Copies

NASA CR-66600
DAC-58130

DEFINITION OF A RESISTOJET CONTROL SYSTEM FOR THE MANNED ORBITAL RESEARCH LABORATORY FINAL REPORT

VOLUME I
SUMMARY

MAY 1968

Prepared under Contract No. NAS1-6702
by Douglas Aircraft Company
Missile and Space Systems Division
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA CR-66600
DAC-58130

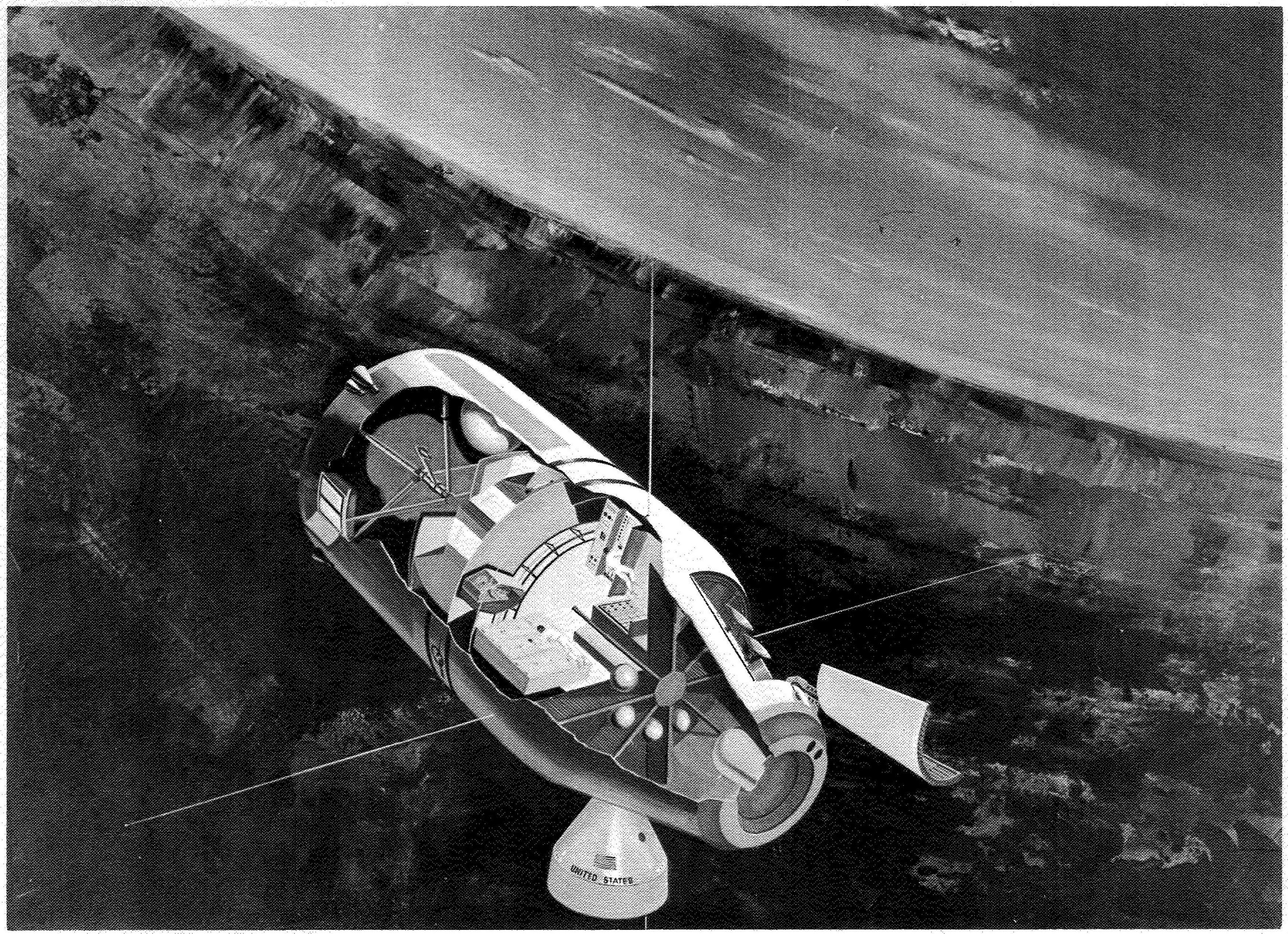
DEFINITION OF A RESISTOJET CONTROL SYSTEM FOR THE MANNED ORBITAL RESEARCH LABORATORY FINAL REPORT

VOLUME I SUMMARY

MAY 1968

BY A. PISCIOTTA, JR. and E.N. EUSANIO

Prepared under Contract No. NAS 1-6702
by Douglas Aircraft Company
Missile and Space Systems Division
Huntington Beach, California
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION


UNITED STATES

PREFACE

This report is submitted to the National Aeronautics and Space Administration's Langley Research Center (NASA-LRC), Langley AFB, Virginia. It has been prepared under Contract No. NAS1-6702 and describes the results of a detailed assessment of the use of a resistojet control system for the MORL.

The study results are documented in five volumes:

DAC-58130	I	Summary
DAC-58131	II	Resistojet Control System Analysis
DAC-58132	III	Biowaste Utilization
DAC-58133	IV	Ground and Flight Test Plan
DAC-58134	V	Resistojet Design and Development

Volume I is a summary report in which the significant results are presented. Volume II contains a detailed definition of the selected resistojet control system, the recommended orbit injection system, the supporting system analyses and integration, and comparative evaluation data. Volume III presents the biowaste utilization analysis. Volume IV details the ground and flight test program for a resistojet control system. Volume V presents the results of the resistojet design and development program. Life test data will be provided in a separately bound addendum to Volume V at the conclusion of the life test.

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

- Mr. T. J. Gordon, Director, Advance Space and Launch Systems
  Huntington Beach, California
  Telephone: 714-897-0311, Extension 2994

PRECEDING PAGE BLANK NOT FILMED.

ABSTRACT

The NASA MORL was evaluated for the orbit injection, orbit operations, and scheduled disturbances encountered during its mission. Parametric system analysis was performed which led to the selection of systems to control the spacecraft. The selected systems were defined and integrated into the baseline MORL. Concurrent with the analysis was the development, fabrication, and testing of 0.044-N (10-mlbf) resistojets using hydrogen (H_2) and ammonia (NH_3) as propellants. The system selected for orbit injection was the J-2S engine of the S-IVB. In addition to providing the highest payload, this system had the additional advantage of placing the S-IVB in orbit for potential use as an orbital workshop or as a counterweight for providing artificial gravity.

For the MORL's orbit-keeping functions, resistojet systems using H_2, NH_3, and the selected biowaste propellant (CO_2) were compared. An NH_3 resistojet system was selected and then integrated into the baseline MORL. The system has four thrustor modules equally spaced about the vehicle periphery. Each module contains six 0.044-N (10-mlbf) thrustors (two forward- and aft-facing pitch and yaw resistojets, and a clockwise and a counterclockwise resistojet). The system is supplied by a common propellant tankage and feed system. The NH_3 system was selected because it required lower power, weight, and volume than the H_2 system. The development status of the NH_3 resistojet and system components was the primary criteria for its selection over the biowaste CO_2 system.

All applicable high-thrust systems were compared for control of the MORL scheduled disturbances (docking and centrifuge operation). A monopropellant hydrazine (N_2H_4) system with four modules, each containing three 44.5-N (10-lbf) thrust engines, was selected and integrated into the baseline MORL. The modules, equally spaced around the periphery of the MORL, are supplied by a common propellant tankage and feed system. The N_2H_4 system was selected on the basis of its simplicity and reliability since a significant difference in weight did not exist between the systems compared.

The examination of the MORL environment control and life support EC/LS) system showed that three potential biowaste propellants were available for resistojet usage: (1) CO_2 from the molecular-sieve beds, (2) H_2 obtained as a by-product of the water electrolysis system, and (3) fecal water from fecal waste. Evaluation of the output collection and storage penalties and the resistojet performance and power requirements resulted in the selection of an all-CO_2 biowaste resistojet system. This system showed significant advantages when compared to NH_3 and H_2 resistojet systems. The biowaste CO_2 system with an open-loop EC/LS system was competitive when compared to both NH_3 and H_2 systems with a closed-loop EC/LS system.

A 0.044-N (10-mlbf) resistojet development program was conducted for both NH_3 and H_2 propellants. It was found that a single resistojet could operate with either propellant. The evacuated concentric-tubular resistojet, which was developed, operates at temperatures in excess of 2200°K, uses ultimate materials, and eliminates the use of static seals. Over 300 hours of development-test cyclic operation was accumulated. Specific impulses of >680 sec for H_2 and >320 sec for NH_3 were obtained at electrical efficiencies of >65% for H_2 and >45% for NH_3. During the development program, significant advances were made to the technology of forming, machining, and joining rhenium components.

A ground and flight test program was formulated for both an NH_3 and H_2 resistojet system. The program consists of ground testing to demonstrate flight worthiness and an experiment flight test to demonstrate the operational capability of the systems. A detailed qualification test plan was formulated for the thrustor module. Ground qualification plans were prepared for the system's critical components. Integrated system tests were specified. The 6-month flight test provides demonstration of spacecraft control, system maintenance, and extended resistojet space operation. Preliminary estimates of program cost and schedule were established.

FOREWORD

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 units for length, mass, and time are meter, kilogram, and second, respectively. Throughout the report, the English equivalent (foot, pound, and second) 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	sec	s
Electric current	ampere	A
Temperature	degree Kelvin	^oK

Supplementary Units

Plane angle	radian	rad

Derived Units

Area	square meter	m^2	
Volume	cubic meter	m^3	
Frequency	hertz	Hz	(s^{-1})
Density	kilogram per cubit meter	kg/m^3	
Velocity	meter per second	m/s	
Angular velocity	radian per second	rad/s	
Acceleration	meter per second squared	m/s^2	
Angular acceleration	radian per second squared	rad/s^2	
Force	newton	N	$(kg\text{-}m/s^2)$
Pressure	newton per sq meter	N/m^2	
Kinematic viscosity	sq meter per second	m^2/s	
Dynamic viscosity	newton-second per sq meter	$N\text{-}s/m^2$	
Work, energy, quantity of heat	joule	J	(N-m)
Power	watt	W	(J/s)
Electric charge	coulomb	C	(A-s)
Voltage potential difference, electromotive force	volt	V	(W/A)

Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	(V/A)
Electric capacitance	farad	F	(A-s/V)
Magnetic flux	weber	Wb	(V-s)
Inductance	henry	H	(V-s/A)
Magnetic flux density	tesla	T	(Wb/m^2)
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

CONTENTS

PRECEDING PAGE BLANK NOT FILMED.

FIGURES

PRECEDING PAGE BLANK NOT FILMED.

TABLES

DEFINITION OF A RESISTOJET CONTROL SYSTEM FOR THE MANNED ORBITAL RESEARCH LABORATORY

FINAL REPORT

VOLUME I - SUMMARY

By A. Pisciotta, Jr. and E. N. Eusanio

INTRODUCTION

Extensive studies by the National Aeronautics and Space Administration (NASA) over the past 5 years have established that a prerequisite for manned space exploration is the development of an Earth-orbital manned spacecraft. In one of these studies (ref. 1), the Douglas Aircraft Company's Missile and Space Systems Division (MSSD) defined such a spacecraft--the Manned Orbital Research Laboratory (MORL). Because the subsystems to support the MORL soon became of primary interest, Douglas was awarded a Phase IIB effort (ref. 2). This involved preliminary studies of advanced propulsion and control systems to verify the feasibility of using a resistojet reaction-control system for performing such functions as attitude control, orbit injection, and orbit keeping.

The conclusions of the Phase IIB Study resulted in the award of a contract for the Definition of a Resistojet Control System for the MORL (Contract No. NAS1-6702) from Langley Research Center to MSSD, in conjunction with The Marquardt Corporation as a major subcontractor. This study, documented in this report, had the following primary objectives:

(1) To establish the feasibility of a resistojet control system to perform all the control requirements for the MORL.

(2) To establish an integrated system for performing attitude control, orbit keeping, and orbit injection for the MORL.

(3) To determine the feasibility of utilizing biowaste as propellant for the resistojet control system.

(4) To develop and test the 0.044-N (10-mlbf) resistojet thrustor as defined by the MORL requirements.

(5) To establish a ground- and flight-test plan for an integrated MORL resistojet control system.

The quantitative approach followed during the study provided parametric design and analysis data for orbital space stations, with the MORL system (ref. 3) used as a baseline. The MORL shown in fig. 1 is a 6.6-m- (260-in.)-diam laboratory with facilities that allow a 6- or 9-man crew to perform a broad-based engineering and scientific experiment program in a low Earth orbit. The laboratory is launched by an uprated Saturn I into a subsynchronous 304-km (164-nmi) orbit at 0.87-rad (50°) inclination. The present study is based on a launch in the 1972 time period to accomplish a 5-year mission. Resupply is available every 90 days through the use of an uprated Saturn I-launched, Apollo-derived logistics vehicle.

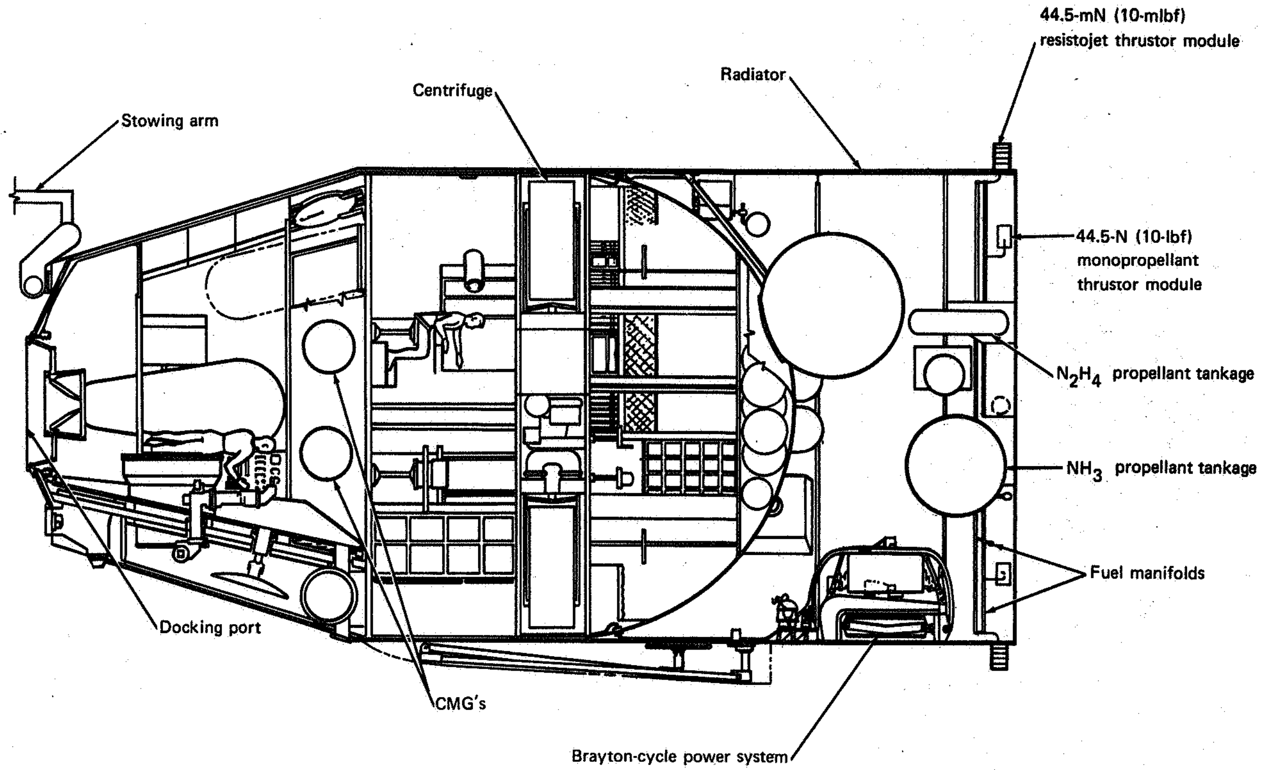


Figure 1. MORL Inboard Profile

SYSTEM ANALYSIS AND INTEGRATION

The system analysis and integration phase of the study included an evaluation of the mission's operational profile, from the time of initial launch and injection into orbit to the cycle of regularly scheduled events required to sustain the 5-year mission. The objectives of this evaluation was to examine the requirements for a MORL reaction control system and to assess the feasibility of modifying the operational profile so that the low-thrust capability of resistojet thrustors could be used more effectively. Also considered was the potential utilization of biowastes from the MORL's EC/LS system as propellant for the resistojet thrustor.

The system analysis was divided into the following areas: (1) orbit injection (2) attitude control and orbit keeping, and (3) biowaste utilization. Candidate systems from these analyses were then integrated with the MORL, and the resulting systems were defined in further detail.

The selected systems are summarized in table 1, along with the primary reasons for their selection.

Orbit injection is accomplished by apogee circularization using the J-2S engine on the S-IVB. Use of the J-2S engine simplifies the MORL propulsion requirements and provides the maximum payload capability. Attitude control and orbit keeping are accomplished by a control-moment gyro (CMG)/resistojet system. The CMG's serve as the primary actuators to control the aerodynamic and gravity-gradient torques, and they provide the maneuvering capability necessary to change vehicle orientation. The resistojet thrustor desaturates the CMG's and performs the orbit-keeping function. Control of the scheduled disturbances is accomplished by a monopropellant thrustor system which also has the capability for backup control.

The MORL inboard profile (fig. 1) shows the location of the ammonia (NH_3) resistojet thrustor modules and the hydrazine N_2H_4) monopropellant thrustor modules. The four resistojet modules each contains six 0.044-N (10-mlbf) thrustors (four pitch or yaw thrustors and two roll thrustors) and are located at $\pi/2$-rad (90^o) intervals around the aft of the vehicle. The monopropellant thrustor modules are spaced at $\pi/4$ rad (45^o) from the resistojet modules, and each contains three 44.5-N (10-lbf) thrustors (one roll, two pitch or yaw).

Orbit Injection

Orbit injection of the MORL was evaluated for apogee circularization by both MORL and S-IVB systems and for a special trajectory using resistojet systems. The payload capabilities of all candidate systems are shown in fig. 2.

Table 1

SELECTED SYSTEMS

Function	System	Primary advantages
Orbit injection	J-2S engine	• Has highest payload capability • Allows the S-IVB to be placed in orbit
Attitude control and orbit keeping	CMG/NH_3 resistojet system Four resistojet modules Six thrustors/module 0.044 N [10 mlbf] each Four CMG's Two double-gimbal (pitch and yaw) 2430 N-m-sec (1790 ft-lbf-sec) each Two single-gimbal (roll) 2210 N-m-sec (1625 ft-lbf-sec) each	• Has lower launch weight, power, and volume than H_2 resistojet system • Is already developed, whereas CO_2 resistojet is conceptual design • Has lower launch weight than high-thrust system (chemical engines) • Eliminates noise, vibration, and CMG unloading transients of high-thrust systems • Has less-complex resupply than LH_2 resistojet or high-thrust systems • Minimizes environment contamination • Has a cold-flow operating mode
Scheduled-disturbance control (docking impact and centrifuge operation)	N_2H_4 monopropellant system Four engine modules Three engines/module 44.5-N [10 lbf] each	• Has superior thrust capability to heated-gas systems • Is less complex and has higher reliability than bipropellant system • Has less-complex resupply than bipropellant system

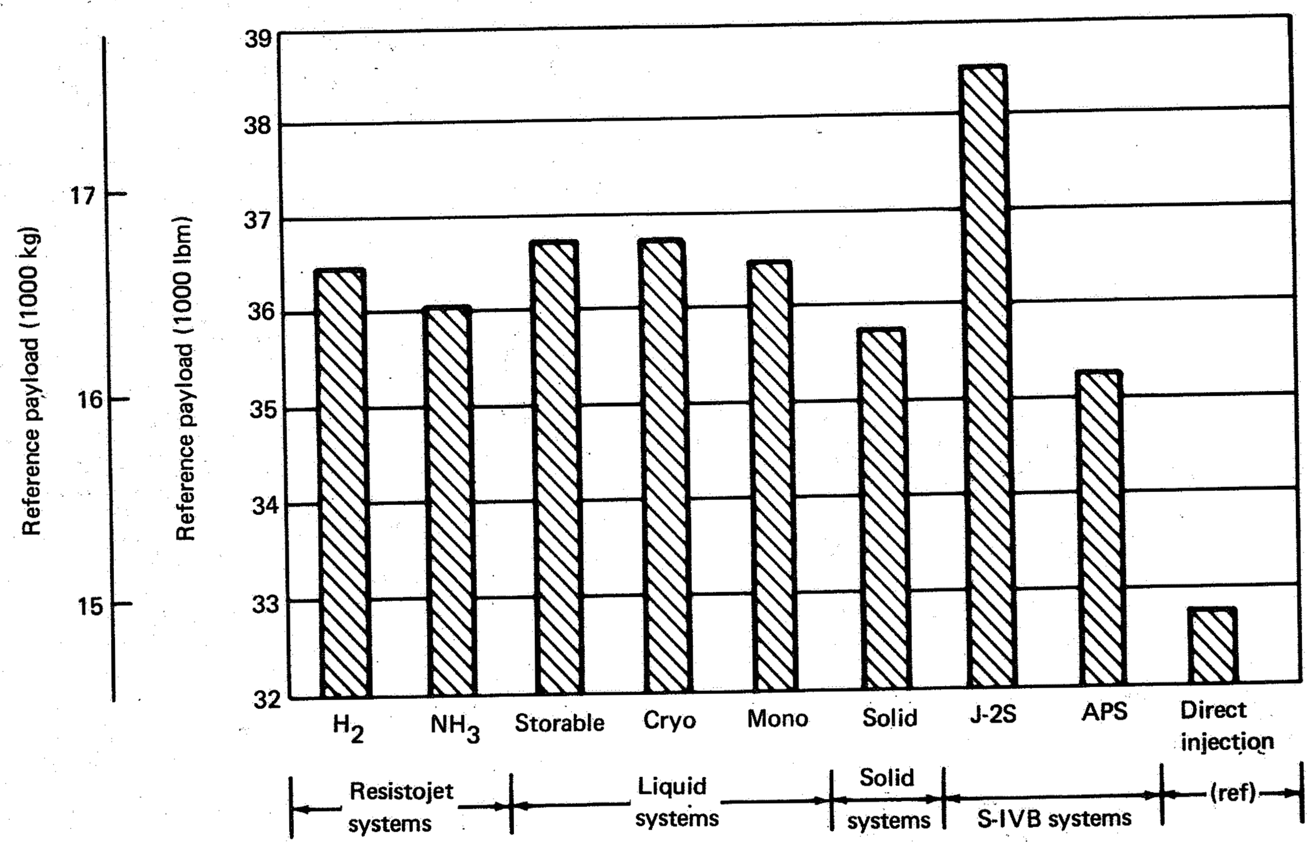


Figure 2. Payload Capability Summary

The direct-injection payload is shown on the right for comparison. Definition of the J-2S engine of the S-IVB as the selected system was based on maximum payload in orbit. This system has the additional advantage of placing the S-IVB in orbit for potential use as a workshop or as a counterweight to provide artificial gravity.

All the liquid systems compared for orbit injection provide approximately the same payload capability. Although the cryogenic O_2/H_2 system is capable of higher specific impulse than the storable bipropellant, it does not provide a higher payload, which results from its higher inert weight. Further, it is not attractive because of the complexity of the feed system. The monopropellant system is less complex than the bipropellant system, but results in a slightly lower payload because of its lower performance.

The solid-propellant systems that were evaluated resulted in poor mass fractions and, consequently, imposed a high payload penalty. Grain geometry and burn time constraints dictate a high-thrust injection system, which results in high control-torque requirements. This therefore necessitated a large, separate attitude-control system during injection, which also imposes a large weight penalty.

The use of resistojet thrustors with a spiral transfer from an initial low-altitude orbit to the final 304-km (164-nmi) circular orbit was evaluated parametrically. As shown in fig. 3, there is an optimum total thrust for each propellant at which the payload is a maximum. This is a direct result of varying the following parameters as a function of thrust level: (1) minimum initial-orbit altitude at a fixed thrust-to-drag ratio and (2) specific impulse for a fixed power level. The thrust levels selected, therefore, were 4.45 N (1 lbf) for H_2 and 3.12 N (0.75 lbf) for NH_3. With these thrust levels, the resultant payload capability with resistojet thrustors is comparable to that obtained with conventional thrustor systems. However, the time required to achieve final orbit is approximately 4.5 days for the H_2 system and about 7.5 days for the NH_3 system. These times are based on spiralling from the lowest initial-orbit altitude consistent with a 2:1 thrust-to-drag ratio constraint.

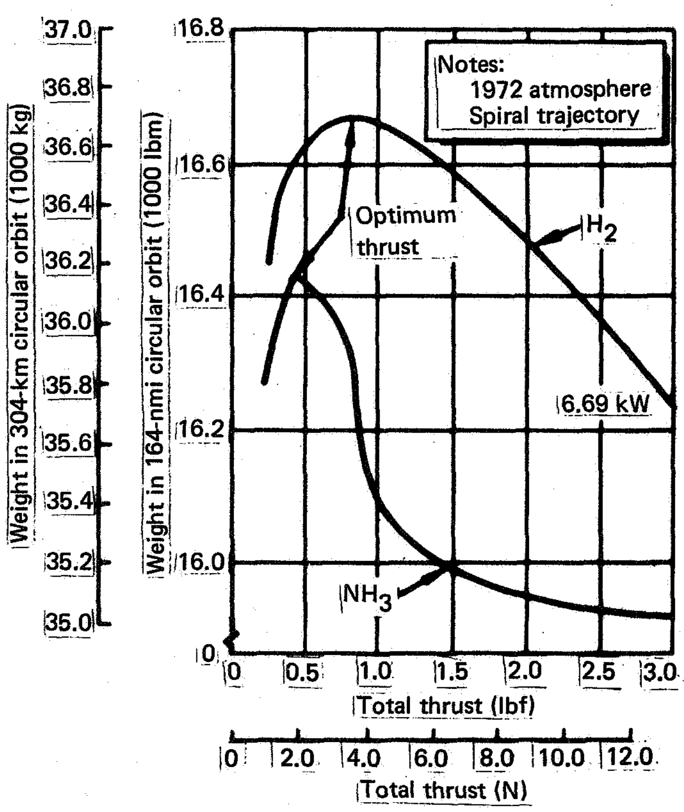


Figure 3. Resistojet Thrust Optimization

The following paragraphs summarize the recommended orbit-injection technique. Fig. 4 schematically shows the recommended launch and apogee circularization injection sequence for an Eastern

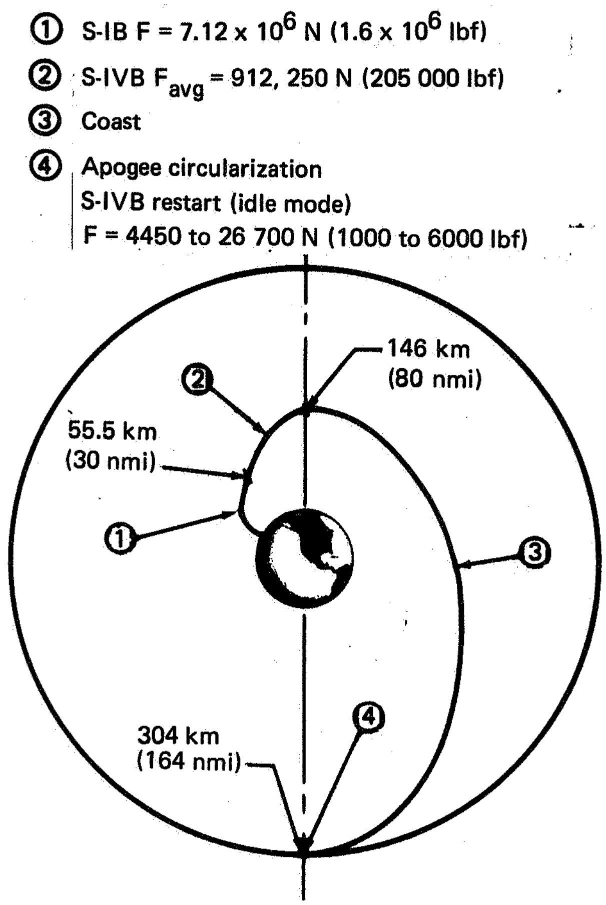


Figure 4. Injection Technique

Test Range (ETR) launch into a 304-km (164-nmi) altitude at a 0.87-rad (50°) inclination. The boost phase, indicated by point 1 in the figure, is provided by the S-IB engines at a total thrust of 7.12×10^6 N (1.6 million lbf). The duration of the boost phase is 150 sec. At an altitude of 55.5 km (30 nmi), the booster is separated from the S-IVB and payload, and the S-IVB's mainstage J-2S engine is ignited (point 2 on the figure). To maximize the payload in orbit, the J-2S engine is programmed for a step variation in thrust level during engine-operation. This is accomplished by operating the J-2S at a higher oxidizer-to-fuel mixture ratio initially, thus providing a high thrust level when flight-path angles are high and gravity losses are greatest. This high, initial thrust level increases the payload weight in orbit, even though there is a decrease in delivered specific impulse. After 300 sec of operation, the flight-path angle is sufficiently reduced so that the high thrust level is no longer advantageous. At this point, a programmed reduction in mixture ratio will cause the thrust level to drop and performance to increase.

At the end of the initial J-2S operation, the vehicle is in a 148- x 304-km (80- x 164-nmi) elliptical orbit. After a coast period of approximately 45 min (point 3), the J-2S is restarted in the idle mode (point 4) to provide a velocity increment of 44.5 m/sec (146 fps) that circularizes the orbit at the 304-km (164-nmi) apogee. At ignition, the idle-mode thrust level is 4.45×10^3 N (100 lbf), building up to 2.67×10^4 N (6000 lbf) steady state in approximately 40 sec.

A total propellant weight of 591 kg (1300 lbm) is required to perform this maneuver. This is well below the 965 kg (2123 lbm) of residual propellants available on the S-IVB. Consequently, the orbit transfer is accomplished with no additional propellant requirement. The resultant payload capability is 17 500 kg (38 461 lbm).

Attitude Control and Orbit Keeping

The attitude-control and orbit-keeping system is required to orient and stabilize the MORL and to maintain the proper orbit altitude during all phases of the mission. The requirements for the orbital phase are a reflection of the mission requirements defined by the Phase IIB MORL Study, which defined a mission orbit altitude of 304 km (164 nmi) and an initial launch date of 1972.

During the performance of the routine Earth-oriented experiments, an attitude-hold accuracy of 8.7×10^{-3} rad ($\pm 0.5^{\circ}$) and a rate limit of 5.2×10^{-4} rad/sec (0.03°/sec) is required. For the precision Earth-oriented and inertial-oriented experiments, the requirement is for an attitude-hold accuracy of 1.74×10^{-3} rad ($\pm 0.1^{\circ}$) with a rate of 1.74×10^{-4} rad/sec (0.01°/sec). The inertial orientation--in which the attitude of the vehicle is essentially fixed--is required for those experiments that have fixed pointing requirements, such as for celestial observations. No precise attitude-hold accuracy is specified for the nonexperimental portion. However, attitude-hold accuracies have been established on the basis of specific mission activities.

Two primary orientations are used during the MORL mission. The local horizontal or "belly-down" orientation is selected for long-term stabilization, since it is easily mechanized and results in minimum aerodynamic drag. Earth-oriented experiments are best performed in the belly-down position. In this orientation, the longitudinal (X-axis) is aligned in the direction of the orbital velocity vector; the yaw (Z-axis) is aligned along the local vertical; and the pitch (Y-axis) is aligned perpendicular to the orbit plane.

The disturbances which affected the control requirements were analyzed and classified into two categories: orbital disturbances and scheduled disturbances. The orbital disturbances, such as gravity gradient and aerodynamic drag, are relatively low in magnitude and are most effectively controlled by the use of the CMG/resistojet system. Scheduled disturbances, such as docking impact and centrifuge operations, require relatively high control torques which can be provided more effectively by the use of a conventional thrustor system.

Orbital-disturbance control. — The effect of the thrust schedule on CMG size was determined by an analysis of the angular impulse which occurs during a worst-case inertial orientation. It was found that near-constant desaturation thrust results in minimum CMG weight. That is, the CMG's are sized to store the largest cyclical disturbance, and the desaturation impulse is applied continuously during the cycle by the resistojet system.

Comparison and evaluation of H_2, NH_3, and biowaste resistojet systems led to the selection of the NH_3 system. This selection was based on reliability, simplicity, launch weight, power requirements, growth potential, and development risk. Although the NH_3 system was selected for use on the MORL baseline, the CO_2 biowaste resistojet remains an attractive candidate for space station application, provided that suitable high-temperature, oxidation-resistant materials are developed.

The thrust schedules used to desaturate the CMG's in the inertial and belly-down orientations are shown in fig. 5. During the inertial orientation, the thrustors are fired in couples to avoid perturbation of the orbit. Orbit keeping, however, is deferred to the belly-down orientation when the thrustors are aligned with the velocity vector. In the belly-down orientation, orbit keeping is accomplished simultaneously with pitch and yaw desaturation by means of firing the thrustors in unbalanced couples. This results in a savings in propellant weight.

A total of 4 hours/day is spent in the inertial orientation, with 0.5 hours spent in maneuvering. The remaining time is spent in the belly-down orientation. This schedule requires a total impulse of 8300 N-sec/day (1870 lbf-sec/day). Constant total thrust throughout the orbit permits a constant power demand from the MORL electrical system.

The locations of the CMG/resistojet thrustor system are shown in fig. 6. The CMG package consists of two double-gimbal CMG's (DG/CMG) and two single-gimbal CMG's (SG/CMG) as described in detail in ref. 4. The DG/CMG provides control moments for pitch and yaw, and the SG/CMG provides control moments for roll. Momentum storage capabilities are 2200 N-m-sec (1625 ft-lbf-sec) per gyro for the DG/CMG, and 2420 N-m-sec (1790 ft-lbf-sec) per gyro for the SG/CMG. The pitch and yaw sizing will accommodate the maximum cyclical-disturbance torques with sufficient momentum reserve to perform maneuvers. The roll sizing will simultaneously handle the maximum gravity gradient and aerodynamic torques and the disturbance generated by 1-g centrifuge operation.

The resistojet thrustor system which provides orbit-keeping impulse and CMG desaturation consists of four thrustor modules located at $\pi/2$-rad (90°) intervals around the MORL aft. Each of the four modules contains six 0.044-N (10-mlbf) resistojet thrustors. The selection of identical thrust levels for pitch, roll, and yaw results in identical thrustors and thrustor modules.

The module design is shown in fig. 7. The modules can be replaced from inside the vehicle by means of removing four Dzus-type fasteners, disconnecting the fuel and electrical lines, and withdrawing the thrustor module from its service position. The thrustors are oriented within the module in three matched pairs, with each pair in parallel but mounted in opposite directions. A common central structure supports the thrustor pairs.

Parametric analysis and preliminary system integration of three resistojet thrustor systems led to a preliminary definition of NH_3, cryogenic H_2, and carbon dioxide (CO_2) biowaste propellant systems as primary candidates. A summary of the pertinent parameters for these systems is presented in table 2. The comparisons were performed for an 8300-N-sec/day (1870-lbf-sec/day) impulse requirement and a 0.044-N (10-mlbf) thrust-level resistojet.

For comparative purposes, gross reliability predictions were made for the resistojet control system for H_2, NH_3, and CO_2. Two alternate configurations were examined for H_2 and NH_3. Alternate A uses a single propellant tank, while Alternate B has redundant tanks. Reliability was expressed as

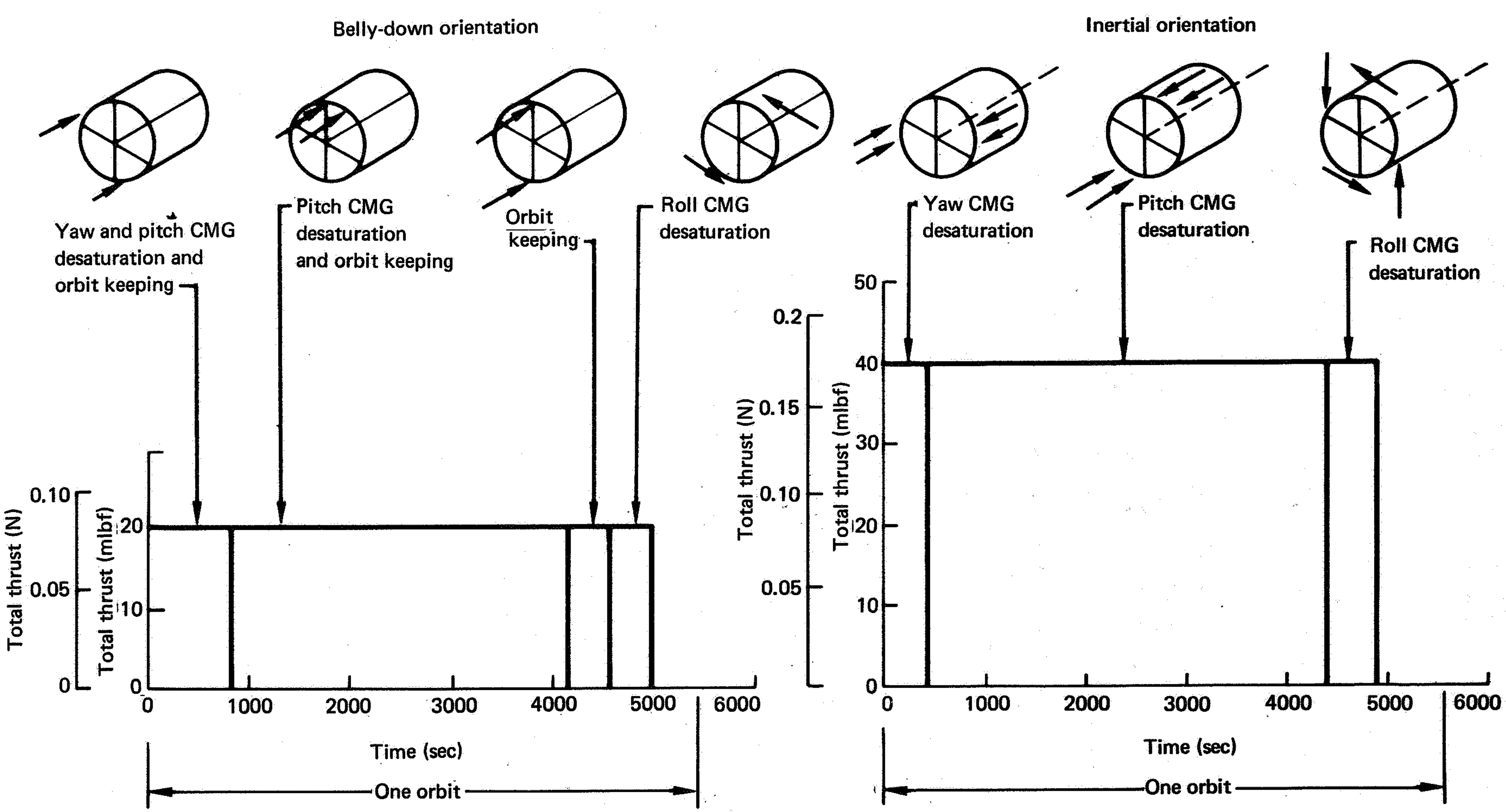


Figure 5. Orbit Operation-Thrust Schedules

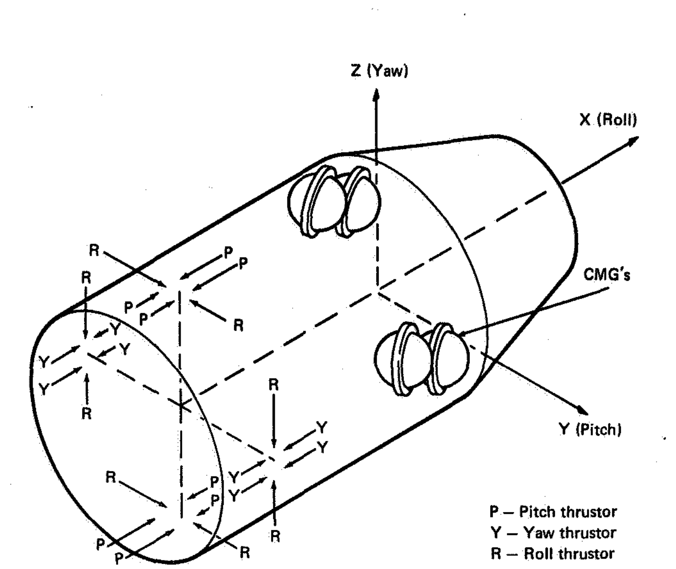


Figure 6. Resistojet Thrustor Locations

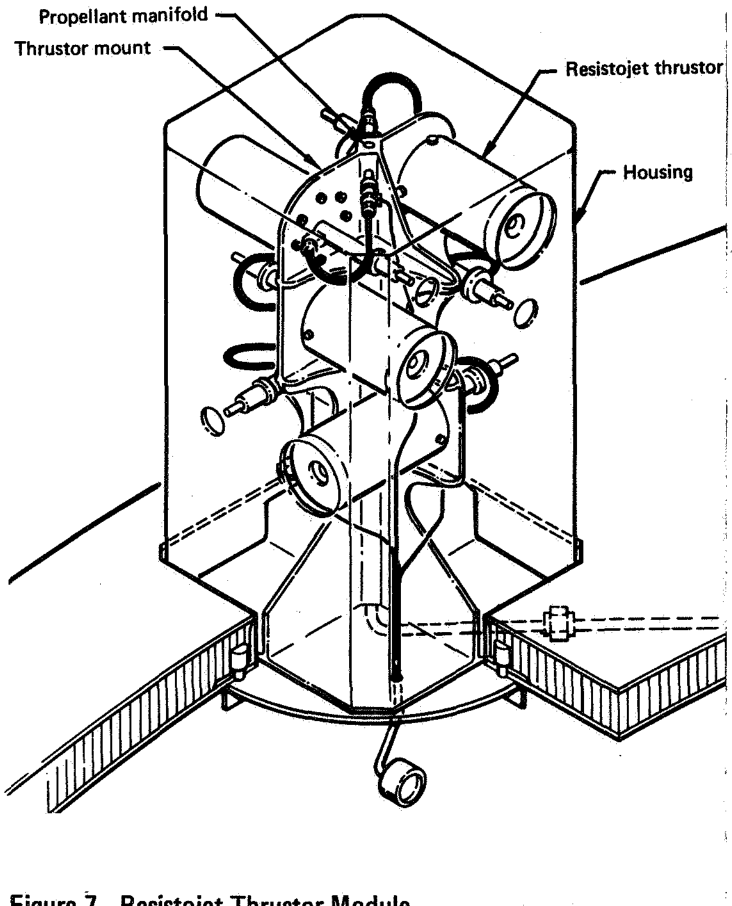


Figure 7. Resistojet Thrustor Module

either probability (1), no system shutdown, and probability (2), no system loss caused by a single failure. Both probabilities were contingent upon the assumption that repair capability was permissible. Since both probabilities vary inversely with each other, the probabilities cannot be maximized simultaneously, but rather, must be traded off to optimize the total resistojet control system reliability. Table 3 presents the results of the comparative reliability analysis.

Of the recommended configurations for attaining the highest probability of no system shutdown, the NH_3 system ranks first. Of the recommended configurations for attaining the highest probability of no system loss, all systems have a probability value very close to unity. The thrustor module has not been considered in this comparative analysis because it is common to all systems and configurations. The probability of no system shutdown--probability (1)--is higher for the single-tank configuration than for the redundant-tank configuration because of the greater number of components in the redundant system. Probability (2) is higher for the redundant-tank system; however, this probability assumes that shutdown is permissible to effect repairs. A more detailed analysis, based on data obtained from tests of the specified components, is required before a final decision on the degree of redundancy can be made. For the purpose of preliminary system definition, the redundant-tank configuration is chosen.

The evaluation of the three resistojet systems, which resulted in in the selection of the NH_3 system, was based on criteria evolved from the guidelines set forth in the statement of work. The NH_3 resistojet

TABLE 2

RESISTOJET SYSTEMS SUMMARY[a]
(Open-Loop EC/LS System)

Parameters	H_2	NH_3	CO_2
Chamber temperature	2420°K (4360°R)	2420°K (4360°R)	1665°K (3000°R)
Delivered specific impulse	735 sec	364 sec	177 sec
Propellant tank volume	3.34 m^3 (118 ft^3)	0.68 m^3 (24 ft^3)	0.25 m^3 (8.8 ft^3)
Total required power/thrustor	249 watts	159 watts	102 watts
Weight assessment for electric power	107 kg (236 lbm)	69 kg (151 lbm)	44 kg (97 lbm)
[b]Total chargeable launch weight	246 kg (543 lbm)	196 kg (431 lbm)	98 kg (216 lbm)
Total chargeable 90-day resupply weight	238 kg (525 lbm)	297 kg (653 lbm)	---

[a]Thrust = 0.044 N (10 mlbf); $P_c = 2.41 \times 10^5$ N/m^2 (35 psia).
[b]Includes weight assessment for power consumption.

TABLE 3

COMPARATIVE RELIABILITY PREDICTIONS

System	Configuration	Probability (1)	Probability (2)
NH_3	Single tank (Alternate A)	0.871	0.983
	Redundant tanks (Alternate B)	0.847	~1
H_2	Single tank (Alternate A)	0.816	0.967
	Redundant tanks (Alternate B)	0.799	~1
CO_2	---	0.839	~1

system best satisfies most of the criteria. It yields a lower launch weight, has a lower power requirement, and has greater growth potential than the cryogenic H_2 system. In addition, the NH_3 system is simpler and more reliable. The launch facilities and prelaunch operations are greatly simplified in that no cryogenic system is required, no chilldown operations are necessary, and a prolonged countdown hold will have no effect on the NH_3 system. The cryogenic H_2 system and the biowaste system present higher development risk than the NH_3 system. Although the H_2 and NH_3 resistojets have the same development status, the cryogenic tankage design and the cryogenic-propellant resupply system will require concentrated development effort.

The selected NH_3 resistojet system is shown schematically in fig. 8. Liquid NH_3 is stored in redundant spherical tanks of 6 Al-4V titanium. The propellant tank contains no positive expulsion system, since the NH_3 is expelled by its own vapor pressure. A relief and vent system prevents overpressurization of the tank. The NH_3 flows from the tank through a shutoff valve which can be used to isolate the tank from the remainder of the feed system. Downstream of the valve, the NH_3 flows through a heat exchanger where it picks up waste heat from the Brayton-cycle radiator loop. This ensures that the flow will be vaporized before entering the pressure regulator.

The NH_3 flows from the heat exchanger to a three-way solenoid valve through a redundant pressure regulator to an accumulator, then to a manifold around the MORL vehicle perimeter which supplies the four thrustor modules.

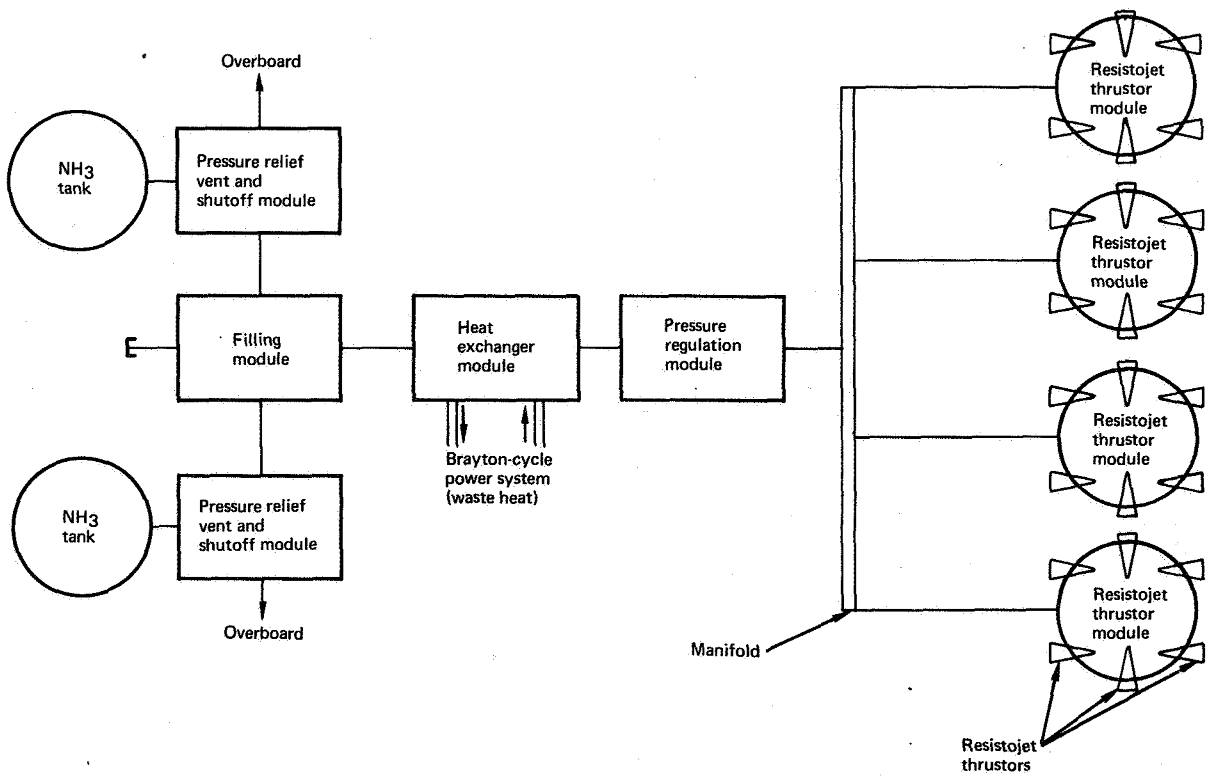


Figure 8. NH_3 Resistojet System

The three-way solenoid valve and redundant regulator system (which maintains the downstream pressure at 2.41×10^5 N/m^2 [35 psia]) guards against the possibility of thrustor outage resulting from regulator failure, thus increasing the reliability of the feed system. A valve and disconnect are at each thrustor module to allow thrustor removal and replacement.

The 0.044-N (10-mlbf) NH_3 resistojet thrustor design is shown schematically in fig. 9. It employs an evacuated concentric-tube concept. The two primary inputs to the thrustor are the electric power and the propellant flow. Ohmic heating takes place primarily in the inner heating element (80%), with the outer elements providing the balance. Gas flow is introduced into the annulus between the inner and outer pressure cases and flows through the concentric passages and down the center heating element, where the temperature of the gas approaches that of the wall before expansion through the nozzle. Heat loss is minimized and electrical efficiency maximized by use of the vacuum jacket with radiation shields, the regenerative passage between the inner and outer pressure case, and the bulk thermal insulation. The thermal and gas pressure loads are minimized by a bellows expansion compensator at the rear of the resistojet. The detailed design of the thrustor, which has been successfully fabricated and performance tested at Marquardt, is discussed later in this document. The performance of the thrustor is given in table 4.

Two power-control concepts were defined in detail. These are (1) ac stepdown and (2) dc inversion and stepdown. The recommended system (dc inversion and stepdown) achieves a ±1% power regulation at the resistojet thrustors. The recommended power-control system is described in the following paragraphs.

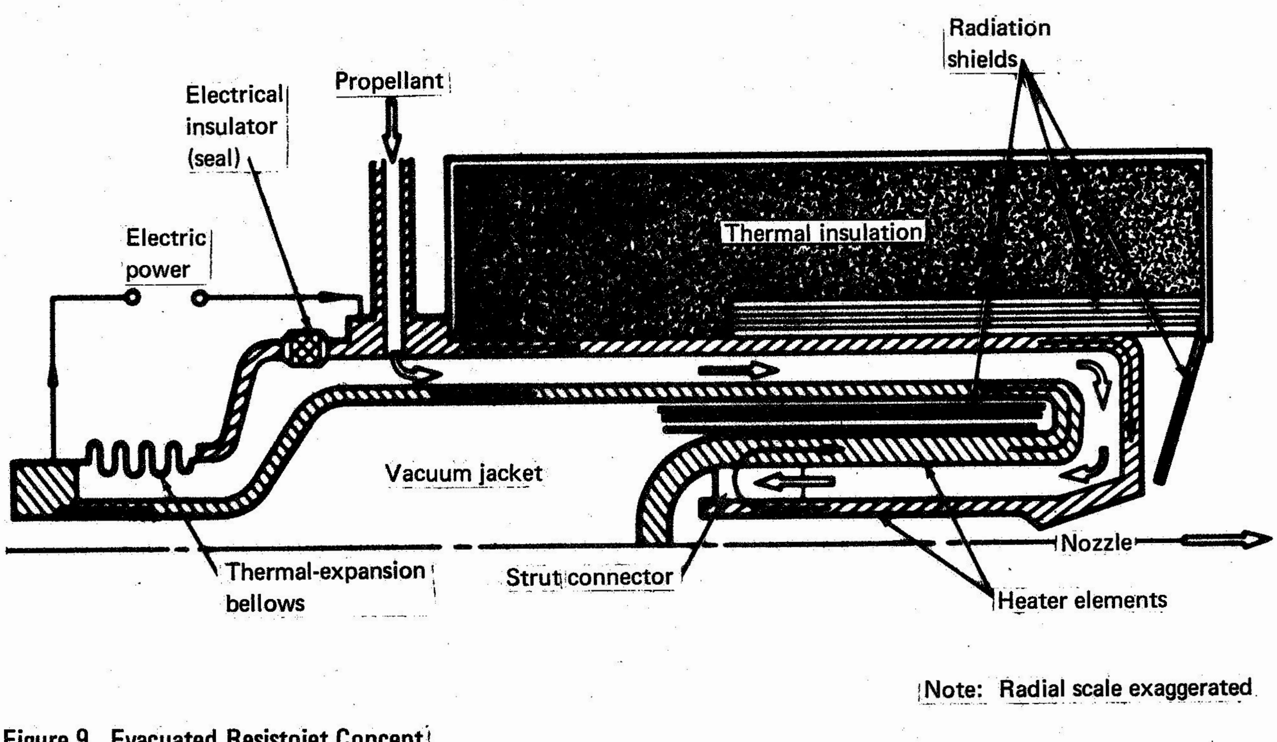


Figure 9. Evacuated Resistojet Concept

TABLE 4

NH_3 RESISTOJET THRUSTOR PERFORMANCE

Parameter	Performance
Chamber pressure	2.41×10^5 N/m^2 (35 psia)
Thrust	0.044 N (0.010 lbf)
Expansion ratio	35:1
Thrust coefficient	1.42
Chamber temperature	2420°K (4356°R)
Delivered specific impulse	364 sec
Required power per thrustor	149 watts
Heater efficiency	81%
Propellant tank pressure	2.2×10^6 N/m (325 psia)
Propellant tank temperature	325°K (125°R)
Throat diameter	0.041 cm (0.016 in.)
Mass flow rate	1.25×10^{-2} g/sec (2.75×10^{-5} lbm/sec)

The NH_3 resistojet electric power is regulated by two 400-Hz, single-phase, 200-volt square-wave inverters, one of which services the entire system, while the other is on standby. Inverter power comes from the 260-Vdc-link bus, and the control power comes from the nonessential 28-Vdc bus. Eight 163-watt stepdown transformers (two for each thrustor module) are used to reduce the 200-volt inverter output to the proper level. Voltage regulation at the resistojets is ±1/2% at 4.8 volts and is achieved through careful design of the distribution system and provision of 1/4% regulation in the inverter.

Fig. 10 shows the electrical-power schematic for each thrustor module for the eight-transformer system. Each thrustor-module power system consists of five subassemblies: (1) primary patch-panel and breaker, (2) power-control connector, (3) step-down transformer, (4) resistojet solenoid switches, and (5) resistojet heater elements. The primary patch-panel and breaker subassembly are located centrally on the vehicle at the resistojet power bus and the inverters. Other subassemblies are located at the thrustor modules.

The control system shown operates as follows: If a signal is applied through the power-control connector, a solenoid valve will be opened to allow propellant to flow in one of the resistojets. This solenoid also closes two electrical contacts that energize the primary of the applicable transformer and connect the secondary winding to the correct heater element.

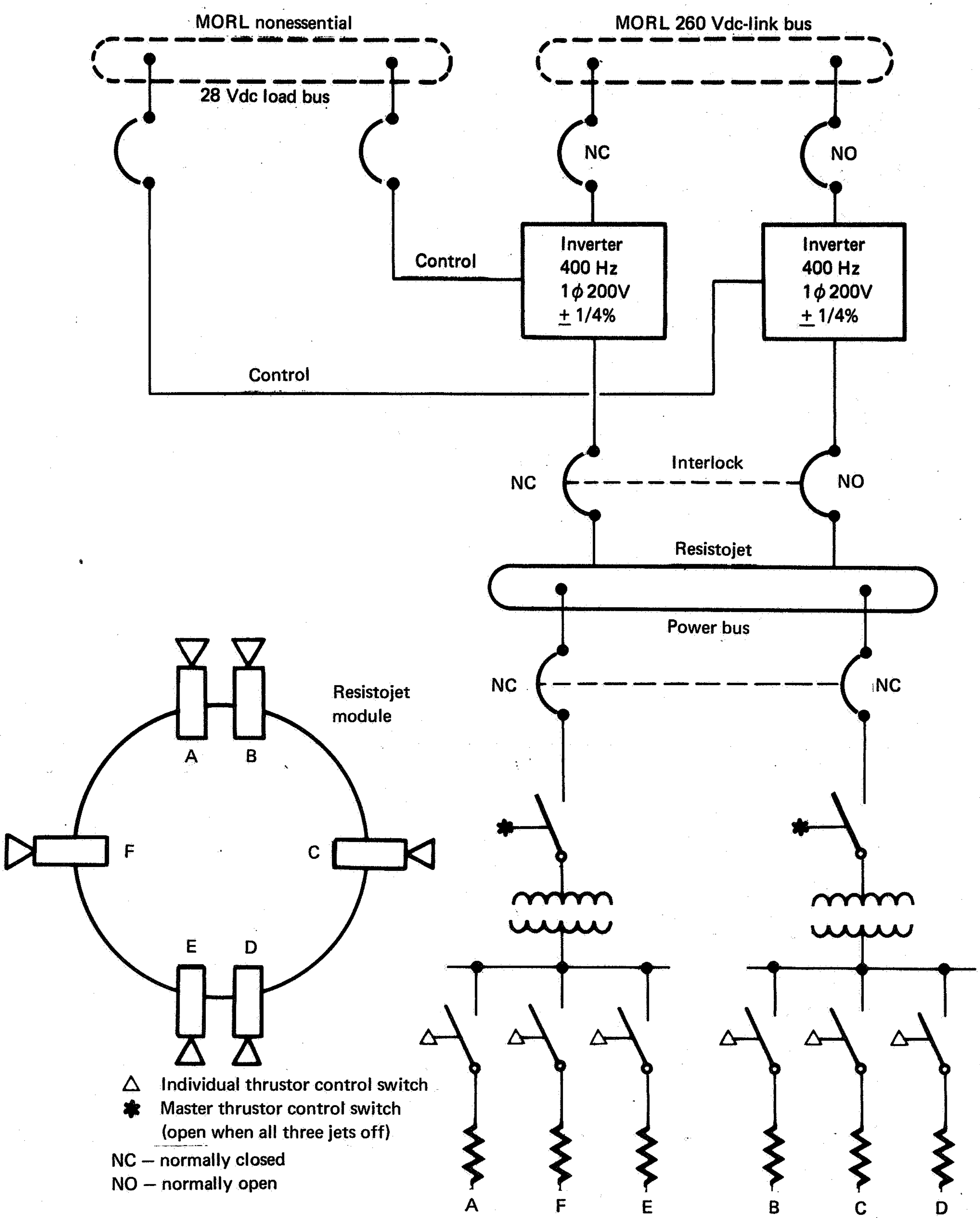


Figure 10. Resistojet Power System Schematic Diagram

Each transformer will dissipate 6.75 watts in the loaded condition. With no load on the secondary of the transformer, the unit would still dissipate 3.6 watts in core losses. To eliminate this unnecessary no-load loss, the system is designed to turn off the primary of the transformer if there is no secondary load.

Scheduled-disturbance control. — The scheduled-disturbance control system is a hydrazine monopropellant thrustor system which provides control through use of four thrustor modules mounted at $\pi/2$-rad (90°) intervals around the aft of the MORL. Each module contains three 44.5-N (10-lbf) thrust hydrazine engines (one roll and two pitch or yaw). See fig. 11. There is a meteoroid shield for the propellant valve end of the thrustors, and the nozzles are exposed to facilitate heat radiation. The modules may be replaced from the inside of the vehicle by means of turning four Dzus fasteners, disconnecting the fuel and electrical connections, and withdrawing or inserting the module by tipping, angling, and rotating it until the module clears the mounting hole. The module is located by pins, and this ensures correct alignment and installation. The performance of the selected system is summarized in table 5. The system provides the high thrust necessary to control the MORL vehicle during the periods of scheduled high disturbances, such as logistics vehicle docking and 9-g centrifuge operation. It also provides back-up attitude-control capability. Table 6 presents the impulse requirements for the system.

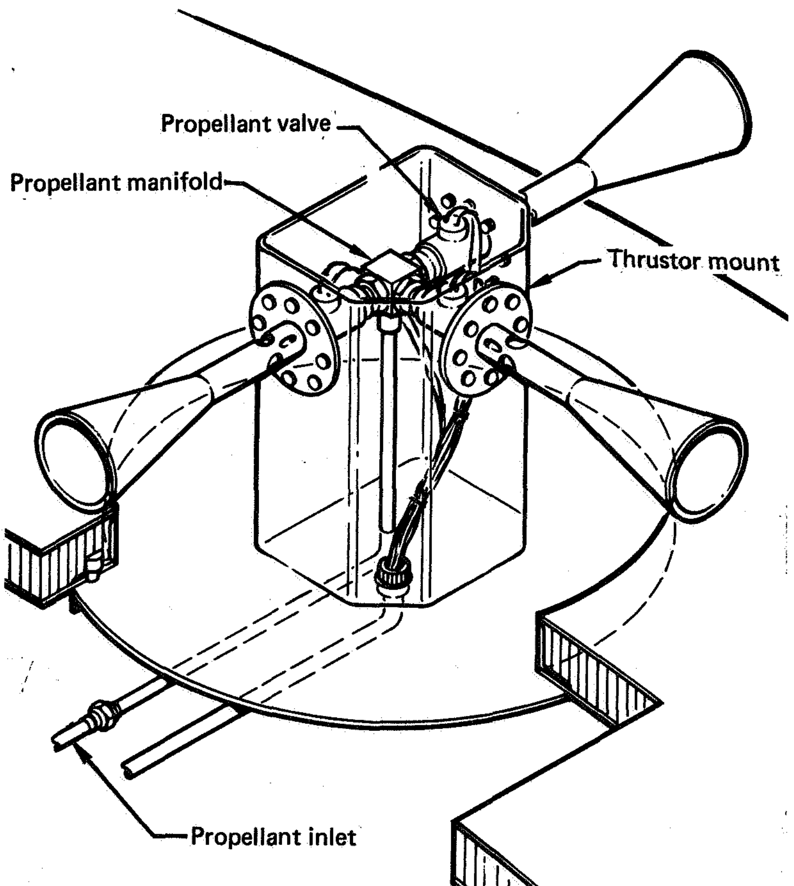


Figure 11. N_2H_4 Thrustor Module

The docking disturbance (based on typical Gemini and Apollo data) is illustrated in fig. 12, in which the logistics vehicle approaches the MORL at a relative velocity of 0.305 m/sec (1 fps), a lateral offset of 0.15 m (0.5 ft), and a vehicle centerline misalignment of 8.7×10^{-2} rad (5°). The combination of these errors results in a 4.35×10^{-3} rad/sec (0.25°/sec) tumble rate. As shown by the curve in fig. 12, the use of two 44.5-N (10-lbf) thrust engines in each axis will null the tumble rate in 17 sec, with a maximum resultant attitude error of $\pm 4.35 \times 10^{-2}$ rad ($\pm 2.5^\circ$). Since this point is on the knee of the curve, it represents an optimum choice in the tradeoff between thrust level and attitude error.

Disturbances are caused by centrifuge operation and are the result of providing a 1-g acceleration for normal crew conditioning and an acceleration

TABLE 5

MONOPROPELLANT SYSTEM PERFORMANCE CHARACTERISTICS

Parameter	Performance
Propellant	N_2H_4
Thrust/engine (12 engines)	44.5 N (10 lbf)
Total impulse (90 days)	1.03×10^5 N-sec (23 150 lbf-sec)
Mission specific impulse	188 sec
Propellant weight (90 days)	56 kg (123 lbm)
Chamber pressure	6.9×10^5 N/m^2 (100 psia)
Expansion ratio	50:1
Chamber temperature	1255°K (2260°R)
Delivered specific impulse (steady state)	235 sec

TABLE 6

REQUIREMENT FOR A SCHEDULED-DISTURBANCE CONTROL SYSTEM

Operation	Impulse/90 days	Pulse width (sec)
Limit cycle	8.9×10^3 N-sec (2 000 lbf-sec)	0.08
Docking	2.0×10^3 N-sec (450 lbf-sec)	11.0
Centrifuge	92.1×10^3 N-sec (20 700 lbf-sec)	0.25
Total	103×10^3 N-sec (23 150 lbf-sec)	

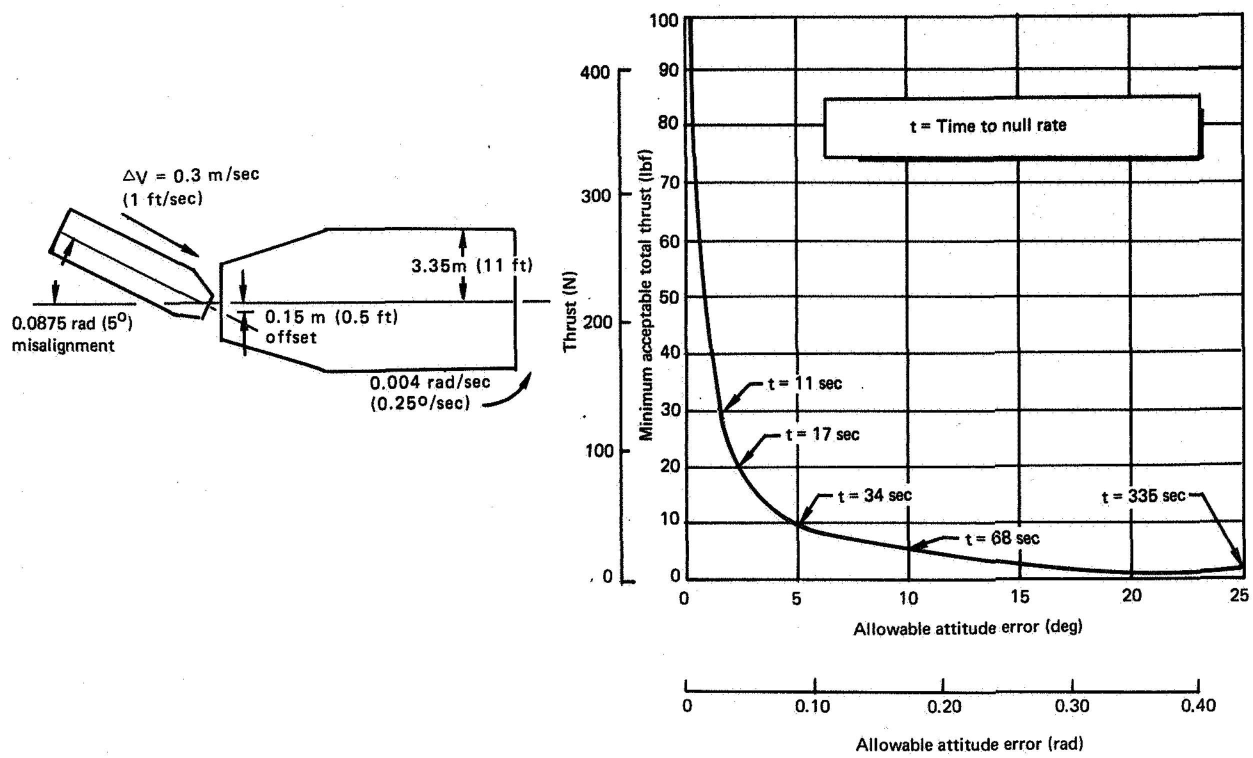


Figure 12. Docking Disturbance

profile peaking at 9-g for re-entry conditioning. The CMG's are sized to store the angular momentum generated by the 1-g operation. The disturbances from the 9-g acceleration are handled by the monopropellant engine.

The 9-g operation alternately accelerates and decelerates the occupants at realistic on-set rates to produce an approximation of the g forces experienced during re-entry. Each centrifuge run lasts about 20 min, including a 1-g hold for 15 min after the re-entry run to more closely simulate an actual re-entry. The peak angular-momentum and disturbance torque generated by the 9-g re-entry simulation is 11 900 N-m-sec (8800 ft-lbf-sec) and 81 N-m (60 ft-lbf), respectively.

During uncontrolled centrifuge operations, there is a momentum exchange between centrifuge and spacecraft which results in the attitude errors shown in fig. 13. The 9-g centrifuge operation produces a maximum roll rate of 0.012 rad/sec (0.7°/sec). At the end of the operation, the roll-attitude error would be 1.18 rad (68°). Pitch and yaw attitude errors are considerably smaller, at approximately 0.26 rad (15°), because a 9-g run extends over only a small portion of the total precession period. To control this disturbance, a 298 N-m (220 ft-lbf) roll moment is required. The scheduled-disturbance control system provides this through use of two 44.5-N (10-lbf) thrust roll engines fired as a couple. The pitch and yaw corrections are achieved by the 44.5-N thrust engines firing in those axes.

The scheduled-disturbance control system also acts as a backup attitude-control system for periods when the CMG's may be inoperative for maintenance. A minimum thrust level of 0.44 N (100 mlbf) on each axis was established on the basis of maneuvering from any orientation to the belly-down orientation. Any thrust level higher than this will be more than adequate; therefore, the system can provide the backup attitude-control function.

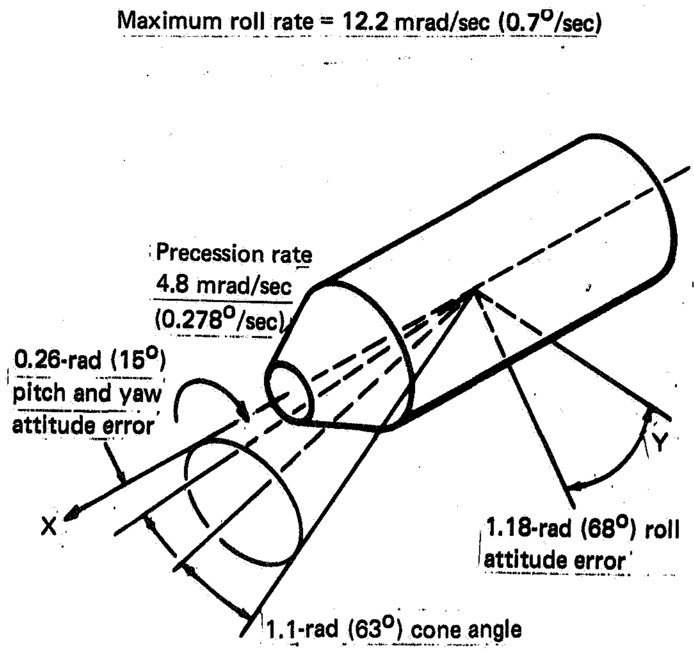


Figure 13. Centrifuge Disturbance

Six different reaction-control systems were initially considered to provide attitude control during the scheduled disturbances affecting the MORL. Three of these are referred to as heated-gas systems and include (1) a stored GN_2 reaction-control system, (2) a cryogenic H_2 system, and (3) an NH_3 system. The other three systems are conventional chemical-propulsion concepts and include (1) an O_2/H_2 cryogenic bipropellant reaction-control system, (2) an N_2O_4/MMH storable bipropellant system, and (3) an N_2H_4 monopropellant system.

The heated-gas systems take advantage of the available waste heat from the isotope Brayton-power system through use of a radiator-fluid heat exchanger. However, it was found that the waste heat is not available at temperatures high enough to greatly improve the propellant specific impulse.

Furthermore, the weights of the heated-gas systems increase with thrust levels, primarily because of the increased propellant weight that results from the low, delivered specific impulse. These factors--high weight and limited thrust capability, in addition to added system complexity--eliminated the heated-gas systems from further consideration.

The O_2/H_2 cryogenic bipropellant system was considered for use with the H_2 resistojet because of propellant commonality. It was found that this system offered no significant performance advantage over the storable bipropellant system because it was much more complex. It, too, was eliminated from further consideration.

The N_2O_4/MMH bipropellant and N_2H_4 monopropellant systems exhibited approximately the same dry weight, while the storable bipropellant requires somewhat less propellant because of its higher specific impulse. In spite of this slight disadvantage, the N_2H_4 monopropellant system was selected because of its relative simplicity, greater reliability, and lower development cost.

The selected system is shown schematically in fig. 14. This system uses hydrazine propellant, which is exothermally decomposed when it passes over a Shell 405 catalyst bed in the thrustor reaction chamber. The propellant is stored in redundant tanks at a pressure of 1722.5×10^3 N/m^2 (250 psia) and an ambient temperature of $324.8^\circ K$ ($585^\circ R$). A metal bellows positive-expulsion system is used to ensure compatibility with the stored propellant over the 5-year mission. This bellows system may be recycled to allow for propellant resupply from the logistics vehicle. Pressurization of the propellant tank is provided by redundant 206.7×10^5 N/m^2 (3000-psia) nitrogen bottles which are allowed to blow down to a minimum of 20.67×10^5 N/m^2 (300 psia) over the 147-day period, thereby ensuring that a propellant tank pressure of 1722.5×10^3 N/m^2 (250 psia) can be maintained at all times.

Biowaste utilization. — The biowaste outputs from the MORL open-loop EC/LS system that are available as propellant for a resistojet control system are (1) CO_2 from the molecular-sieve beds, (2) H_2, a by-product of the water electrolysis system, and (3) fecal water (H_2O) from fecal waste. (See fig. 15.) These EC/LS outputs were evaluated to establish the most advantageous biowaste resistojet system. In this evaluation, the best collection systems for each of the outputs were established, with the primary criterion being the collection power requirement. It was also necessary to determine the resistojet performance and power requirements of the biowaste propellants as used individually and in combination. The result of this evaluation was the selection of an all-CO_2 biowaste resistojet system for the MORL. This system was then compared with the cryogenic H_2 and NH_3 resistojet systems for both open-loop and closed-loop (O_2 regeneration) EC/LS systems.

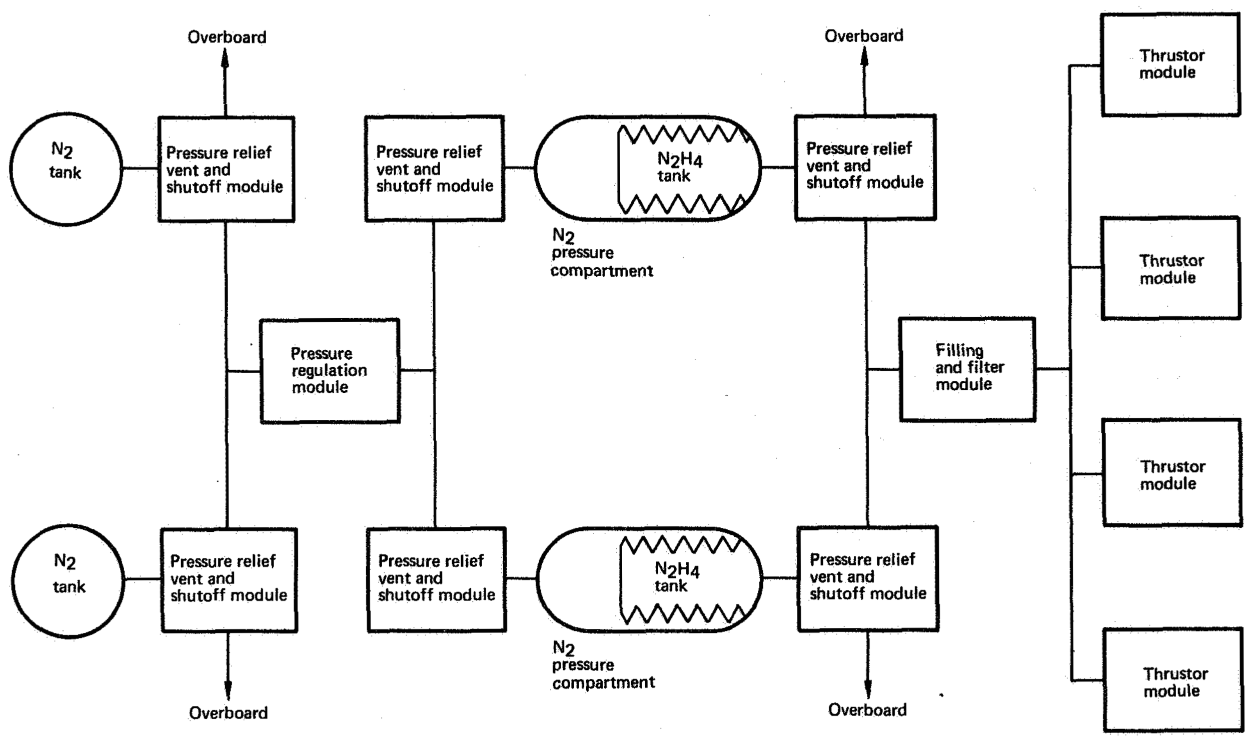


Figure 14. Monopropellant N_2H_4 System

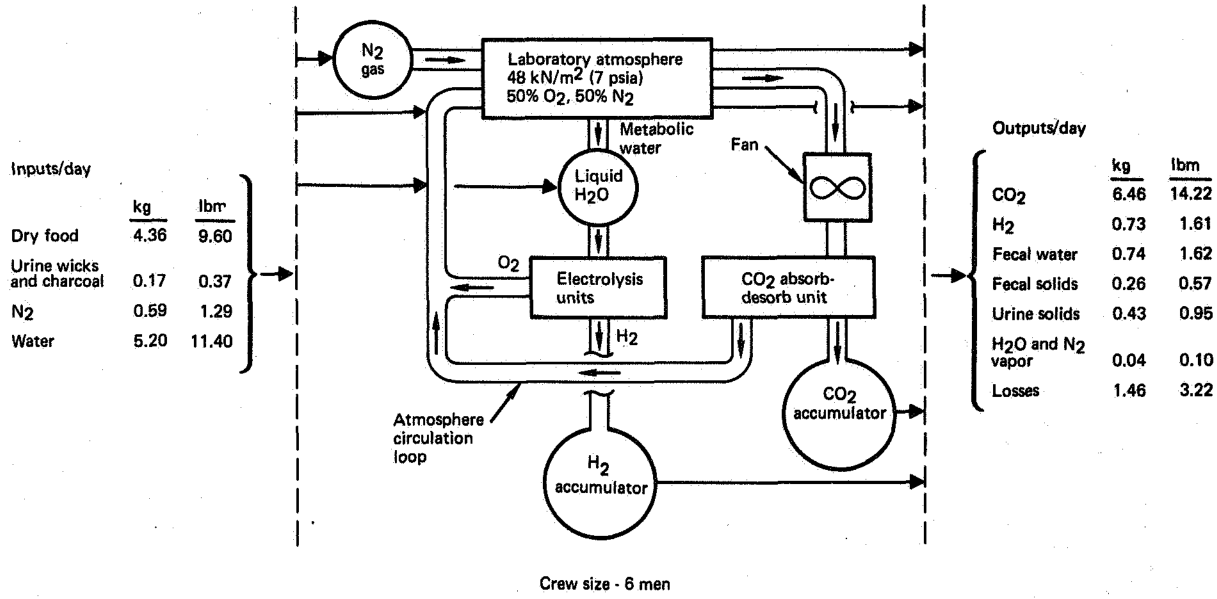


Figure 15. EC/LS System – Approximate Mass Balance

The following paragraphs delineate the collection systems evaluated, define the collection system selected for each biowaste output, and compare the collection systems with regard to power and weight.

The CO_2 collection system, shown in fig. 16, consists of a three-stage compressor with intercooling heat exchangers, an accumulator, and the associated valves and plumbing. CO_2 is desorbed from the molecular-sieve beds. The beds control the partial pressure of CO_2 in the atmosphere and are normally desorbed by the application of waste heat to the bed material and simultaneous exposure directly to space. The CO_2 can be collected instead of vented to space by means of pumping the bed down to a desorption pressure of 1.38×10^4 N/m^2 (2 psia) and discharging to an accumulator at the desired storage pressure. A storage pressure of 1.03×10^6 N/m^2 (150 psia) was selected as a result of a tradeoff of thrustor power, collection power, compressor weight, and accumulator volume.

Two methods of H_2 collection were analyzed: (1) compression and storage of the H_2 after it leaves the electrolysis cells and (2) operation of the electrolysis cells at a pressure sufficient to vent the H_2 at the desired pressure. The second method was chosen, since it resulted in lower weight and power penalties. (See fig. 16.) Cell operation at high pressure is achieved by increasing the reference water pressure. This method is particularly

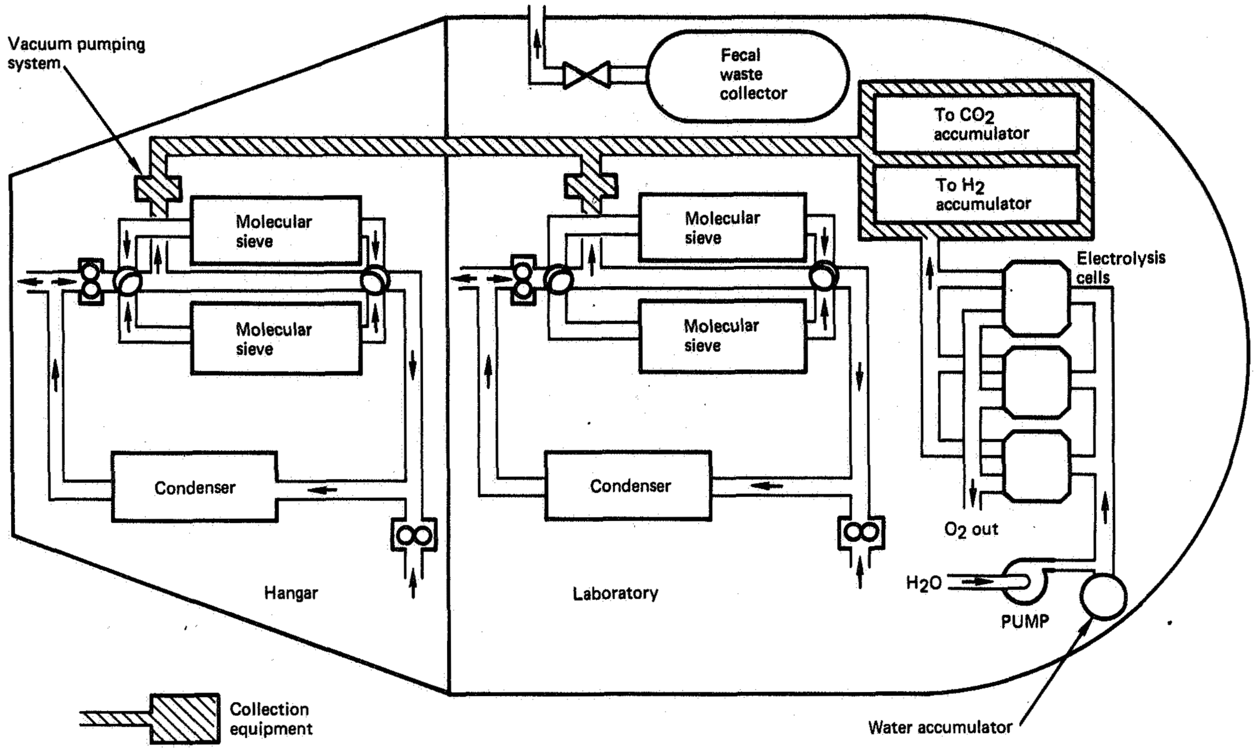


Figure 16. EC/LS Collection System

attractive because a water accumulator actually feeds the electrolysis cells, and the water-pump accumulator is designed so that an entire day's water supply is pumped to operating pressure in only 6 min. Thus, the water-pumping power penalty is negligible. As the reference water pressure is increased, the O_2 accumulator pressure is also automatically increased [1.03×10^4 N/m^2 (1.5 psia)] above the water pressure, thus minimizing the size of the O_2 accumulator.

Several concepts for collecting water were evaluated on the basis of a total vehicle system analysis. The selected concept operates on the principle of waste-heat evaporation with pyrolysis of the vapors. This process is the same as the one used on the baseline MORL. Wastes are collected in a spherical tank which, when filled, is replaced by an empty one. Instead of venting the tank to space between uses, a heating loop evaporates water from the feces, and a vapor pyrolysis/condensation loop collects sterilized water. The water storage tank has a bladder that expells the contents for use by the reaction-control system. The fecal-water collection system requires an additional 25 watts of power and weighs approximately 18 kg (40 lbm).

The weight and power penalties for the H_2, CO_2, and fecal-water collection systems are compared in fig. 17. From the standpoint of weight and power, the fecal-water collection method was therefore eliminated from

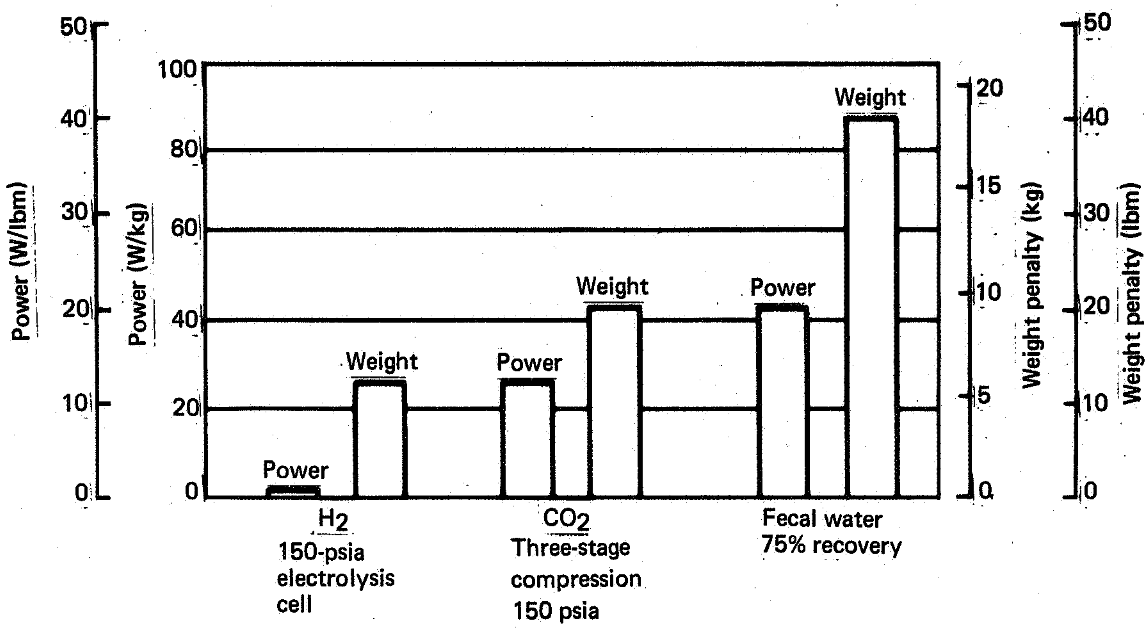


Figure 17. Biowaste Collection Penalties

further consideration. For comparative purposes, a figure-of-merit for power consumption is shown, which is the average power (in watts) required to collect the daily output, divided by the daily output in pounds.

Table 7 summarizes the performance and power requirements for the biowaste propellants used individually and in combination. The delivered specific impulse and the resistojet minimum-required power are based on the selected operating point of 2.76×10^5 -N/m^2 (40-psia) chamber pressure and 1665°K (3000°R) chamber temperature. Higher chamber temperatures are not feasible because of the oxidizing nature of CO_2 and water vapor. Analysis of test data on water electrolysis cells show that the H_2 output also contains sufficient oxidizing impurities to warrant its classification as an oxidizing propellant. The data indicate that the usage of biowaste mixtures has a significant increase in performance over independent usage (that is, the same total propellant quantities fired in separate thrustors for each propellant). This gain is attributable to the chemical kinetic effects of the reaction. However, the use of biowaste combinations results in increased complexity in control and hardware.

CO_2 individually can provide the required daily total impulse of 8.32×10^3 N-sec (1870 lbf-sec) with sufficient margin for increasing requirements. H_2 can provide 4.31×10^3 N-sec/day (970 lbf-sec/day) if used independently. The MORL daily total impulse can also be obtained with

TABLE 7

BIOWASTE RESISTOJET PERFORMANCE AND POWER REQUIREMENTS[a]

Propellant or propellant combinations	Delivered specific impulse, sec	Resistojet minimum[b] required power, watts	Usable daily output, kg	(lbm)	Daily[c] total impulse, 10^3 N-sec	(lbf-sec)
H_2 (biowaste)	602	143.0	0.73	(1.61)	4.31	(970)
CO_2	177	41.5	6.45	(14.2)	11.3	(2535)
H_2O (fecal)	246	103.0	0.55	(1.21)	1.32	(298)
0.9 CO_2 + 0.1 H_2 (mixture)	255	72.0	7.20	(15.83)	18.0	(4050)
0.9 CO_2 + 0.1 H_2 (independent usage)	221	69.6	7.20	(15.83)	15.6	(3505)

[a]0.044-N (10-mlbf) thrust; $P_c = 2.76 \times 10^5$ N/m^2 (40 psia), $T_c = 1665^\circ$K.

[b]100% heater efficiency.

[c]MORL daily total impulse requirement--8.32 x 10^3 N-sec (1870 lbf-sec).

combined usage of biowaste H_2 and CO_2 if it is desired to take advantage of the H_2 high specific impulse. Fecal water can provide a daily total impulse of only 1.32×10^3 N-sec (298 lbf-sec) and has the highest specific impulse-to-power ratio. This fact, combined with the highest collection power penalty (see fig. 17) and the difficult storage and usage requirements, makes the utilization of fecal water unattractive.

As a result of this evaluation, a preliminary definition of an all-CO_2 biowaste resistojet system and a combined biowaste H_2 + CO_2 resistojet system was made. Each system provides a daily total impulse requirement of 8.32×10^3 N-sec/day (1870 lbf-sec/day).

Table 8 summarizes the significant performance parameters of the two systems. One used CO_2 alone, the other uses all the H_2 output available, plus sufficient CO_2 to make up the required total impulse. The values shown are based on collecting only that propellant required to satisfy the total impulse requirements. The excess is vented overboard, thus reducing the collection penalty.

The CO_2 system is simpler and requires less power. The CO_2/H_2 system is attractive because it is potentially capable of greater total impulse if required by future changes in mission definition. The CO_2 system, however, is the most advantageous biowaste system for the specific MORL mission on which the study is based.

TABLE 8

MORL BIOWASTE-PROPELLANT CANDIDATES

Performance parameters	CO_2	$0.678\ CO_2 + 0.322\ H_2$
Delivered specific impulse[a]	178 sec	373 sec
Required resistojet power[a]	42.0 watts	100.5 watts
Collection power[b]	52.0 watts	18 watts
Total power	94.0 watts	118.5 watts
Daily CO_2 quantity[b]	4.8 kg (10.5 lbm)	1.55 kg (3.41 lbm)
Daily H_2 quantity[b]	0	0.73 kg (1.61 lbm)
Daily total propellant quantity	4.8 kg (10.5 lbm)	2.28 kg (5.02 lbm)
Specific impulse-to-power ratio	1.87 sec/watt	3.14 sec/watt

[a] 0.044 N, 2.76×10^5 N/m^2, 1665°K (10 mlbf, 40 psia, 3000°R).
[b] 8.32×10^3 N-sec/day (1870 lbf-sec/day).

To further evaluate the potential of the biowaste resistojet system, a comparison was made between the CO_2 resistojet system and the NH_3 or H_2 resistojet system with closed-loop EC/LS.

In the closed-loop or O_2 regeneration mode, the CO_2 and H_2 are not available for propulsion but are recombined in a hydrogenation unit to form water and carbon. The water is then recycled through the electrolysis units. The use of the closed-loop system results in the addition of 116 kg (255 lbm) of O_2-regeneration hardware, which is offset by the saving of 114 kg (250 lbm) of water and tankage weight. However, an assessment penalty must be imposed for an increase in the power requirement of 288 watts and for system reliability, maintainability, and operability considerations. Spare parts will be required for the added hardware, and crew time will increase for monitoring, operating, and maintaining the more complex closed-loop system. In return for these penalties, the make-up water which is normally resupplied is not required, resulting in a net reduction in combined reaction-control system and EC/LS logistics weight.

An evaluation of launch weight, power, and logistics requirements was performed for the MORL baseline system and is summarized in table 9. The table shows that the biowaste CO_2 resistojet system with an open-loop EC/LS system has a significantly lower system launch weight and electric-power requirement than the H_2 and NH_3 resistojets with the closed-loop EC/LS system. The logistics resupply weight is, however, higher for the biowaste system. This assessment shows that even with O_2-regeneration capability, a biowaste CO_2 resistojet system operating with an open-loop EC/LS system is still competitive if launch penalties are involved. A detailed study of the vehicle and its mission objectives must be performed, and the results will depend primarily on the criteria established for assessment.

The biowaste system will appear more advantageous for a vehicle with a basic open-loop EC/LS system since, normally, it is not simple to convert an open-O_2 EC/LS system to a closed-O_2 EC/LS system. O_2 regeneration is an alternate operating mode for MORL, and many other changes to accommodate O_2 regeneration are already included in the baseline system. These include water electrolysis, CO_2-collection capability, increased waste-heat provisions, and increased capability for waste-heat rejection. If a total tradeoff is accomplished, an even more pronounced launch weight and operating-power advantage may occur for a biowaste CO_2 resistojet system. Furthermore, the advantage of the biowaste system is enhanced with increasing vehicle impulse requirements. In this event, the resistojet power requirements and resistojet-system launch weights would show increased system gains. The most noticeable effect, however, would be in logistics resupply, which would increase for both the H_2 and NH_3 systems and reduce the resupply advantages of these systems.

TABLE 9

INTEGRATED EC/LS RESISTOJET SYSTEM COMPARISON

EC/LS system	Closed loop H_2	Closed loop NH_3	Open loop CO_2
Resistojet system			
Thrustor system avg power	574 watts	366 watts	236 watts
Oxygen regeneration power	388 watts	388 watts	---
Total power	962 watts	754 watts	236 watts
Weight assessment for power at 136 kg/kW (300 lbm/kW)	169 kg (372 lbm)	130 kg (287 lbm)	44 kg (97 lbm)
Resistojet system launch weight	140 kg (307 lbm)	127 kg (280 lbm)	54 kg (119 lbm)
Oxygen-regeneration hardware weight	116 kg (255 lbm)	116 kg (255 lbm)	--- ---
Open-loop water and tankage weight	--- ---	--- ---	114 kg (250 lbm)
Total chargeable launch weight	425 kg (934 lbm)	373 kg (822 lbm)	212 kg (466 lbm)
Total chargeable 90-day resupply weight	238 kg (525 lbm)	296 kg (653 lbm)	467 kg (1030 lbm)

RESISTOJET DEVELOPMENT AND TEST

The objective of this phase of the study was to develop and test a resistojet thrustor to demonstrate the performance predictions used in the MORL Phase IIB Study. This work was performed by The Marquardt Corporation under subcontract to Douglas.

Two models of the 0.044-N (10-mlbf) resistojet were constructed. Both had essentially the same heat-exchanger design. Model I demonstrated the feasibility of using rhenium in the fabrication of high-temperature elements. Model II incorporated design changes primarily for improved component fabricability and ease of assembly.

Table 10 summarizes the design parameters of both models for operation on H_2 and NH_3. Model II takes advantage of a higher chamber pressure and, hence, lower gas temperature for the same delivered specific impulse, as shown in figs. 18 and 19. This change gives a greater life from sublimation. Further improvement with increased chamber pressure is limited by the lowest practical diameter for the nozzle throat.

Fig. 20, a cross-section of Model II, shows the improved version which is to be the subject of life testing. The heat-exchanger elements were made by the rhenium vapor-deposition process (reaction of rhenium pentachloride on H_2 gas at 970°K). In this process, rhenium is deposited in a controlled

TABLE 10

0.0445-N (10-mlbf) RESISTOJET PERFORMANCE SUMMARY

Parameter	Model I		Model II	
	H_2	NH_3	H_2	NH_3
Specific impulse (sec)	718	347	720	348
Propellant flow (g/sec)	0.00633	0.0131	0.00631	0.01305
Electric power (watts)	245	168	226	154
Terminal voltage (volts)	6.0	4.95	5.71	4.71
Current (amperes)	40.9	33.9	39.6	32.7
Initial power in gas (watts)	26	8	26	8
Total power (watts)	271	176	252	162
Overall efficiency				
Total power (η_o)	0.58	0.43	0.62	0.47
Electric power (η_o^*)	0.641	0.45	0.692	0.49
Nozzle (power) efficiency	0.63	0.53	0.66	0.55
Heater efficiency (η_H)	0.92	0.81	0.94	0.85

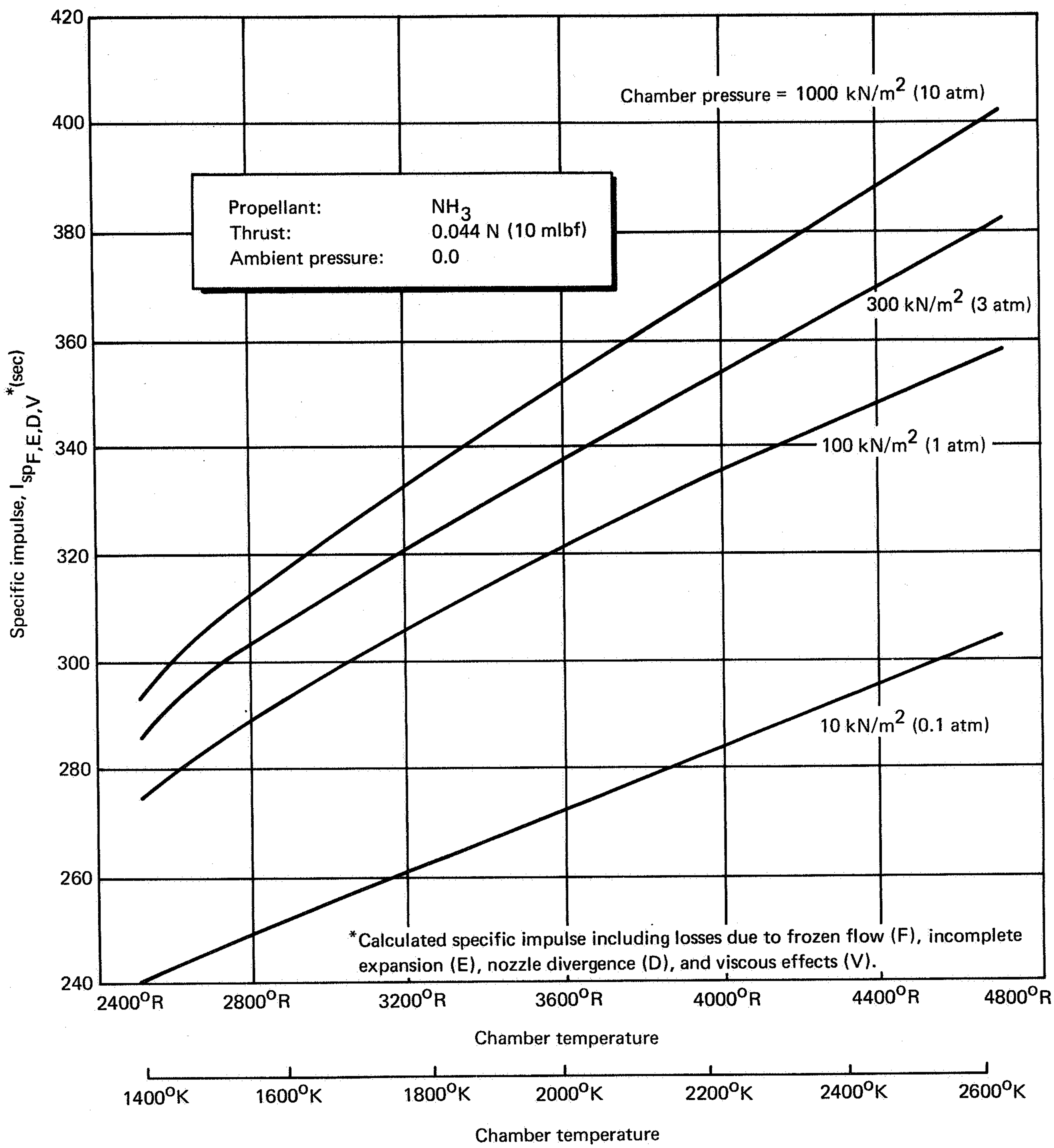


Figure 18. Resistojet Delivered Specific Impulse – NH_3

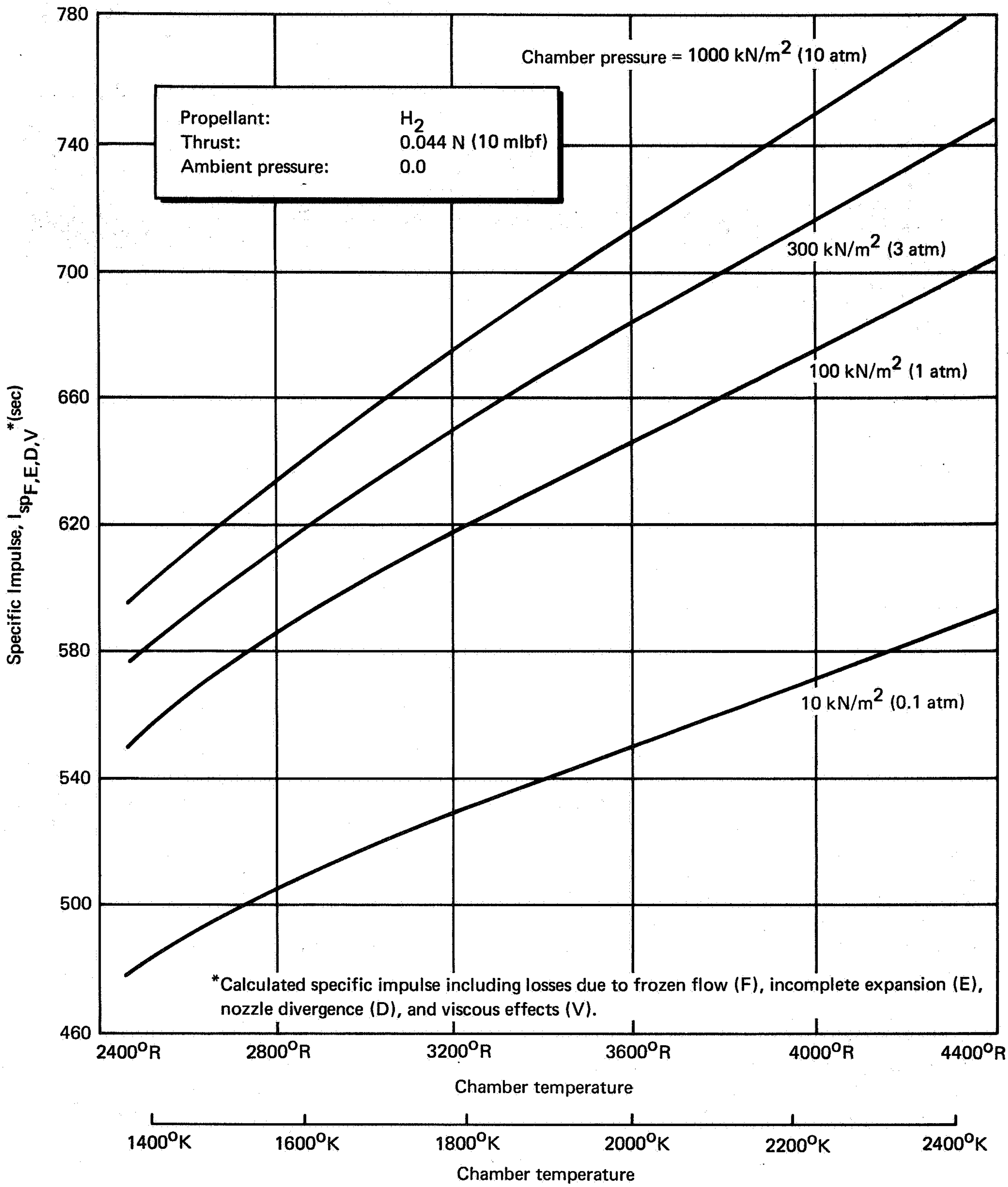
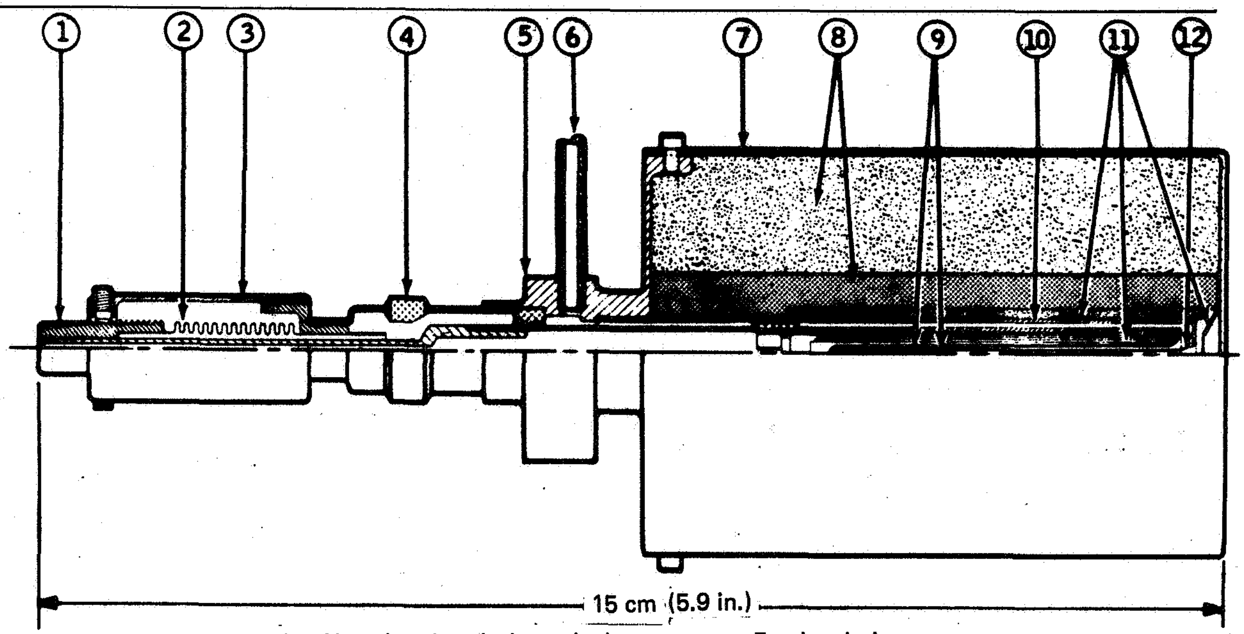


Figure 19. Resistojet Delivered Specific Impulse – H_2



1	Negative electrical terminal	7	Insulation cover
2	Thermal expansion compensator	8	Thermal insulation
3	Guide	9	Heating elements
4	Electrical insulator	10	Pressure case
5	Mounting flange	11	Radiation shields
6	Propellant inlet and positive terminal	12	Nozzle

Figure 20. Model II Resistojet Thrustor

manner on titanium mandrels that are precision machined to the inside contour of the heat-exchanger element. The finished outside diameter or contour is then obtained by precision grinding with special diamond tools. The mandrels are subsequently removed by a solution of hydrofluoric acid.

On the Model II, the pressure cases were rolled and tungsten-inert-gas (TIG) welded from sintered rhenium sheets. The rhenium parts are assembled by electron-beam welding. The fittings are joined by gold brazing (82% gold/18% nickel). Since there are no sliding joints, as in previous models, a bellows is included to prevent yielding or bowing of the heater tube by differential thermal expansion. The assembly is pressure-balanced against the bellows spring force so as to have negligible axial load on the inner element. The welded assembly eliminates sudden changes in electrical characteristics which were inherent in earlier models with sliding joints.

The resistojet requires an electrical insulator which must be tightly sealed to two metal parts; previously this was done with a boron-nitride insulator and mechanical compression seals. However, some doubt exists as to the ability of this arrangement to withstand high temperatures, as well as pressures and temperature cycles for long periods of time. The adoption of insulator joints of ceramic brazed to stainless steel has solved the problem. Since this type of joint is smaller and is in a cooler location [as shown in fig. 20 (part no. 4)], the possibility of failure is further reduced. Boron-nitride is used for electrical insulation only in relatively cool locations when H_2 is present.

Experimental Results

Six development thrustors were built and extensively tested for an accumulated period of over 300 hours at temperatures in excess of 2200°K (3960°R). Two were Model I's and four were Model II's. The heat exchangers differed in the fabrication techniques of the rhenium elements.

The Model I thrustor first demonstrated that the rhenium could be used to fabricate high specific-impulse miniature electrothermal thrustors. The general, semi-empirical, performance-prediction method for the candidate propellants in small rockets was verified experimentally for NH_3 and H_2 with these thrustors. Fig. 21 shows the performance of the Model I thrustors. The specific-impulse goals were essentially achieved with a value of 739 sec on H_2 and 344 sec on NH_3. The thermal-insulation design, while effective at the start of test (heater efficiency $[N_H] = 0.93$ and 0.81 for H_2 and NH_3, respectively), deteriorated rapidly over a period of 25 hours.

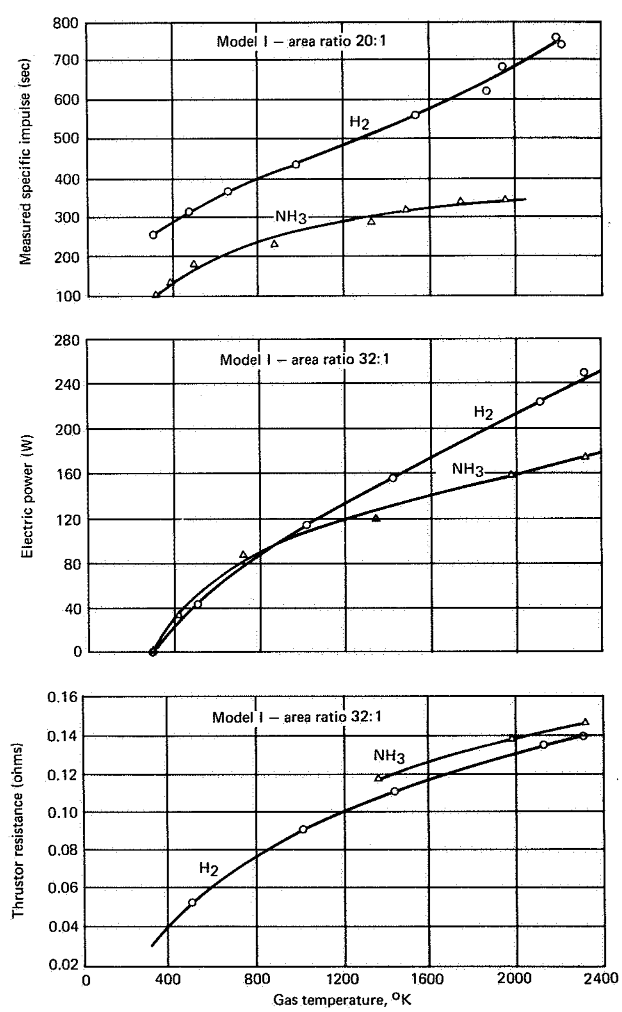


Figure 21. Performance Characteristics – Model I Resistojet

The external thermal-insulation package for Model II consists of three stages of insulation material: thin, multiple-radiation shields, followed by two stages of low-conductivity insulation, the last stage being Min K-2000 with a thermal conductivity of 4.6×10^{-4} watts/cm°K at a continuous service temperature of 1270°K. The capabilities of this package were subsequently demonstrated in a 100-hour test on H_2 at a specific impulse of 750 sec. The maximum skin temperature was about 570°K (1025°R).

There were no dimensional changes in the nozzle throat during the 100-hour tests. This is an important result since it is a controlling parameter under the constant-supply pressure mode of operation.

In operation, critical loading on the inner element, both steady-state and transient, requires a design employing the smallest possible bellows diameter for thermal-expansion compensation. The bellows spring constant must be chosen so that the thermally induced force through the bellows is balanced at design by the pressure (piston) force. Thermal creep will otherwise occur at the high temperature considered. Proper balancing produces a stable design.

Design Verification Tests

Model II (shown in fig. 22) met all the objectives of the design verification tests. These tests demonstrated the ability to start and stop suddenly from the high specific-impulse condition and showed a stable performance of an operation period of 20 hours each at >680 sec for H_2 and >320 sec for NH_3. The unit was cycled from full power on H_2 at a 67% duty cycle for 24 hours and, similarly, on NH_3 for 3 hours. Total testing of 80 hours was accomplished on this unit.

In these tests, no special effort was made for high-response values or automatic timing; hence, thrust response was of the order of a few seconds. The tests did demonstrate that simple on-off control of propellant pressure and voltage was adequate. The unit reached 95% of design values (thermally) within 300 sec after a nonpowered period of 30 min.

It is important to note that the cell pressure must be significantly lower than that required to give a nozzle-pressure ratio predicted by inviscid flow theory. An effect not well understood with viscous nozzles is that a pressure of 10 microns Hg is required to represent space performance. Tests were taken at 10 microns Hg. The performance, represented by figs. 23 and 24, must therefore be considered conservative; this partially explains the difference from the theoretical performance predictions (the dashed curve in fig. 23).

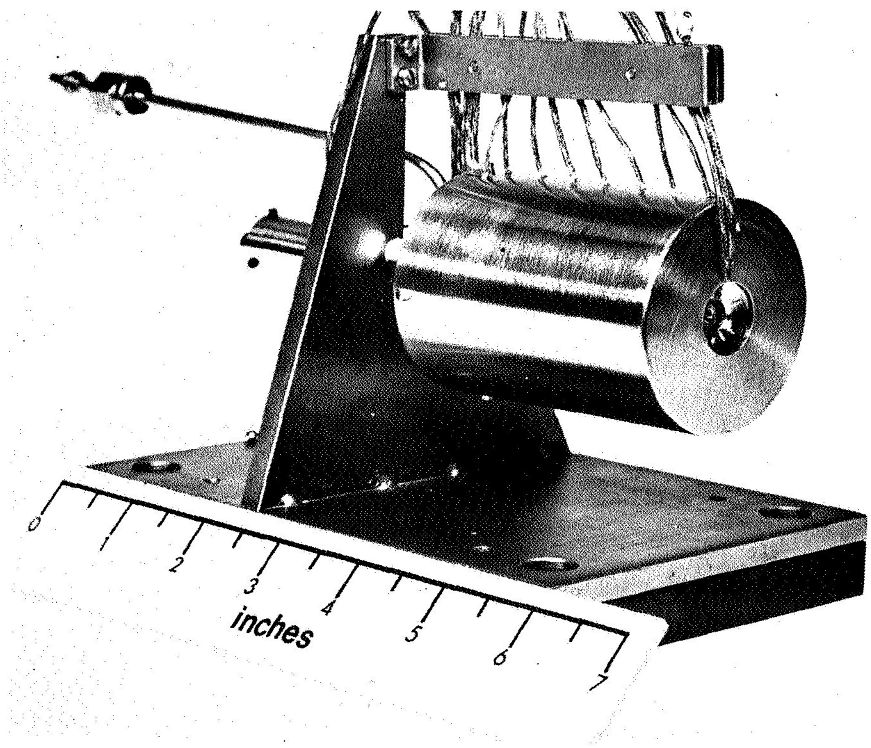


Figure 22. Model II Resistojet after Design Verification Tests

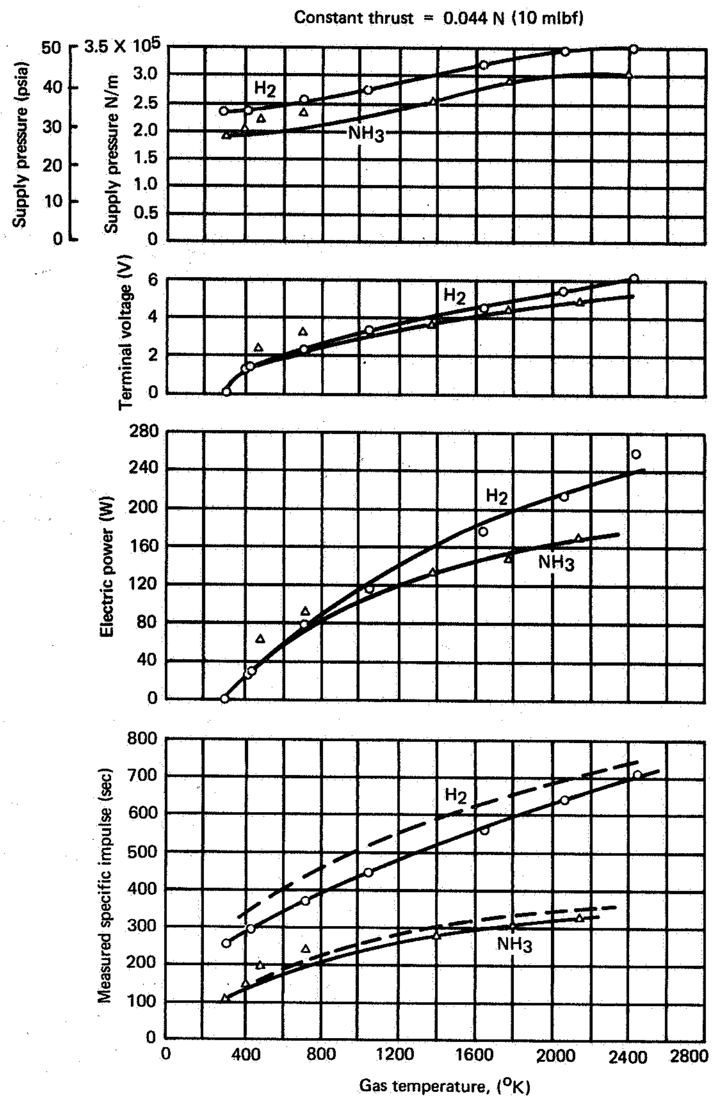


Figure 23. Performance Characteristics – Model II Resistojet

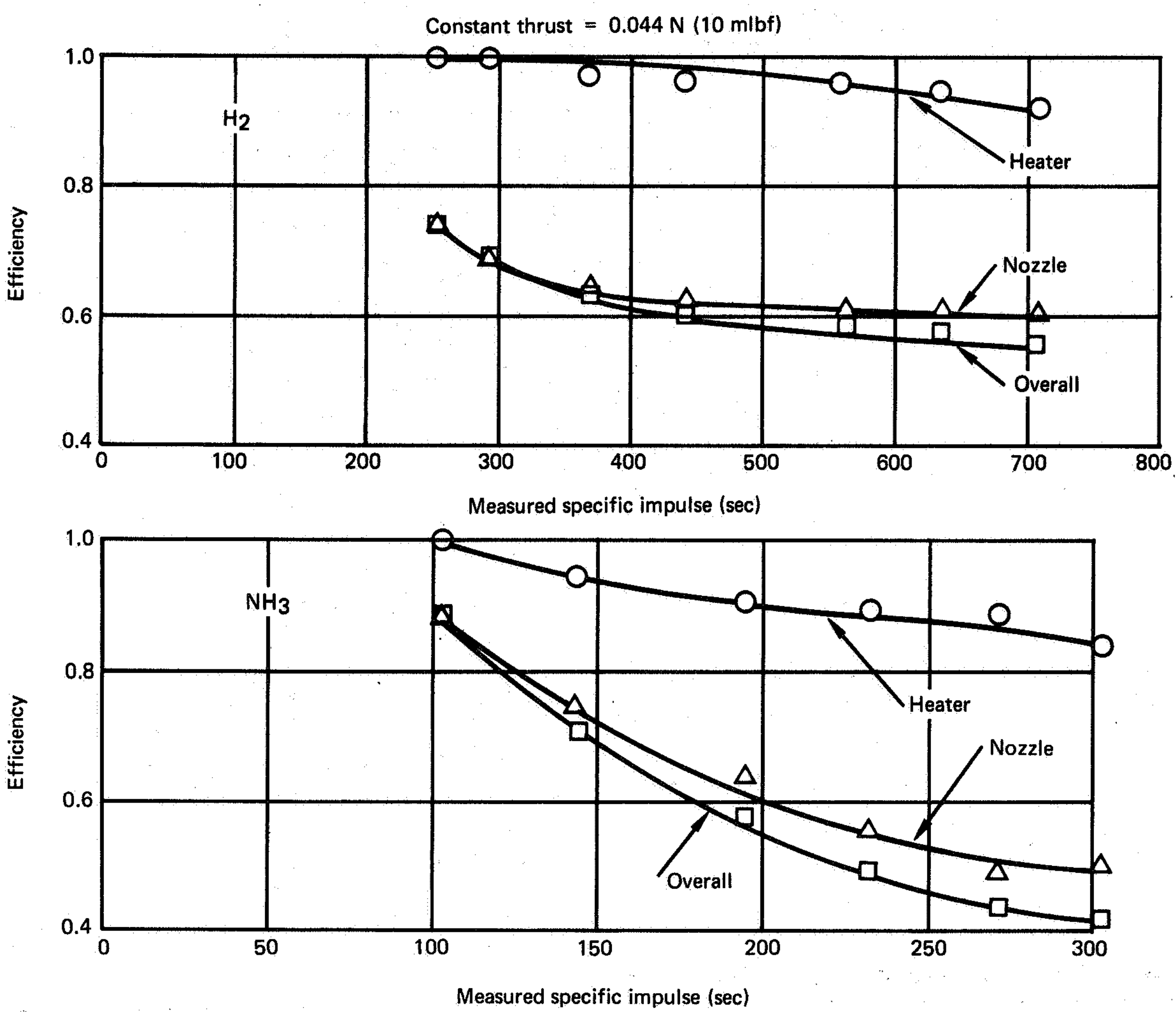


Figure 24. Power Efficiencies – Model II Resistojet

RECOMMENDATIONS FOR MODIFICATIONS TO BASELINE MORL

The significant changes to the baseline MORL subsystems which are recommended as a result of this study are as follows:

(1) The use of an NH_3 resistojet-thrustor system for desaturating the CMG's and for orbit keeping. This system replaces the storable-bipropellant system which used nitrogen tetroxide (N_2O_4) and monomethylhydrazine (MMH) propellants.

(2) The use of a monopropellant N_2H_4 thrustor system that provides a total of 89-N (20-lbf) thrust in each axis for controlling such high disturbances as those caused by docking or by 9-g centrifuge operation.

(3) The elimination of the need for the MORL reaction-control thrustors to provide the orbit-injection impulse. This impulse can be provided more effectively by the S-IVB if the availability of a mainstage engine capable of operating at a reduced thrust can be assumed. The J-2S engine satisfies this requirement and is therefore the recommended system. This change will enable the MORL reaction-control thrustors to be optimized for the mild duty cycle associated with controlling the spacecraft during high disturbances.

(4) A modification to the EC/LS system which will enable it to operate the electrolysis cells at 1030 kN/m^2 (150 psia) regardless of whether biowaste H_2 is used as a propellant. This change is justified by the large reduction in volume at a small increase in weight for both the O_2 and H_2 accumulators.

The net results of these recommended changes are as follows:

(1) The launch weight of the MORL is reduced by 330 kg (725 lbm) (see table 11). If the resistojet system is assessed with a weight penalty proportionate to its share of the total power demand, the weight advantage is reduced by 69 kg (151 lbm), for a net advantage of 261 kg (574 lbm). This net advantage, coupled with a decrease in S-IVB weight because of the J-2S engine, results in an increase in discretionary payload of 758 kg (1665 lbm).

(2) The 90-day resupply weight chargeable to the system is reduced by 68 kg (150 lbm).

(3) The resupply and transfer of an oxidizing propellant, with the possible hazards of hypergolocity, toxicity, and corrosiveness, are eliminated.

TABLE 11

WEIGHT COMPARISON SUMMARY

System	Bipropellant (Phase IIB)		NH_3 Resistojet/ N_2H_4 Monopropellant	
MORL	kg	(lbm)	kg	(lbm)
Chargeable weight at launch	548	(1 205)	218	(480)
Weight assessment for electrical power	---	---	69	(151)
Total	548	(1 205)	287	(631)
Reference payload*	16 437	(36 165)	17 195	(37 830)
Logistics vehicle				
Chargeable weight at launch/90 days	448	(985)	380	(835)

*Weight capability to a 304-km (164-nmi) orbit minus propulsion-chargeable launch weight and weight assessment for power.

GROUND AND FLIGHT TEST PLAN

The selection of an NH_3 resistojet reaction-control system for the MORL necessitated the definition of a test program to achieve an operational system. This section summarizes the recommended approach for demonstrating operational capability of the resistojet control system. This approach consists of a flight test of an experimental resistojet system, preceded by limited ground qualification test.

The established test programs were based on an evaluation of the resistojet system current status, the potential launch and operational requirements, and the system operational life requirements. Careful evaluation of the Apollo Applications Test Requirements (ref. 5) for systems with long-duration operation and/or open-ended missions showed that schedule and cost constraints would prohibit full-duration ground qualification testing. Therefore, the test program philosophy limits the ground qualification test to only a demonstration of the system's flight worthiness. This is followed by flight test of an experiment system to demonstrate operational capability.

Successful completion of the program will permit the use of a resistojet control system to provide CMG desaturation and orbit keeping of advanced Earth-orbital spacecraft. The use of such a low-thrust system will permit the attainment of the increasingly stringent requirements for spacecraft orientation that are imposed by sophisticated astronomical experiments. Such a system would also minimize, if not totally eliminate, the environmental contamination of the spacecraft that is caused by particulate exhaust products from conventional rocket engines. The resistojet system would provide the necessary impulse at low-thrust and low-noise levels, eliminating these disturbing effects on the spacecraft, the operating experiments, and the astronaut activities. In addition, since the resistojet system uses a single propellant and provides a higher specific impulse than the conventional bipropellant engines, the amount of propellant and the resupply complexity are significantly reduced. The combined effects of these system advantages justify the qualification and flight-worthiness efforts required to permit usage of a resistojet system on the long-duration manned spacecraft anticipated for the next decade.

The flight test was formulated to accomplish the following objectives:

(1) Demonstrate the resistojet's capability to control the spacecraft.

(2) Demonstrate the astronaut's ability to perform system maintenance.

(3) Demonstrate propellant resupply.

(4) Operate the experiment for a sufficient duration to permit the post-test prediction of the system's operational life.

(5) Provide for recovery of one or both thrustor modules for post-flight examination.

The equipment to be used in both ground and flight testing consists of the following assemblies: tankage fill and drain, propellant feed, power control, command controller, thrustor module (two required), and propellant resupply (see fig. 25). The recommended propellant for the experiment system is NH_3, but the potential use of LH_2 resulted in the definition of an alternate propellant tankage and feed assembly.

The thrustor modules are to be mounted diametrically opposed on the vehicle shell. The other assemblies are to be mounted in an unpressurized area of the spacecraft, except for the command controller, which is to be installed in the spacecraft control console. The launch weight, volume, and power requirements for both the NH_3 and H_2 experiment systems are summarized in table 12.

The above described experiment system will be used in the flight test program--a 26-month effort--consisting of system manufacturing, vehicle installation, orbital operations, and experiment evaluation phases.

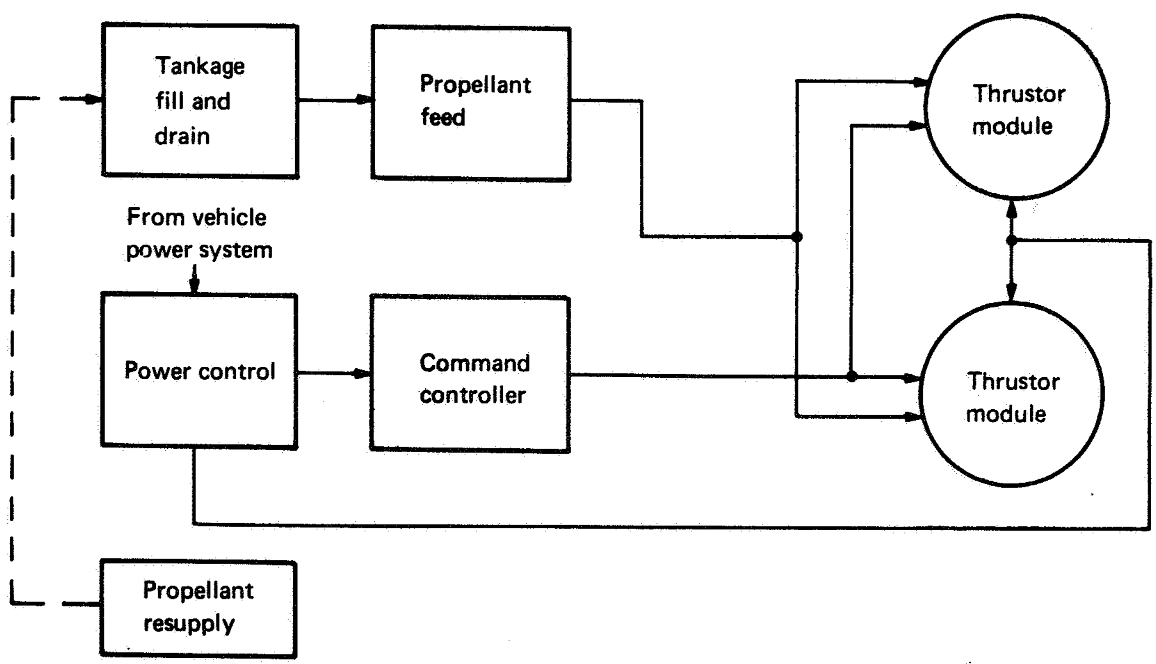


Figure 25. Resistojet Control System Experiment-Package Block Diagram

TABLE 12

EXPERIMENT SYSTEM WEIGHT VOLUME AND POWER

Identification	Weight kg	(lbm)	Volume m^3	(ft^3)	Power Maximum (W)	Average (W)
NH_3 experiment	225	(495)	0.33	(11.7)	665	345
H_2 experiment	177	(390)	156	(55.2)	1035	530
NH_3 propellant resupply	(197.5)	(435)	0.319	(11.25)	---	20
H_2 propellant resupply	←(Not identified)→					

The orbital operations or experiment phase is a 6-month effort in which the following sequence of events will be performed:

(1) Translation maneuvers, then return to the original orbit (with two or four thrustors firing).

(2) Rotation maneuvers, then return to the original orientation (with two thrustors firing).

(3) Orientation maneuvers, inertial and local horizontal, then return to original orientation (with a maximum of four thrustors firing).

(4) Opposed-thrustor operation on various duty cycles (with two opposed thrustors firing).

(5) Removal and replacement of a thrustor module. Astronaut extra-vehicular activity (EVA) is required to accomplish this function. It is anticipated that this event can be completed in less than one orbit.

(6) Accomplishment of propellant resupply operations. Astronaut EVA is required to accomplish this function. It is anticipated that this event can be completed in less than one orbit.

(7) Removal of a thrustor module, placement of it into a container, and securing it in the return spacecraft (astronaut participation required). This event can be completed in less than two orbits.

These functions fall into three primary experimental phases: (1) maneuvering demonstrations (functions 1, 2, and 3), (2) EVA demonstrations (functions 5, 6, and 7), and (3) firing demonstrations (function 4). Each of these phases were defined to satisfy the flight-test program objectives. The requirements for each of the phases, the astronaut participation and training, and the relationship to the program objectives are summarized in the following paragraphs.

The maneuvering demonstrations will be performed twice during the experiment for a period of 8 to 16 orbits each (at the start and end of the experiment). The maneuvers will provide resistojet performance and performance degradation data (if any) to assist in the determination of resistojet operational life.

In the EVA exercises, the astronauts will demonstrate their ability to perform system maintenance and propellant resupply. Three EVA's will be performed: (1) thrustor module removal and replacement, (2) propellant resupply, and (3) thrustor module removal and placement of module in the re-entry spacecraft. The recovered thrustor module will be returned to Earth for post-experiment test, evaluation, and inspection.

The firing demonstration will take about 170 days of the experiment period. Two opposed thrustors will be fired simultaneously on varied duty cycles. Appropriate selection of thrustors and their operating duty cycles will provide different accumulated operating time for each pair of thrustors. Effects of the various operating times will be assessed on the recovered module and will assist in the determination of resistojet operating life.

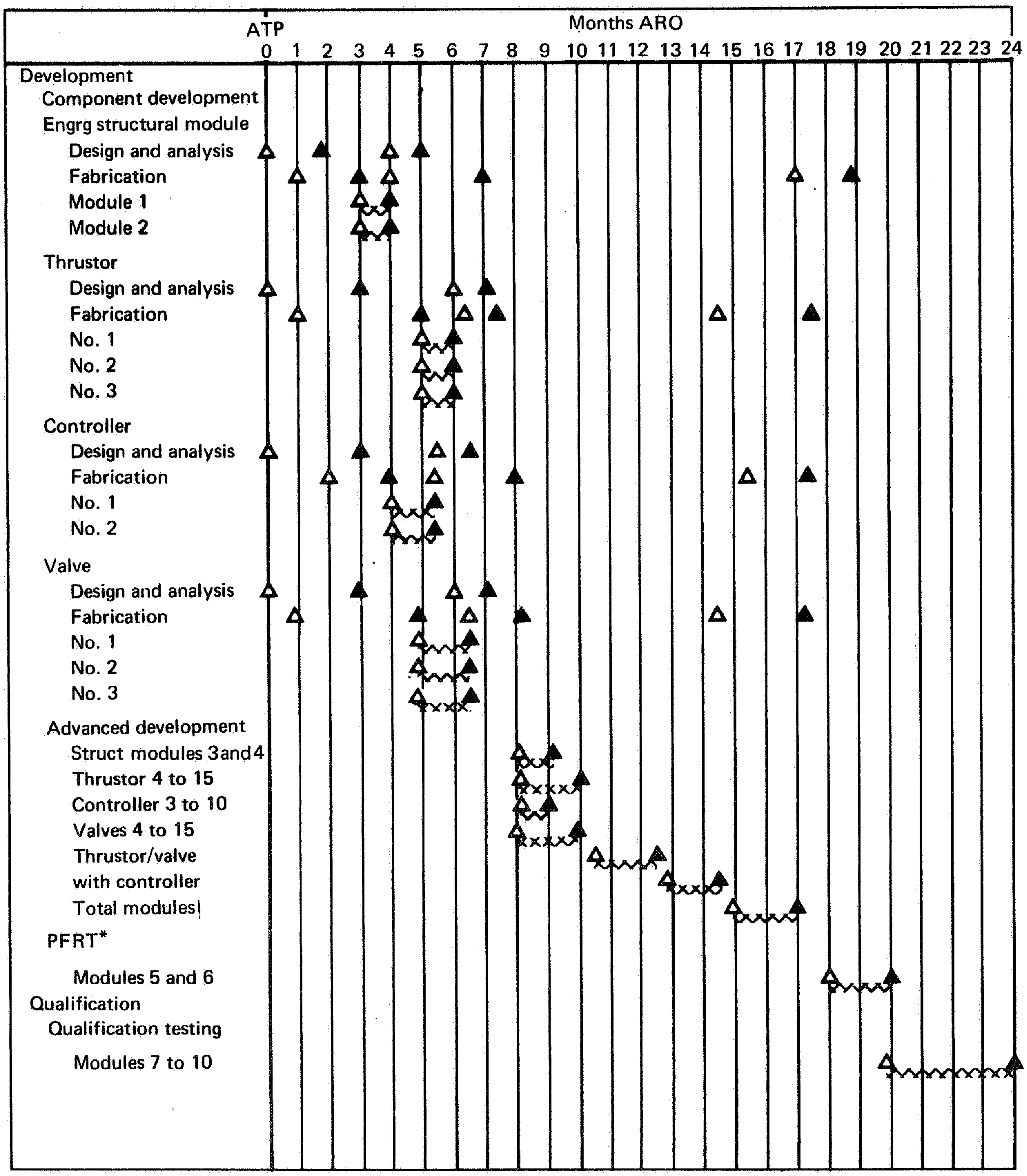
The ground-test program was formulated in accordance with Saturn launch requirements and the operational requirements for a MORL-type spacecraft. The preliminary qualification requirements for all system components were established. A detailed qualification test plan was formulated for the resistojet thrustor module. Critical components of the experiment system were evaluated, and qualification test plans were established for the inverter, the transformer, the propellant-flow regulator, and the LH_2 propellant tankage and feed system. An integrated system test program was also formulated.

The test program for the thrustor module is a 24-month effort, consisting of 19 months of development testing and 5 months of qualification testing. The development effort includes the design and fabrication of and experimentation on the thrustor module components (resistojet, valve, controller, and structural module) and the determination of the associated acceptance test procedures and criteria. Assembled modules will then be subjected to both acceptance testing and overall functional tests to guarantee the operational performance of the module prior to qualification testing.

The primary purpose of qualification testing of the thrustor modules is to demonstrate that the module has no weakness to environmental stress and other conditions expected to arise during operational service.

The quantities of components and modules to be tested and the program schedule is shown in fig. 26.

The ground-test programs, through qualification, for the critical components of the experiment system consist of phases identical to those specified for the thrustor module.



*Preliminary flight-rating tests – to guarantee operational performance prior to qualification tests.

Legend:
Start △ Complete ▲ Test

Figure 26. Qualification Test Schedule

The test program for the integrated system is a 16-month effort consisting of three major phases:

(1) Acceptance testing, which will verify that the end-item hardware conforms to the applicable specifications and performance as a basis for acceptance.

(2) Reliability testing, which will establish a significant level of engineering confidence in the performance of flight-type hardware and ground-support equipment (GSE).

(3) Integrated-systems testing, which will verify that all assemblies will meet system performance requirements when integrated and that these assemblies are physically, functionally, and operationally compatible with interfacing systems, including GSE.

The total ground- and flight-test program can be completed, through experiment evaluation, in 4.5 years (see fig. 27). The ground-test program, through integrated system test, will require 2.5 years; the flight system can be launched 1 year later or 3.5 years from the program's authority to proceed (ATP).

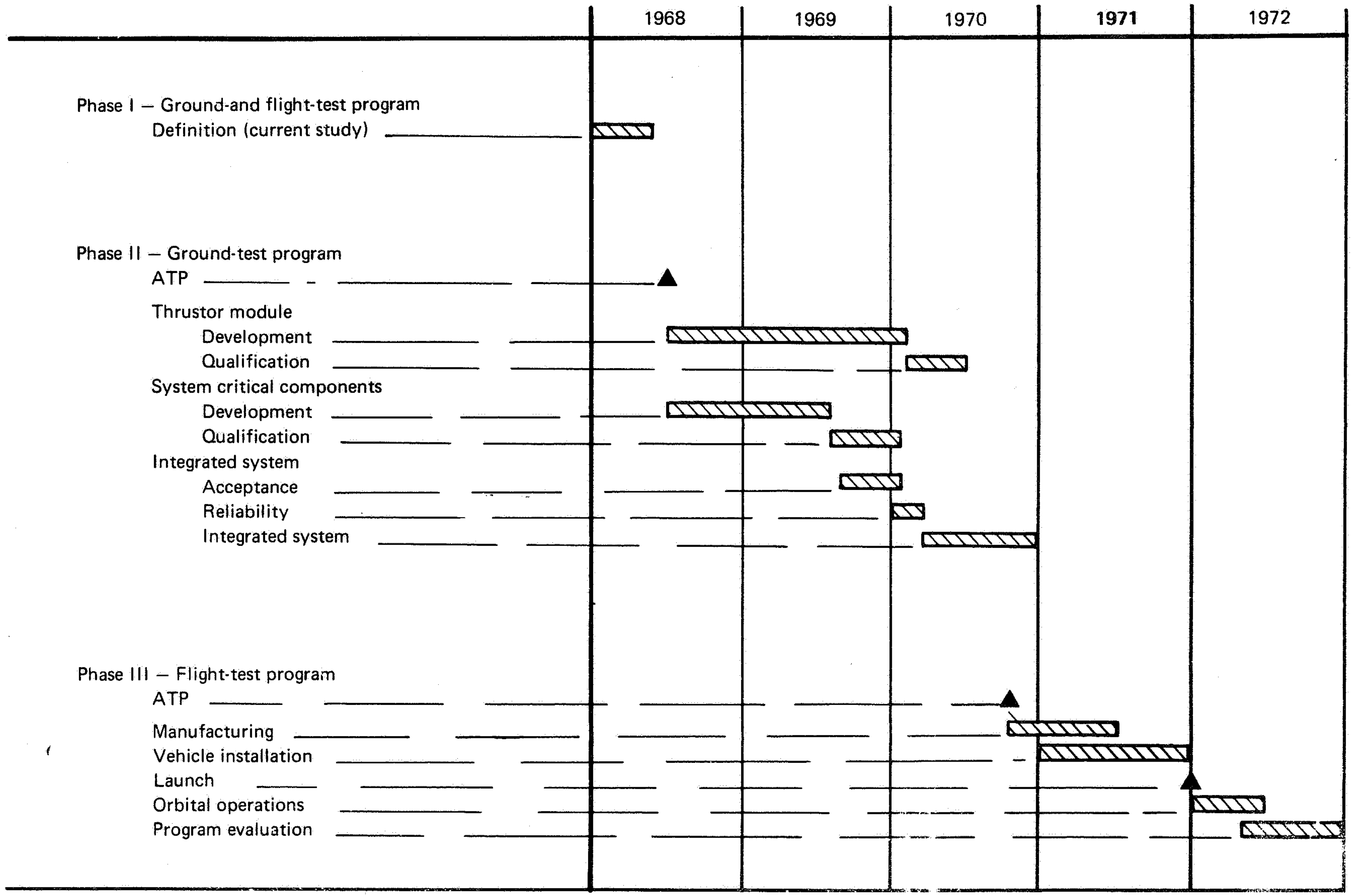


Figure 27. Ground and Flight Test Schedule

PRECEDING PAGE BLANK NOT FILMED.

REFERENCES (VOL I)

1. Report on the Optimization of the Manned Orbital Research Laboratory (MORL) System Concept, Douglas Report No. SM-46071, September 1964.

2. Report on the Development of the Manned Orbital Research Laboratory (MORL) System Utilization Potential--Task Area IV, MORL System Improvement Study, Book 5, Douglas Report No. SM-48819, December 1965.

3. Report on the Optimization of the Manned Orbital Research Laboratory (MORL) System Concept — Subsystem Performance Specifications, Douglas Report No. SM-48150, September 1964.

4. Report on the Development of the Manned Orbital Research Laboratory (MORL) System Utilization Potential — Task Area IV, MORL System Improvement Study, Book 3, Douglas Report No. SM-48817, December 1965.

5. Apollo Applications Test Requirements. NASA Office of Manned Space Flight, Report No. NHB 8080.3, October 13, 1967.