This allows identical, high-ratio (10:1) compressors to be used for both propellants. Intermittent compressor operation permits efficient design (10-percent duty cycle for increased life) and eliminates the need for multiple stages.

Having established the design concept, a survey was undertaken to determine what current compressor concepts met the system requirements. The results showed that a rotary vane compressor could be used for the low-pressure-ratio blower and that a piston compressor would meet the high-pressure-ratio requirements. Table 1 summarizes the characteristics of the two compressors. Both concepts are within the state of the art, but development will be required. In particular, the rotary vane concept must be adapted for space use (this type is currently used for auto smog control pumps), and the piston compressor requires design and development effort to establish bore, stroke, and cycle rate (pump efficiency) and to define piston lubrication (pressure and temperature should be low enough for dry lubrication).

Power Conditioning Mechanization

The resistojet power distribution and control assembly provides power and power conditioning for the thrustor heater, the propellant storage assembly,

Table 1
COMPRESSOR CHARACTERISTICS

Design Requirement	Propellant	
	CH_4	CO_2
Low-pressure blower		Not required
Inlet pressure	1.07×10^5 N/m^2	
Capacity	0.305×10^{-2} m^3/min	
Compression ratio	2.7:1	
Power	0.013 horsepower	
Efficiency	60 percent	
Duty cycle	Continuous	
Outlet pressure	2.15 to 2.8×10^5 N/m^2	
Reservoir		
Size	0.167 m^3 (resistojet system)	0.39 m^3 (EC/LS equipment)
High-pressure compressor		
Inlet pressure	2.15 to 2.8×10^5 N/m^2	Same
Capacity	1.39×10^{-2} m^3/min	Same
Power	0.35 horsepower	Same
Efficiency	70 percent	Same
Compression ratio	10:1	Same
Run time	2.7 min per 30 min	7.0 min per 136 min
Duty cycle	10 percent	5 percent
Outlet pressure	0.69 to 2.76×10^6 N/m^2	Same
Speed	200 cycles/min	Same

and propellant flow control. Assembly design was based on normal system operation, in which thrustors fire in pairs and a maximum of four thrustors operate simultaneously. However, the maximum number of thrustors operating at one time in one module was restricted to two. The assembly design, furthermore, was required to include features necessary for resistojet operation at varying power levels (resistojet performance levels).

The approach selected for thrustor heater operation (Figure 9) draws power from the high-efficiency, 115-volt ac Space Station power bus. Current regulators are located beneath and adjacent to each thrustor module, and step-down transformers are located at each thrustor. This approach, although somewhat heavier than use of a centralized dc inverter with transformers at each thrustor, provides optimum thrustor operation with different (selected) propellants, overall improvement in system efficiency, longer potential lifetimes for thrustor heaters, better reliability, and modular maintainability.

Power distribution and control elements for propellant storage and propellant flow control draw power from both the 115-volt ac, three-phase and 28-volt dc buses. Direct-current solenoid and bistable actuator valves were selected over ac types on the basis of size, weight, power, efficiency, and wiring complexity. The CH_4 and CO_2 compression pumps use the three-phase ac source to minimize weight and simplify wiring installation.

SYSTEM OPERATION

The overall operation of the resistojet system consists of two primary functions: propellant collection and propellant usage. Propellant collection has previously been described. Propellant usage operation and control encompass the three major areas shown in Figure 10.

Thrustor Selection

The P/RCS thrustor arrangement provides at least two (and usually more) different potential thrustor combinations for each operating mode and each orientation. The S/AC subsystem logic determines thrustor pairings based on orientation, but additional logic is required to select the actual thrustors to be used. Two primary sets of thrustors and one secondary (backup) set are available for each operating mode (orbit-keeping, dump, etc.). If there are no inhibits due to malfunctions, the set with the least total firing time is used. A schematic of the selection process is shown in Figure 11.

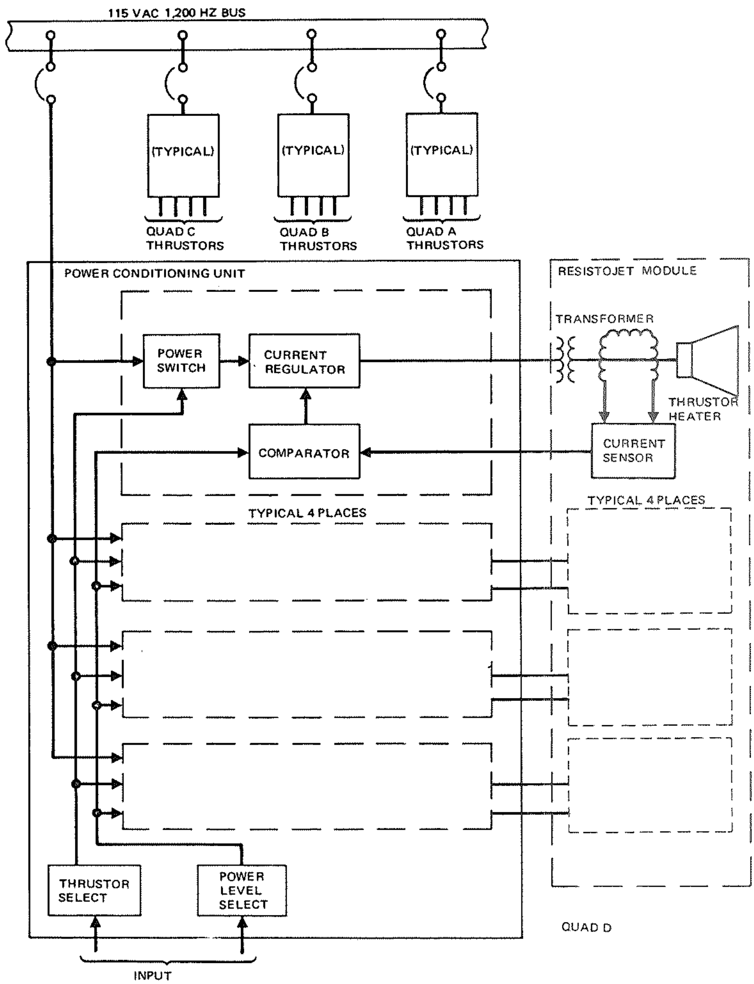


Figure 9. Resistojet Power Control Block Diagram

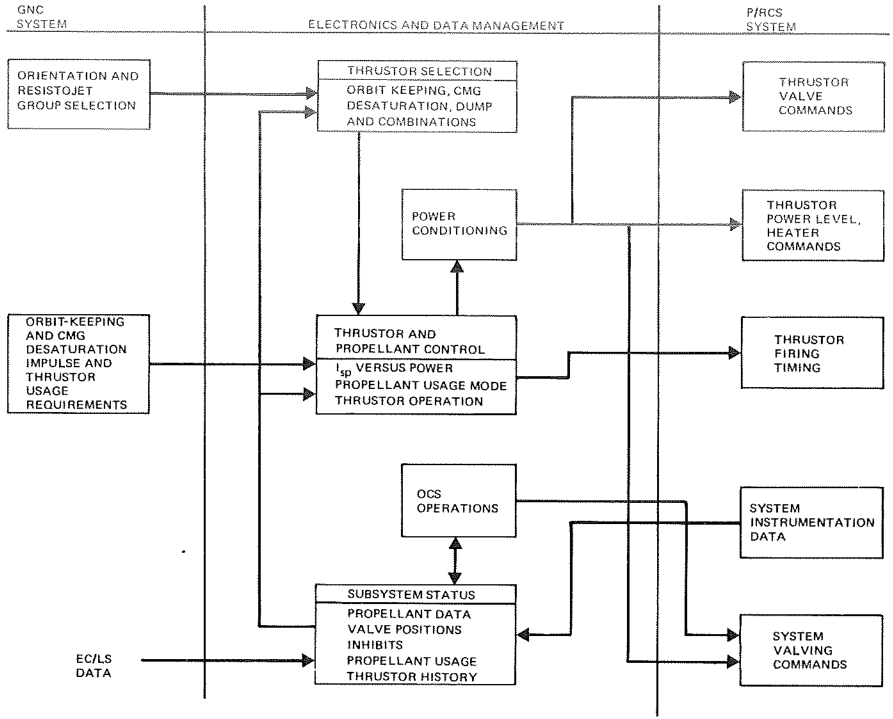


Figure 10. Biowaste Resistojet Operation and Control

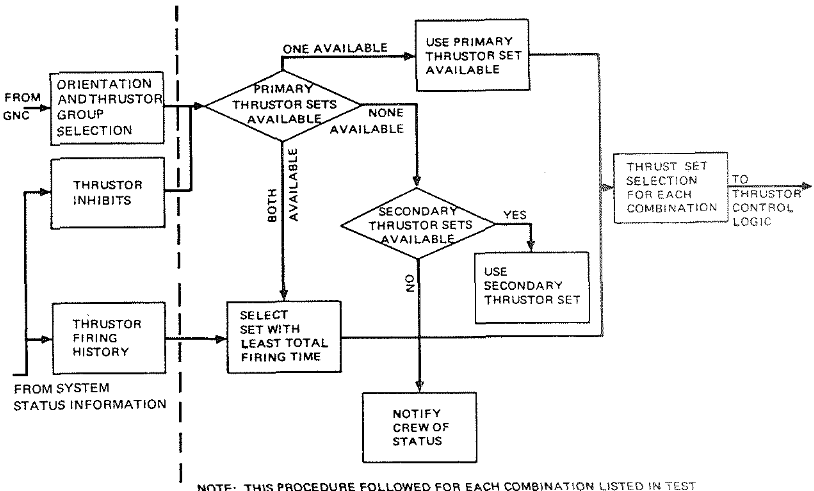


Figure 11. Thrustor Selection Logic

Subsystem Status

Normal system operation is fully automatic and requires crew participation only for periodic status checks and equipment checkout, and possibly for trend analysis (most trend analysis is done automatically or by ground personnel). Included in the automatic operating mode are fault detection, isolation, switching, and crew warning for the components and assemblies listed in Table 2.

Operational status checks and trend analysis occur once a day or less for the purposes of determining system status, verifying performance, and revealing potential problems. Components and instrumentation involved are:

- Positions of all valves
- Pump speed
- High- and low-pressure manifold pressures
- Storage tank pressures and temperatures
- Propellant usage history
- Thrustor usage history
- Thrustor power consumption
- Vaporizer usage
- Status of electronics

Table 2
FAULT DETECTION AND ISOLATION

Component or Assembly	Fault	Action or Procedure (Automatic)
Pump	Excessively high or low pump speed	Turn off pump and isolate by closing appropriate valves.
Pump	Out-of-limit interstage temperature	Same
Storage bottle and high-pressure manifold	Excessive pressure	Vent gas(es) through relief assembly.
Regulator	Out-of-tolerance regulation	Switch to alternate regulator and isolate by closing appropriate valves.
Flow control valve	Failure closed or open	Switch to alternate feed system and isolate by closing cross-feed valves.
Thrustor	Heating element malfunction	Switch to alternate thrustors.
Thrustor	Out-of-tolerance power consumption	Same
Thrustor	Inlet valve will not close	Switch to alternate thrustors and isolate module.
Fittings	Leakage	Determine source and isolate, switch to alternate assembly.
Power distribution and control assembly	--	Further design is required to identify failure modes. Switching to a redundant assembly would be the first step.
H_2O vaporizer	Out-of-tolerance heat input	Switch to alternate vaporizer. Turn off heaters and close isolation valves (possibly vent for pressure release).
H_2O storage bottles	Out-of-tolerance pressure	Switch to alternate tank and isolate.

Thrustor and Propellant Control

Updates of impulse requirements occur once per orbit. At this time, it is necessary to review these requirements and the system status, and to generate control commands for the next orbit. Figure 12 shows the logic used to update the system and determine these commands. The logic is also shown for incorporating the water supplement assembly and mixed-propellant provisions. Both these options significantly affect system operating (software) logic.

INSTRUMENTATION

Instrumentation included in the resistojet system provides for the generation and distribution of system performance parameters and equipment status information for control and operation. Signals from the instrumentation sensors furnish inputs for system control (through the data management subsystem multiprocessor) for checkout, fault isolation, and replacement, and for engineering data retrieval through the onboard display system, onboard data storage, and ground communication link. The sensors are of the analog and discrete event types. Parameters to be monitored and their quantity are summarized in Table 3.

EFFECTIVENESS ANALYSIS

A reliability, maintainability, and fault isolation analysis of the resistojet system indicates that the design is easily maintained and highly reliable (better than 99.99 percent probability of mission success with maintenance and repair on orbit). Further, the design concept facilitates fault isolation and repair through a high degree of accessibility and use of interchangeable equipment.

The results of the mission success reliability analysis are shown in Table 4.

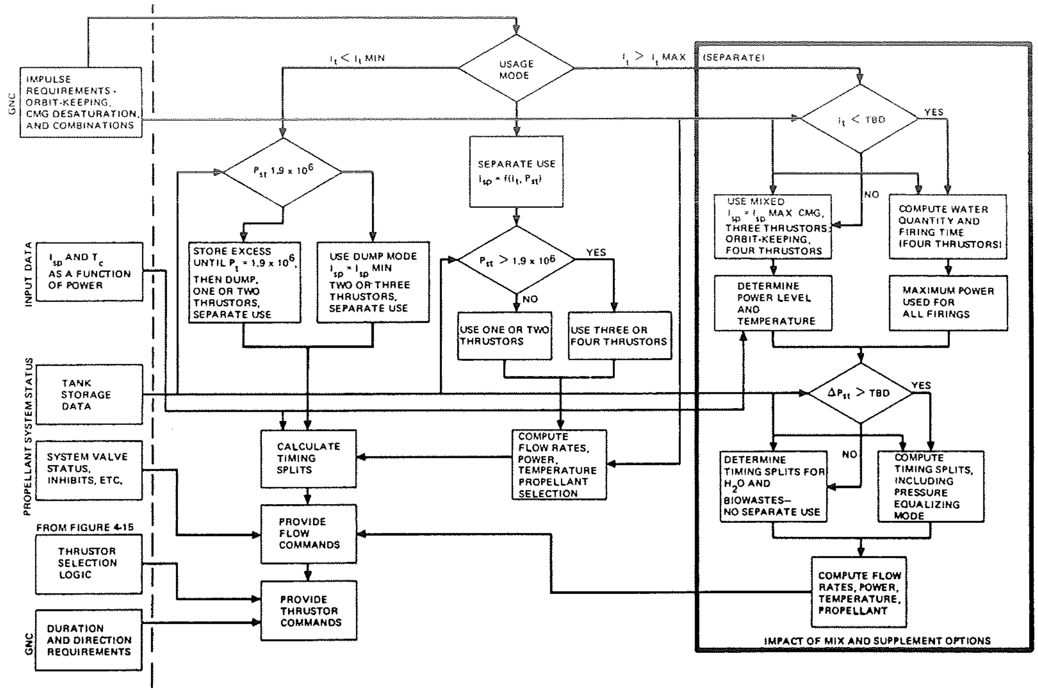


Figure 12. Thrustor and Propellant Control Logic

Table 3
INSTRUMENTATION SUMMARY

Parameter	Quantity
CO_2 and CH_4	
Pressure	20
Temperature	14
Speed	16
Position	58
Current	32
Voltage	32
Power conditioning unit operation	16
Total	188
Additional Requirements for Water Usage	
Pressure	2
Temperature	10
Quantity	2
Position	13
Vaporizer operation	8
Total	35

Table 4
RESISTOJET SYSTEM RELIABILITY SUMMARY

Configuration	Probability of Mission Success
System	0.999975
System without H_2O equipment	0.999943
Propellant handling equipment only	0.999994
Propellant handling less H_2O equipment	0.999968
CO_2 propellant handling equipment only	0.994550
CH_4 propellant handling equipment only	0.994101
Power distribution and control equipment	0.999990

Section 3
SYSTEM DESIGN REQUIREMENTS

The resistojet system was designed on the basis of requirements resulting from a detailed evaluation of propellant availability, propellant performance goals, and impulse requirements and control mechanization.

PROPELLANT AVAILABILITY

As a part of the Space Station Program, the degree of EC/LS closure was established on the basis of system and integrated system analyses. The closed water, partially closed oxygen subsystem shown in Figure 13 meets the Space Station requirements, reduces resupply needs, and provides the biowastes for use by the resistojet system.

The EC/LS design concept consists of three complete, interconnected subsystems, one in each of the three major compartments of the expanded capability Space Station. Each subsystem is capable of supporting the entire 12-man crew. This arrangement provides redundancy for crew safety and permits continued Space Station operation in the event of a subsystem failure.

Wash water condensate and urine are collected by the EC/LS subsystem for purification and electrolysis (partial oxygen replenishment) and storage (potable water supply). Additional oxygen is recovered through use of a Sabatier reactor.

Carbon dioxide is collected and directed to the Sabatier reactor, along with hydrogen from the electrolysis cell. Ideally, CH_4 and water are produced. However, since there is insufficient H_2 to react all of the CO_2, a mixture of CO_2 and CH_4 is available for use as biowaste propellant.

Without adding system complexity, excess CO_2 can be collected from the output accumulator of the CO_2 molecular sieve, and a predominantly methane propellant can be collected from the Sabatier outlet. This is the selected method. The water obtained from the Sabatier outlet is stored for onboard usage. Any excess is available for use as resistojet propellant.

The Space Station EC/LS biowaste outputs for the system described above, with a 12-man crew and with an atmosphere leakage rate of 0.91 kg/day

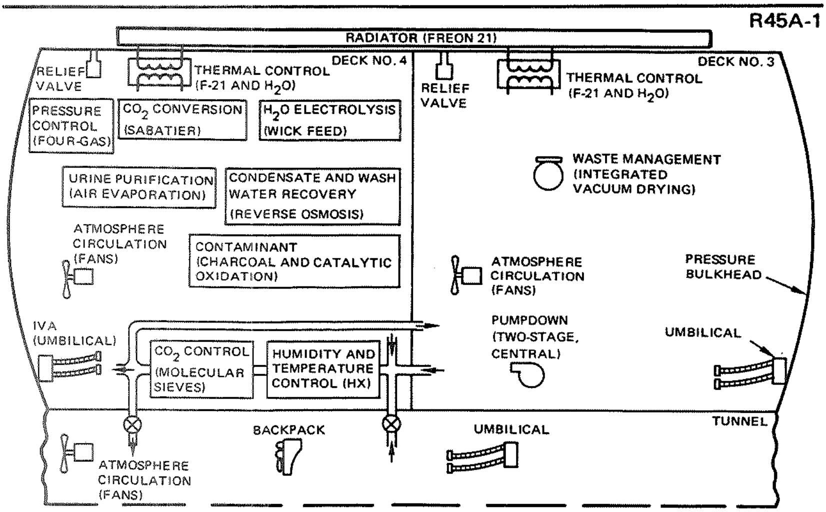


Figure 13. Baseline EC/LS Subsystem (Closed Water, Partially Closed Oxygen)

(2 lb/day), are shown in Table 5. The values indicated are for the independent collection of CO_2 and CH_4 propellants and are based on 3- to 5-percent CO_2-rich operation of the Sabatier reactor to assure full reaction of all H_2. Table 5 also shows the constituents of the biowaste gases available for resistojet usage. Water was included, since excess could be available.

Figure 5 shows a schematic of the interface between each of the EC/LS subsystems and the biowaste resistojet system. Separate CO_2 and CH_4 collection was assumed. The interface pressures to be maintained are:

- CO_2 – 2.15×10^5 to 2.8×10^3 N/m^2 (31 to 42 psia)
- CH_4 – $1.07 \times 10^5 \pm 3.44 \times 10^3$ N/m^2 (15.5 ±0.5 psia)

The interface is controlled by the EC/LS subsystem to prevent resistojet system malfunctions from affecting EC/LS operation.

The effects of food wetness and cabin leakage on the biowaste outputs were evaluated. It was found that, since the crew's total water intake is constant, an increase in food wetness will decrease drinking water consumption and provide a corresponding increase in excess water.

Space Station leakage was evaluated over a range of 0 to 9.1 kg/day (0 to 20 lb/day). The results are shown in Figure 14. Within this range, the constituent allocation was found to be essentially linear. The biowaste variation in

Table 5
SPACE STATION EC/LS BIOWASTE OUTPUTS

Average Leakage Rate of 0.91 kg/day (2 lb/day)

Biowastes	Biowaste Constituent, kg/day (lb/day)					Total Biowaste, kg/day (lb/day)
	CH_4	CO_2	N_2	O_2	H_2O	
CO_2	0	4.94 (10.85)	0.04 (0.08)	0.01 (0.03)	0	4.99 (10.96)
CH_4	2.67 (5.88)	0.24 (0.53)	0.06 (0.14)	0	0.05 (0.11)	3.04 (6.66)
H_2O	0	0	0	0	0.29 (0.63)	0.29 (0.63)

leakage rate is attributable to more complete reaction of the available CO_2 in order to replenish atmospheric O_2. Thus, more CH_4 and less CO_2 are available with increasing leakage rate. Water is affected in that more H_2 is required to reduce CO_2, and O_2 is required for direct makeup. The resulting effect of increased atmospheric leakage is a reduction of impulse availability.

PROPELLANT PERFORMANCE GOALS

The evaluation of propellant performance goals consisted of two major tasks: determination of resistojet performance and power goals (supported by Advanced Rocket Technology, a funded subcontractor) and an investigation of practical resistojet operating modes to match the varying system impulse requirements to the highest degree possible. The performance and power goals for biowaste propellants and mixtures of biowaste propellants were determined as a function of chamber temperature and thrust level, with consideration of the maximum operating limits resulting from material and fabrication technique limitations and the formation of contaminating effluents.

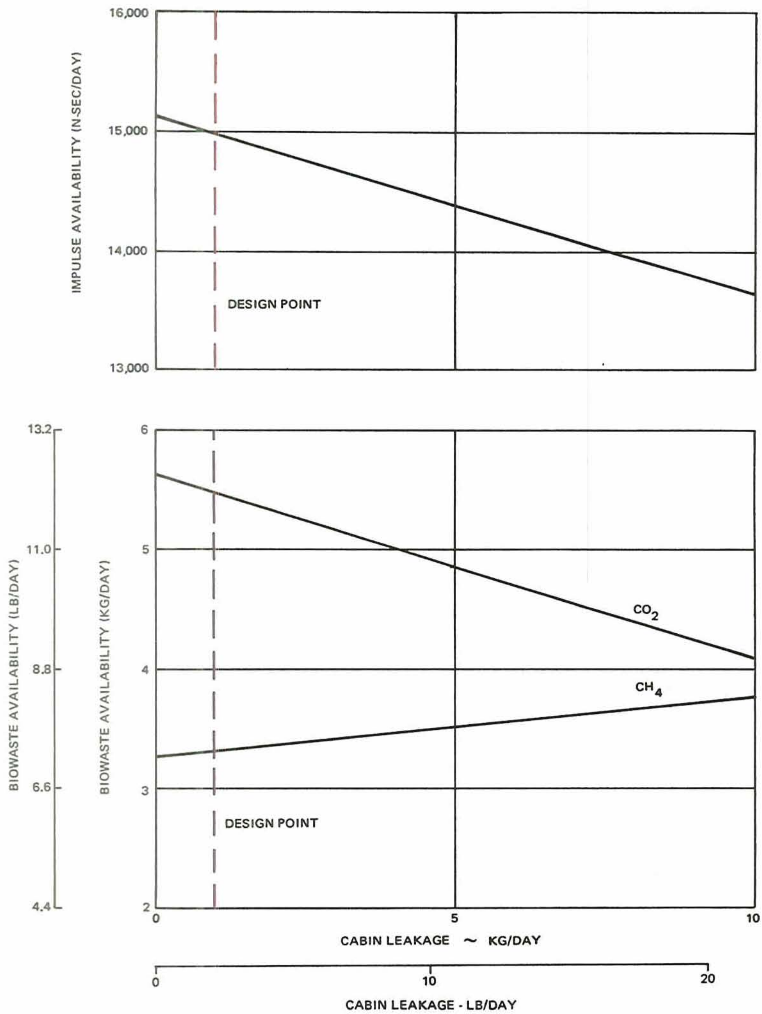


Figure 14. Atmosphere Leakage Effect on Biowaste and Impulse Activity

Resistojets designed for maximum performance with CO_2, CH_4, and H_2O must incorporate features and materials different from those previously developed and proven for NH_3 and H_2. These differences result from the additional requirements to avoid interactions with heat exchanger surfaces (either carbon deposition or chemical attack) and to design for frozen flow throughout the thrustor.

The propellants and propellant combinations considered, and their EC/LS sources, are listed in Table 6. The independent propellants (CH_4, CO_2, H_2O) were evaluated to ascertain their performance goals, and a mixture of CO_2 and CH_4, as available from the Sabatier outlet, was evaluated to determine if system benefits could be derived with a single collection source. The additional H_2O-CH_4 and CO_2-CH_4 mixtures were evaluated to determine whether mixing of propellants would permit an increase in CH_4 resistojet chamber temperature.

The major areas of the evaluation were ideal performance, heater performance (including pressure loss and chemical kinetic effects), nozzle efficiency (including kinetic effects), and application of the nonadiabatic and nonideal flow loss factors present in actual resistojet designs. Evaluation of flow and heat transfer variables was based on a model consisting of a self-heated, direct-contact tube exchanger followed by a conventional expansion nozzle. For the flow rates considered, the flow was laminar throughout. The specific performance goals for 0.111-N (0.025-lb) thrustors individually designed for each of the propellants are summarized in Table 7.

Operation modes were analyzed on the basis of the parametric performance data generated. The following conclusions were reached:

- Propellants should be used separately (at least with contemporary thrustors).
- Performance is not a function of thrust level for the Space Station thrust range considered.
- Variable power (chamber temperature) is an efficient means of matching resistojet performance to impulse requirements and substantially reducing power usage.

IMPULSE REQUIREMENTS AND CONTROL MECHANIZATION

The impulse requirements for the resistojet system were derived on the assumptions that primary attitude control is provided by the Space Station

Table 6
PROPELLANT CANDIDATES

Propellant	Source	Composition		
		Species	Mole Fraction	Mass Fraction
CO_2	Molecular sieve waste output (scrubbed from spacecraft atmosphere)	CO_2	0.984	0.989
		N_2	0.012	0.008
		O_2	0.004	0.003
CH_4	Sabatier waste output	CH_4	0.917	0.832
		CO_2	0.054	0.133
		N_2	0.014	0.020
		H_2O	0.015	0.015
CO_2 and CH_4	Combined outputs	CO_2	0.405	0.647
		CH_4	0.572	0.333
		N_2	0.012	0.012
		O_2	0.001	0.002
		H_2O	0.010	0.006
H_2O	Water recovery	H_2O	1.000	1.000
CO_2 and CH_4	Combined outputs in stoichiometric ratio of nominal propellants	CH_4	0.488	0.262
		CO_2	0.488	0.720
		N_2	0.012	0.011
		O_2	0.004	0.002
		H_2O	0.008	0.005
H_2O and CH_4	Combined outputs in stoichiometric ratio of nominal propellants	CH_4	0.483	0.434
		CO_2	0.028	0.069
		N_2	0.007	0.010
		H_2O	0.483	0.487

Table 7
SPACE STATION (CONTEMPORARY) RESISTOJET DESIGN GOALS
Supply pressure = 3.039×10^5 N/m^2 (3 atmospheres)
F_{design} = 0.111 N (25 mlb)

Factor	Propellant CO_2	CH_4	CO_2 and CH_4 (MR = 2:1)	H_2O	CO_2 and CH_4 (MR = 2.75:1)	H_2O and CH_4 (MR = 1.1:1)
$\dot{m}$,g/sec	0.0647	0.0520	0.0653	0.0462	0.0685	0.0552
I_{sp}, sec	175.3	218.2	173.7	245.4	165.5	205.4
P_e, w	127.5	119.7	94.6	153.2	91.0	94.2
A^*_{geo},m^2	1.96×10^{-7}	1.95×10^{-7}	1.95×10^{-7}	2.17×10^{-7}	1.96×10^{-7}	2.03×10^{-7}
T,°K	1,600	1,000	1,000	1,600	1,000	1,000

CMG's and that the two functions provided by the resistojet are orbit-keeping and CMG desaturation. The impulse requirement variations over the 10-year life of the Space Station were established for the orbit altitude range of 371 km (200 nmi) to 556 km (300 nmi) for the horizontal, perpendicular-to-orbit-plane (POP), and inertial orientations shown in Figure 15. The Jacchia 1964 model atmosphere was used in determination of impulse requirements.

The variation of orbit-keeping impulse requirements with orbit altitude is shown for the primary vehicle orientations in Figure 16. At the nominal design point, the impulse required [8,900 N-sec/day (2,000 lb-sec/day)] is within the availability of the biowaste gases. At the lower altitudes, the increasing impulse requirements necessitate the use of a supplemental propellant.

It should be noted that there is a power limit for the system. Tentatively established at 500 W average, this limit restricts the system capability to 22,300 N-sec/day (5,000 lb-sec/day). This figure also indicates that, for the higher orbits, the system has excess impulse capability and should be operated in a dump mode at cold flow conditions to maximize biowaste usage and minimize system power consumption.

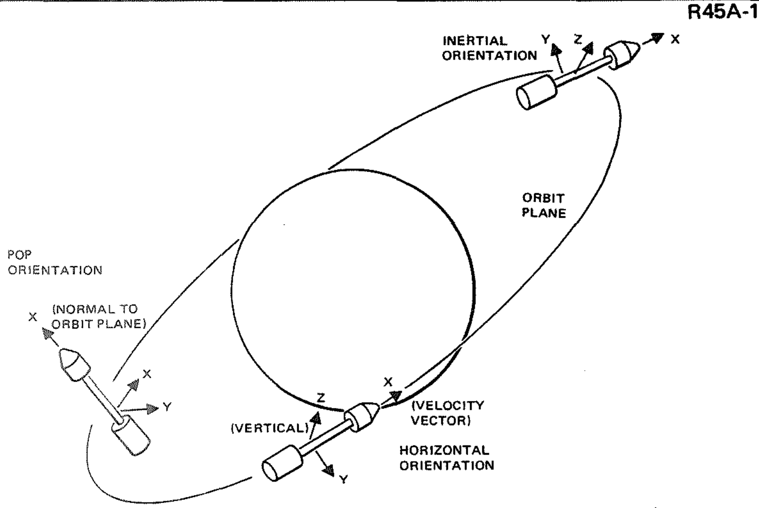


Figure 15. Space Station Orientations

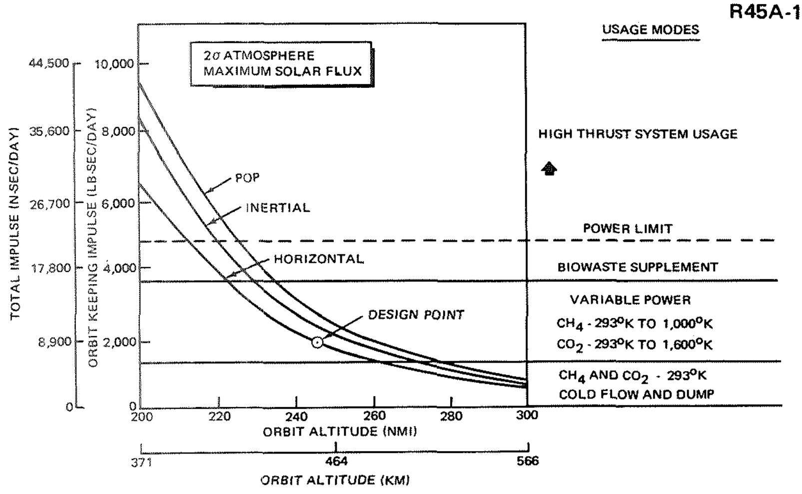


Figure 16. Space Station Orbit-Keeping Requirements and Usage Modes

The variations in Space Station orbit-keeping and CMG desaturation over the 10-year mission duration are shown in Figure 17. Orbit-keeping dominates CMG desaturation for the greater portion of the mission for both the horizontal and POP orientations. The low-thrust operation of the resistojets permits combining the CMG desaturation and orbit-keeping functions; hence, with appropriate thrust scheduling, CMG desaturation is obtained as a byproduct of orbit-keeping.

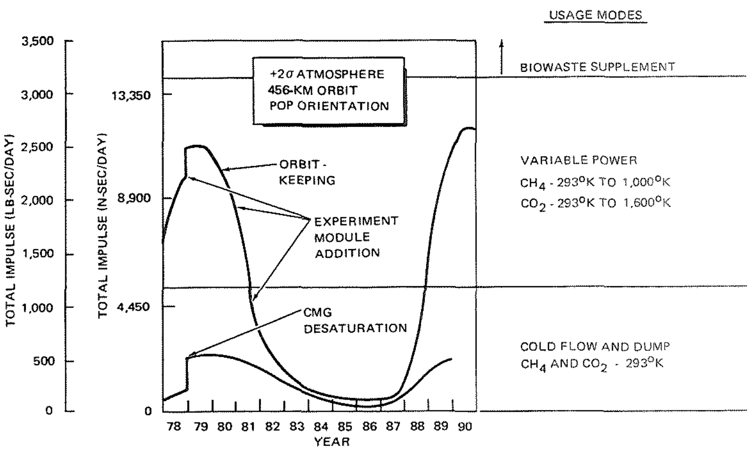


Figure 17. Space Station Total Impulse Requirements and Usage Modes

The variation in impulse requirements dictates that the resistojet system use a supplemental propellant during years of peak solar activity and at the lower orbital altitudes. During the low-impulse years, Space Station power is saved by resistojet operation at reduced power levels. These features also provide for more efficient and effective usage of the biowaste gases.

The wide range of impulse requirements results in resistojet thrust level selection being a compromise among power, duty cycle, and number of thrustors. This problem is magnified by the necessity of using all the biowaste, allowing for the inclusion of the supplemental propellant, and operating within the vehicle power limit. As a result of these considerations, a 0.111-N (25-mlb) thrust level was selected. At the maximum impulse capability of 22,300 N-sec/day (5,000 lb-sec/day), this thrust level provides a maximum duty cycle of approximately 80 percent for thrustor operation.

A block diagram of the resistojet system control functions is given in Figure 18. The dashed line shows the interface between the guidance, navigation, and control subsystem and the propulsion system. The control mechanization for the Space Station included the considerations necessitated by use of the high-thrust system as a backup to the resistojet system. The control mechanization of the propulsion system emphasized the closed-loop GNC mechanization for orbit-keeping and for CMG desaturation using resistojets.

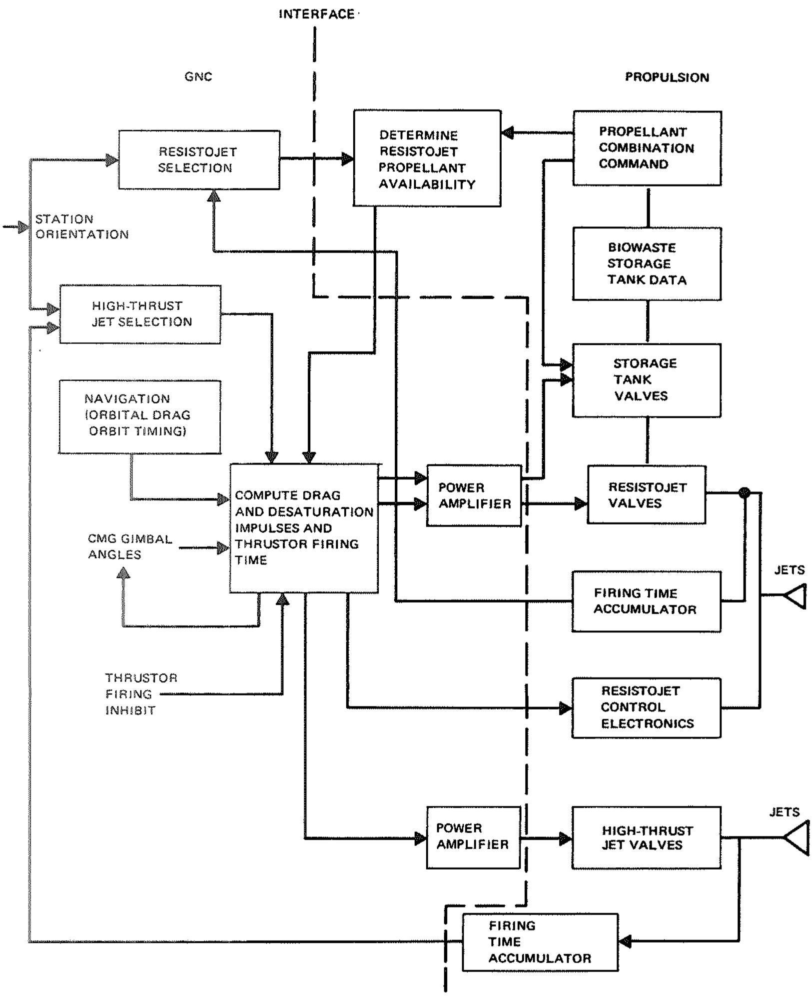


Figure 18. Resistojet System Control

The basic resistojet control functions involving the GNC system are shown in Figure 18. The orientation of the Space Station determines the thrustors to be used for orbit-keeping, CMG desaturation, and the combination of these functions. With the availability of the resistojets and the propellant capacity identified, the impulse capacity for the resistojets is determined. The status of the CMG gimbal angles and the integrated output of the accelerometer determines the impulse requirements at the end of each orbit. The resistojet capacity is compared with the measured impulse requirement, which defines a deficit or surplus resistojet capacity. The deficit desaturation capacity is made up with the high-thrust system, while the orbit-keeping deficit may either be deferred or made up with the high-thrust system. The firing time of each jet is determined and supplements the information used in jet selection. High-thrust or low-thrust firing can be inhibited to minimize contamination and high-thrust attitude transients that might affect sensitive experiments.

With the low-thrust biowaste resistojet system, the orbit-keeping and desaturation impulses are applied at a rate a few times greater than the drag and CMG saturation impulse accumulation rate. Therefore, the resistojet thrustors fire through large portions of the orbit. CMG desaturation is most efficiently done at certain orbit positions. The orbit-keeping impulse should be applied in equal pulses spaced 180 deg apart for the horizontal orientation (Figure 19) and in equal pulses spaced 90 deg apart for the POP orientation

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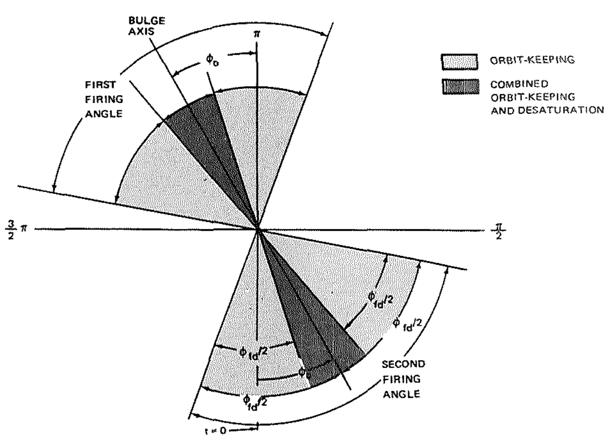

Figure 19. Orbit-Keeping and Desaturation Firing Periods (Horizontal Orientation)

(Figure 20). CMG's are desaturated simultaneously with orbit-keeping at specific times. Figure 21 shows a typical thrust cycle for the horizontal orientation and identifies the thrustor firings.

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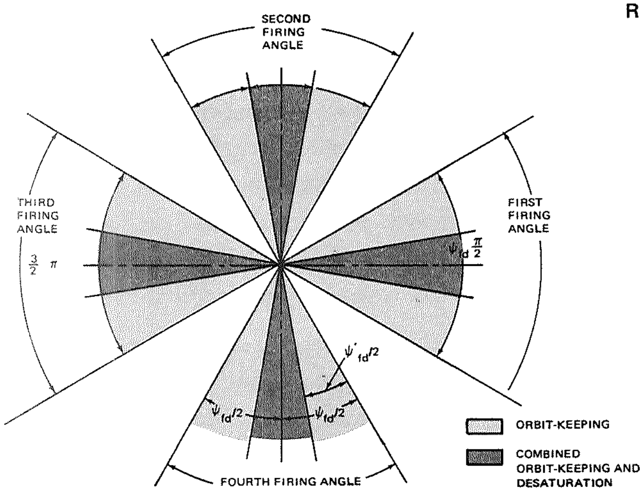

Figure 20. Orbit-Keeping and Desaturation Firing Periods (POP Orientation)

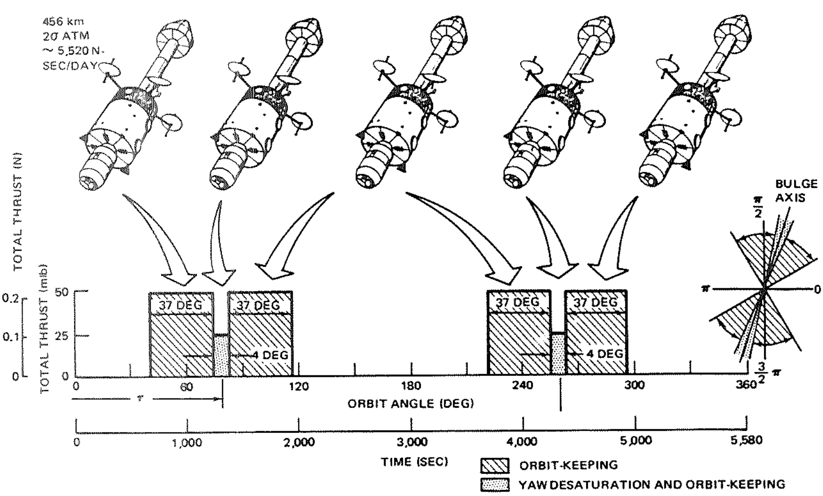

Figure 21. Typical Orbit Operation Thrust Schedule

Section 4
DEVELOPMENT PROGRAM

The approach recommended for expeditious attainment of an operational biowaste resistojet system consists of the design, development, and test activities required to achieve three major program objectives:

- Development of flight-weight biowaste resistojet prototype components and assemblies, with emphasis on components requiring advanced technology
- Demonstration of prototype component performance and operating life characteristics in a functionally simulated resistojet system
- Demonstration of prototype EC/LS-resistojet performance, operating life, and maintenance in an integrated system.

The program consists of three primary efforts, as shown in Figure 22.

COMPONENT DESIGN AND DEVELOPMENT

Component design and development includes the activities needed to establish component requirements and to carry out the necessary design and development. The detailed component design requirements are established, and detailed evaluations of existing electrical and mechanical components are made to determine the need for development activities. Determination of the component and assembly design and development requirements establishes vendor and subcontractor design and development efforts. Component and assembly development for prototype flight-weight units are carried out to meet the performance requirements and to withstand critical dynamic environments.

SYSTEM DEVELOPMENT TESTING

System development testing encompasses three phases: component verification and interface tests, system operational and life tests, and integrated EC/LS-resistojet system tests (including GNC interfaces). A "breadboard system test unit" with prototype flight components is used. The design of the breadboard unit allows each component to be tested individually to verify

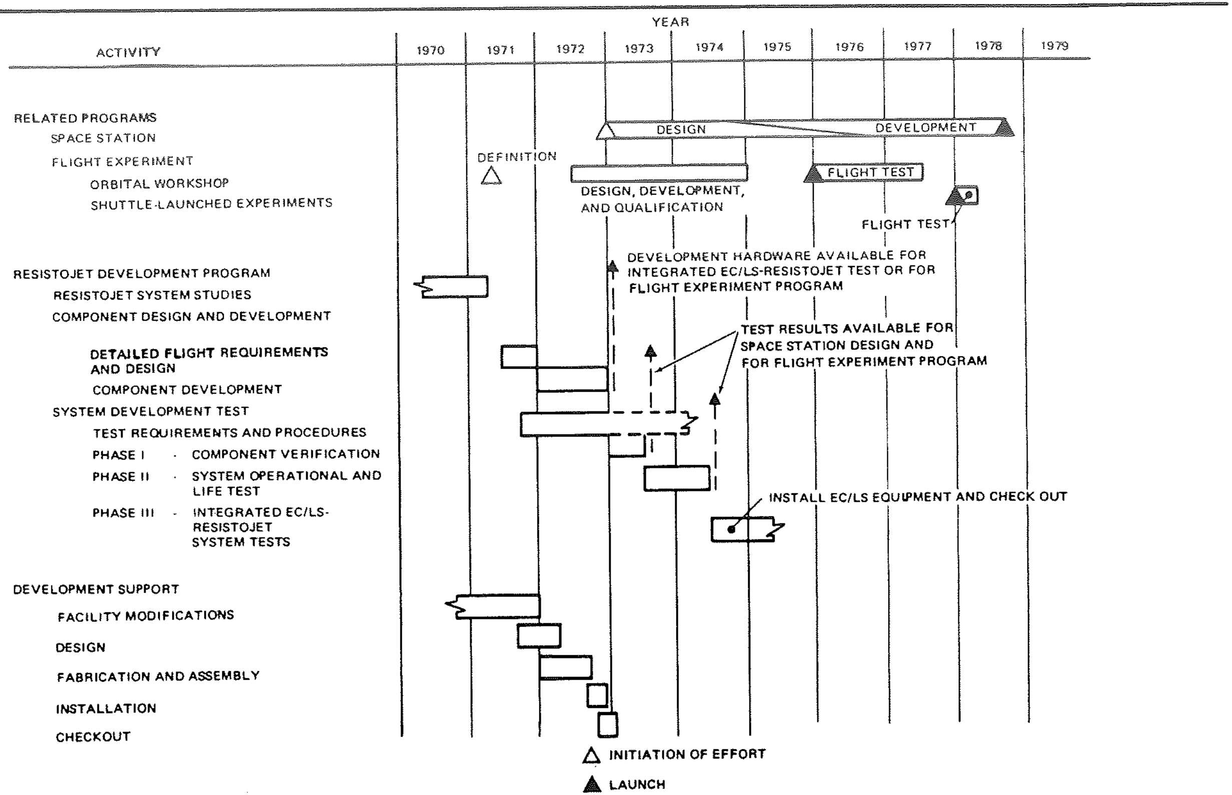

Figure 22. Development Program Schedule

performance and component interface compatibility (Phase I). The components are then operationally and life-tested at either the assembly or the system level (Phase II). Phase III system tests are conducted using the outputs of the EC/LS molecular sieve and the Sabatier reactor. Completion of this effort demonstrates the adequacy of the operational system design concept, the performance of the integrated system, and reliability over the range of expected operating conditions.

SYSTEM DEVELOPMENT SUPPORT

System development support includes test facility modifications and test installation design, fabrication, assembly, installation, and checkout. The system test configuration and special test equipment required to conduct the system development tests at Langley Research Center are defined in this effort. Also included is the development of a system control computer program to simulate the flight-operational relationships of the various interfaces and system functions.

The program schedule was established with the test completion milestones noted in Figure 21 so that the test results could be used on an Orbital Workshop or Shuttle-launched flight experiments, as well as in the Space Station Program. The development approach is compatible with other system approaches.

TEST CONFIGURATION

The system development test configuration for Test Phases I and II (Figure 23) consists of the functionally simulated breadboard system test unit, a test cell with a vacuum chamber, a test control center, an instrumentation center, special test equipment, and support facilities. The breadboard portion of the test configuration for Phase III (Figure 24) is identical, except that the EC/LS interfacing equipment to supply CO_2 and CH_4 is installed in lieu of the K bottles used in Phases I and II.

The test unit will permit operation of up to four resistojets. With the adjustable regulators, the installation will allow components to be omitted and will permit individual components or groups of components to be tested without operating the complete system.

The development program is based on an evaluation of the current status of the resistojet system and on the potential launch date as well as on perform-

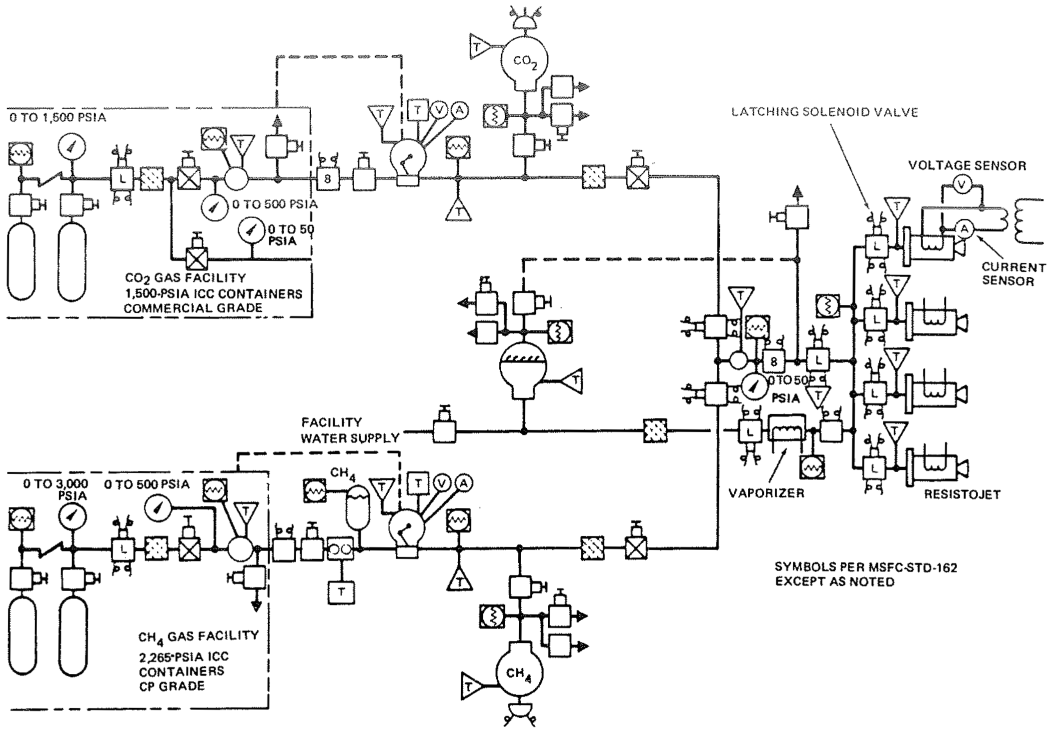

Figure 23. Schematic of Resistojet System (Test Phases I and II)

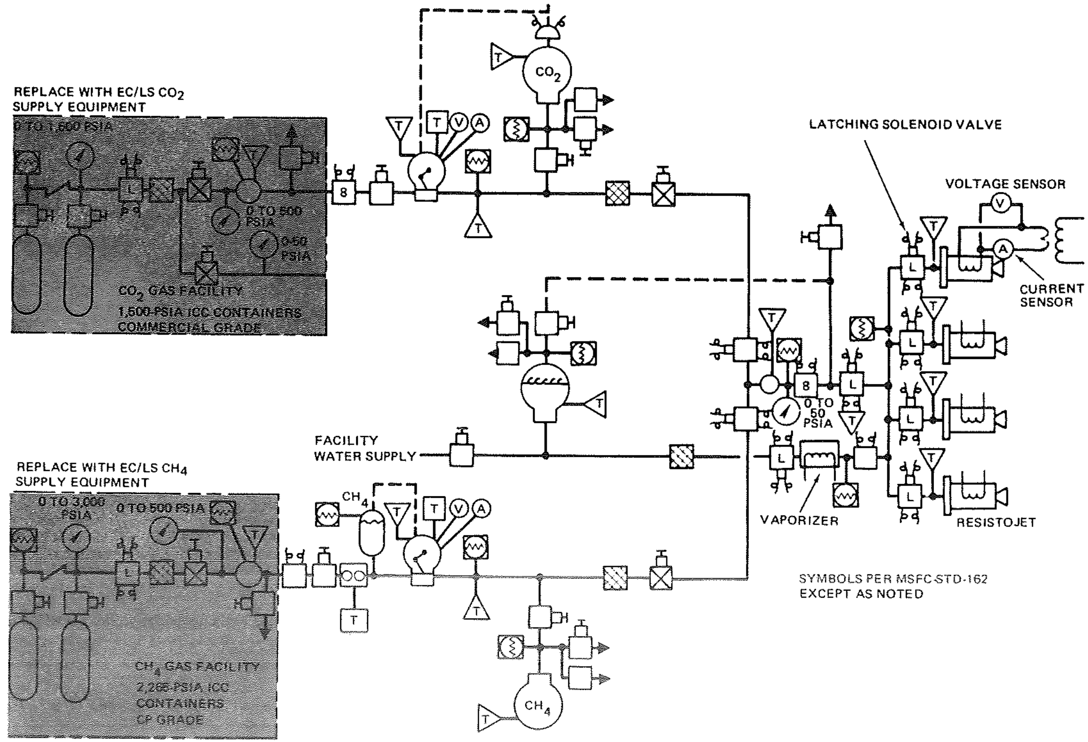

Figure 24. Schematic of EC/LS-Resistojet System Test

ance, operational, and system life requirements. The technology development necessary for the system is identified in accordance with the supporting research and technology (SRT) definitions used in the Space Station Program. SRT items are:

- Resistojet heater element materials
- Biowaste resistojet (vapor-fed)
- Water vaporizer
- Verification of resistojet operating characteristics with actual biowastes
- CO_2 and CH_4 compressor assemblies

The results of an evaluation of design and development schedule and cost are presented in Figure 25 and Table 8. The status of non-SRTcomponent and assembly development have been assessed and defined in a general development category.

A resistojet assembly specification has been prepared for the performance, design, product configuration, and development test requirements for a flight-weight prototype resistojet assembly. This specification also gives guidance and direction to the ongoing development effort.

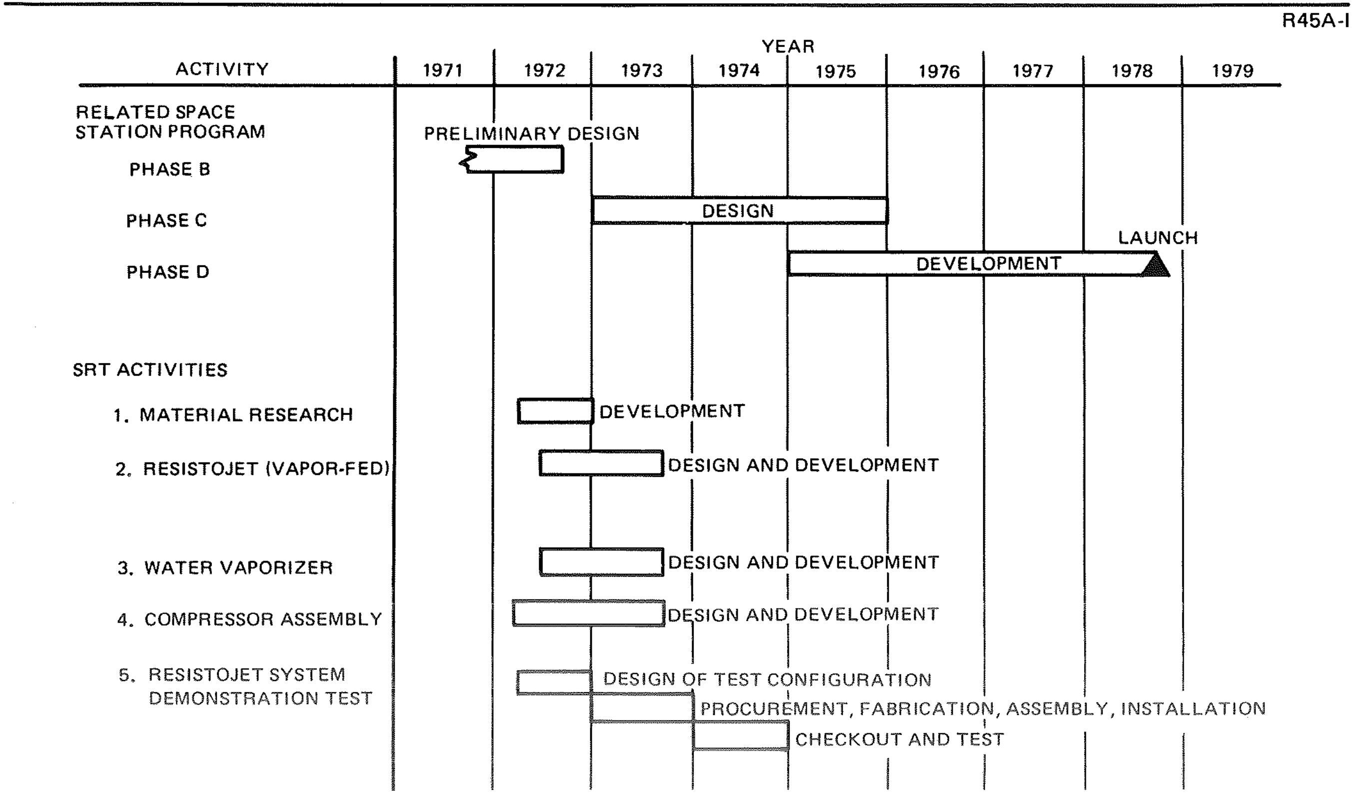

Figure 25. Design and Development Schedule

Table 8
DESIGN AND DEVELOPMENT COST ESTIMATE FOR SRT ITEMS

SRT Item	Cost (millions of dollars)	Remarks
Material research	0.1	Scheduled over 9 months
Resistojet		Develop to flight prototype status
Baseline	1.2 to 2.0	Hot gas valve development required
Water vaporizer	0.5 to 1.0	Develop to flight prototype status. Control device requires testing
Compressor assemblies	0.8 to 1.2	Develop flight prototype assembly (CO_2 and CH_4)
Resistojet system	2.0 to 3.0	Integral EC/LS-resistojet system test
Demonstration test		Component and assembly development cost not included. Other SRT items assumed to be developed. Remaining hardware to satisfy test requirements assumed to exist Facility cost not included. Design, procurement, fabrication, assembly, and installation costs included All test and test-related costs included
Total	4.6 to 7.3	

Note: Alternate thrustor concepts are not included.

Section 5
SPACE BASE RESISTOJET SYSTEM

The Space Base resistojet system design (Figure 5-4 of Volume I) is nearly identical to that for the Space Station. The major differences occur in:

- The EC/LS-resistojet system interface
- Storage capacity
- Resistojet thrust level and thrustor concept
- Power distribution and control

Design requirements and their effects upon commonality with the Space Station have been identified.

EC/LS-RESISTOJET SYSTEM INTERFACE

The locations of the nine EC/LS systems of the Space Base are shown in Figure 26. The interface for the systems in the zero-gravity core is identical to that for the Space Station. Collection for the rotating modules, however, requires pumping in the core, rather than at the EC/LS unit in the rotating modules. This concept was selected to minimize the hazards and leakage associated with long runs of high-pressure lines.

The interface mechanization of the multiple systems is shown in the system schematic. The gaseous outputs of the three aft systems are manifolded together, as are those of the two forward systems and the four rotating hub systems. This arrangement furnishes as much redundancy as possible without completely duplicating each collection assembly.

STORAGE CAPACITY

The increased quantity of available biowaste (four times as much as on the Space Station) requires more storage capacity and larger thrustors. The storage capacity of the space Station system is two days, but for the Space Base this can probably be reduced to one day or less because the EC/LS cycle time is unchanged, and therefore, transient damping is not a function of crew size. The total Space Base storage capacity selected is twice that of the Space Station, thereby requiring larger tanks or additional tanks.

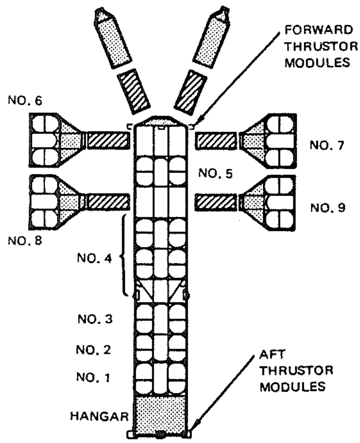

Figure 26. EC/LS Locations on Space Base

RESISTOJET THRUST LEVEL AND THRUSTOR CONCEPT

The Space Base thrust level has been identified for operation with the output of a 48-man crew and a duty cycle of 25 to 80 percent. The thrust level selected is 0.222 N (50 mlb). This will require scaling of the Space Station resistojet and is considered a minor development program. However, an advanced concept resistojet would provide greater total impulse and hence a higher thrust level (0.333 N, or 75 mlb).

POWER DISTRIBUTION AND CONTROL CAPACITY

The increase in thrust level to 50 or perhaps 75 mlb requires two to three times the power-handling capability of the resistojet power distribution system for the Space Station, particularly in the high-current portions of the thrustor module. Although the Space Station design concept is applicable to the Space Base, additional sequencing and thrustor firing inhibits may be required.

SPACE BASE DESIGN REQUIREMENTS

The resistojet system design requirements for the Space Base were based on evaluation of propellant availability, propellant performance goals, and impulse requirements and control mechanization.

Propellant Availability

The EC/LS system concept for the Space Base is essentially identical to that for the Space Station. The composition of the biowastes for the Space Base is identical to that for the Space Station, but the quantities are four times as great. The values given in Table 9 are based on a crew of 48 and a leakage rate of 3.75 kg/day (8 lb/day). The supplemental propellant analysis again indicates water to be the most desirable supplement, both for commonality with the Space Station design and for effective usage of the EC/LS water excess on the Space Base.

Propellant Performance and Operation Mode Assessment

The propellants were evaluated for the thrust level of 0.222 N (50 mlb) and the higher heat exchanger temperature limits envisioned for advanced resistojet concepts. The results of the evaluation are given in Table 10.

CH_4 cannot be used as a single propellant for advanced resistojets. It is included in Table 10 for reference only. However, evaluation of mixtures with CH_4 showed that the possibility of using CH_4 as a central confined jet (secondary flux) in a steam outer sheath (primary fluid) to protect the thrustor walls from carbon disposition is very attractive.

Table 9
SPACE BASE EC/LS BIOWASTE OUTPUTS

Leakage Rate = 3.75 kg/day (8 lb/day) Average

Biowastes	Biowaste Constituent, kg/day (lb/day)					Total Biowaste, kg/day (lb/day)
	CH_4	CO_2	N_2	O_2	H_2O	
CO_2	0	19.0 (43.33)	0.145 (0.32)	0.055 (0.21)	0	19.2 (43.86)
CH_4	10.7 (23.52)	0.96 (2.12)	0.255 (0.56	0	0.20 (0.44)	12.11 (26.64)
H_2O	0	0	0	0	1.15 (2.52)	1.15 (2.52)

Table 10

ADVANCED RESISTOJET DESIGN GOALS

Supply pressure = 3.039 X 10^5 N/m^2 (3 atmospheres)

F_{design} = 0.2224 N (50 mlb)

	Propellant					
Factor	CO_2	CH_4	CO_2 and CH_4 (MR = 2:1)	H_2O	CO_2 and CH_4 (MR = 2.75:1)	H_2O and CH_4 (MR = 1.1:1)
$\dot{m}$,g/sec	0.1070	0.0601	0.0779	0.0759	0.0821	0.0662
I_{sp}, sec	211.9	377.2	291.1	298.9	276.2	342.8
P_e, w	367.5	585.0	468.8	447.1	450.6	513.1
A^*_{geo},m^2	3.81×10^{-7}	3.51×10^{-7}	3.59×10^{-7}	4.23×10^{-7}	3.62×10^{-7}	3.80×10^{-7}
T_{gas},°K	2,200	2,200*	2,200	2,200	2,200	2,200

*Shown for reference only. Carbon formation results at chamber temperatures in excess of 1,000° K.

Mixtures of CH_4 and CO_2 could potentially cause deposition of carbon due to the reaction

$$2CO \rightarrow C\ (s) \text{ and } CO_2$$

No advanced thrustor concept has reached the design stage, and considerable feasibility and demonstration testing would be required before such a thrustor could be incorporated into a vehicle design. If development is undertaken, the thrustor should be compatible with mixed propellants that may be employed in advanced system concepts.

Impulse Requirements and Control Mechanization

The impulse requirements for the Space Base were established for the same atmosphere model, orbital altitude range, and vehicle orientation used for the Space Station. Figure 27 shows the Space Base orbit-keeping impulse variation with altitude. The Space Base requires use of supplemental propellant at the lower altitudes and has excess propellant capacity at the higher altitudes. In general, the impulse requirements of the Space Base are 1.5 to 2.0 times

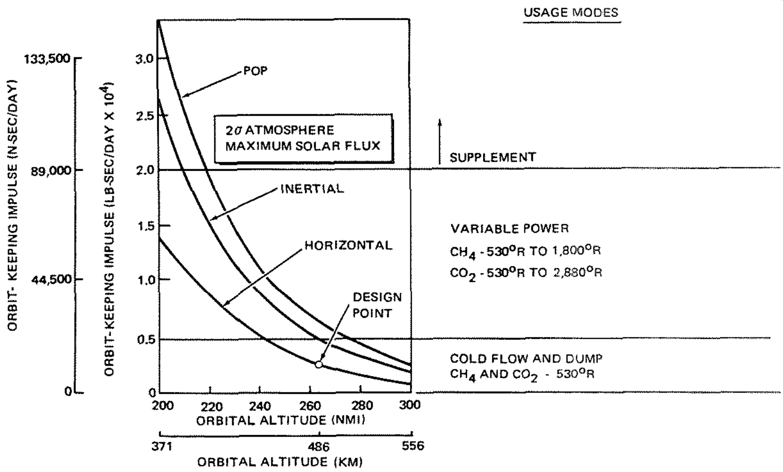

Figure 27. Space Base Orbit-Keeping Requirements and Usage Modes

those of the Space Station. However, the available quantity of biowaste is four times as large. Operation of the Space Base with a duty cycle range similar to that of the Space Station would require a 0.222-N (50-mlb) thrust level for a contemporary resistojet. The added impulse capability of advanced concept resistojets would require a 0.333-N (75-mlb) thrust level. The system effects of higher thrust level would necessitate larger power distribution and control equipment.

The closed-loop mechanization for Space Base orbit-keeping and CMG desaturation is the same as described for the Space Station.

SPACE STATION-SPACE BASE COMMONALITY

The 48-man Space Base, as identified in the NASA Phase B Space Station Program, will evolve from a 12-man Space Station. Therefore, a primary goal is to maximize commonality between the Station and Base.

The results of a study to compare the Space Station and Space Base resistojet design requirements and characteristics, to assess commonality, and to determine the development impacts of any differences are shown in Table 11. The systems are nearly identical, with the only major differences involving the number of EC/LS-P/RCS interfaces, resistojet thrust level (and possibly thrustor and vaporizer design), and power distribution capacity. This high degree of commonality, including identical functional requirements, minimizes impacts on system development.

Table 11
SPACE STATION-SPACE BASE COMMONALITY

Impact Area	Design Features		Design Requirements		Design and Development Impact
	Space Station	Space Base	Space Station	Space Base	
EC/LS					
Number of modules and interfaces	3	9	Total collection capability from each unit	Same	Minimal. May need to include some or all of extra units in development. See below under system design.
Quantity	7.9 kg/day	31.5 kg/day	Total collection	Same	Increased capacity, depending on number of additional units used in tests
S/AC					
Impulse required	See Figures 16 and 17	See Figure 27	—	At nominal design point, 1.5 to 2 times Space Station	Lower impulse relative to capability results in lower power level. See also thrustor performance and thrust level. Operational and timing impact only.

Table 11
SPACE STATION-SPACE BASE COMMONALITY (Cont)

Impact Area	Design Features: Space Station	Design Features: Space Base	Design Requirements: Space Station	Design Requirements: Space Base	Design and Development Impact
Supplement	H_2O and high thrust	H_2O if EC/LS excess is available, otherwise high thrust	Use water to 5,000 lb-sec/day (total), then high thrust	Water as available, then high thrust	
System Design					
Collection and interface	Pump at each EC/LS unit, central storage	Same, plus transfer across rotating seal for storage	Collect at each end of Space Station	Collect at five locations on core plus four on hubs. Transfer across rotating seal between core and hubs	Development of collection technique to obtain gases across rotating interface may require significant effort. Otherwise, minimal impact.
Number of storage bottles	Four, 0.76 m dia	Probably four to six with larger diameter	Storage capability for two days' output	Probably less than Space Station	Little impact. Possibly additional bottles with associated plumbing and instrumentation.

Table 11
SPACE STATION-SPACE BASE COMMONALITY (Cont)

Impact Area	Design Features		Design Requirements		Design and Development Impact
	Space Station	Space Base	Space Station	Space Base	
Plumbing and leakage	See Vol. I, Fig. 2-2	Similar to Space Station	Thrustors at each end	Same	Additional units and distances require extra plumbing and increased leakage potential.
Flow control	—	—	—	—	Identical, but larger flow capacity.
System Operation	—	—	—	—	Similar, but extra EC/LS units may require added system logic.
Thrustor Performance Thrust level	25 mlb	50 mlb contemporary, 75 mlb advanced	80-percent duty cycle at 5,000 lb-sec/day	Contemporary: adequate dump handling	Contemporary: little impact. Thrustors scale up easily.
Performance level (Operating temperature)	CH_4 1,800°R CO_2 2,880°R H_2O 2,800°R	Contemporary: same Advanced: CO_2, H_2O, and CH_4 mixes, 3,960°R	—	—	Same

Table 11
SPACE STATION-SPACE BASE COMMONALITY (Cont)

Impact Area	Design Features		Design Requirements		Design and Development Impact
	Space Station	Space Base	Space Station	Space Base	
Thrustor design	Evacu-ated, concentric tube; possibly others	Contemp-orary: same Advanced: several under study	—	—	Same
Power Distribution	—	—	Four-thrustor capability	Same	Significant (2 to 3 times) power requirement. Additional sequencing and inhibits may be required to limit power.

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