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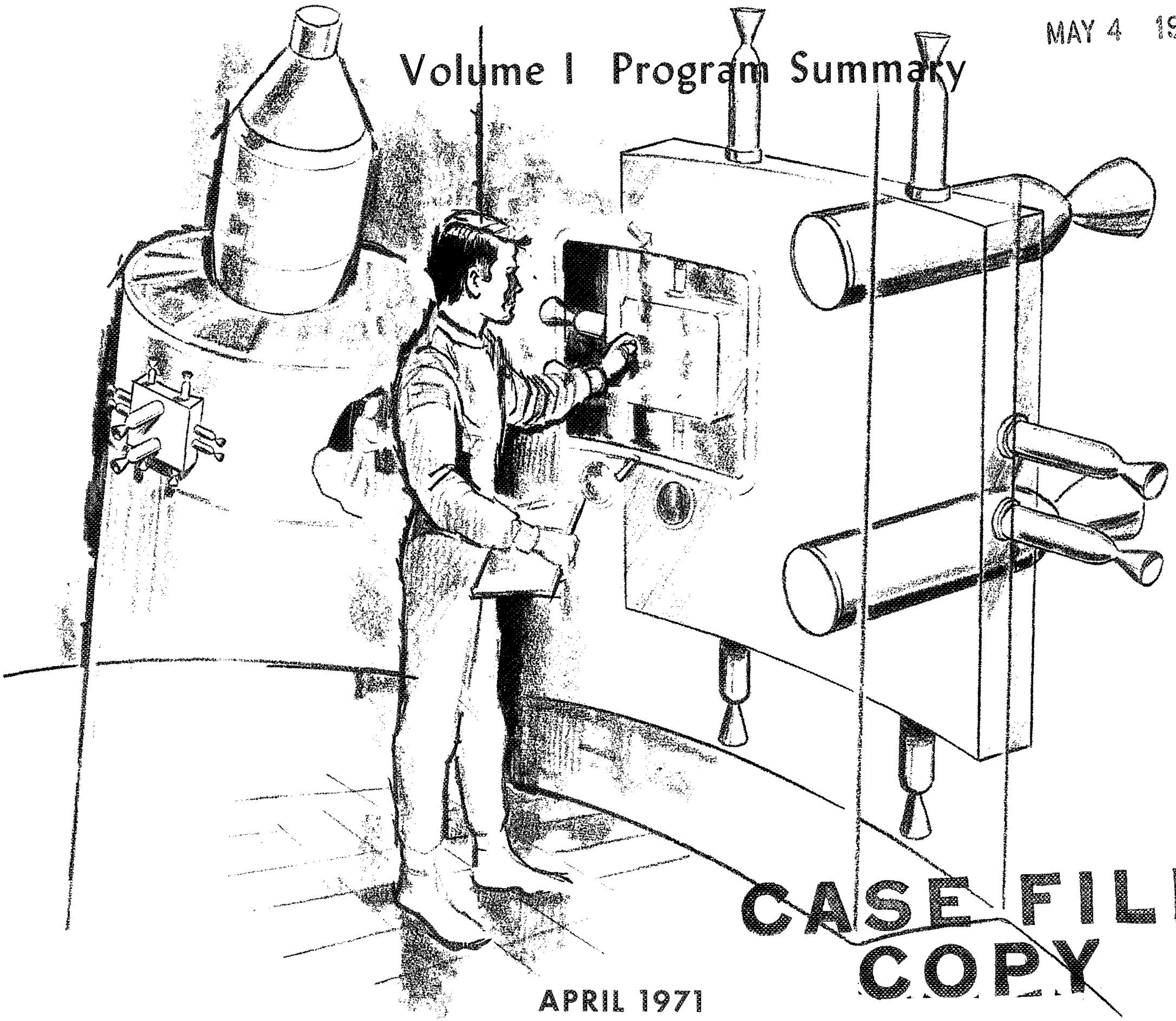
Resupply/Repair of Solid or Hybrid Attitude Propulsion Subsystems

Final Report

Volume I Program Summary



APRIL 1971

Prepared For:
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

MARTIN MARIETTA
DENVER DIVISION

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RESUPPLY/REPAIR OF SOLID OR HYBRID ATTITUDE PROPULSION SUBSYSTEMS FINAL REPORT

Volume I
Program Summary

April 1971

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FOREWORD

This document describes the results of the study on the resupply/repair of solid or hybrid attitude propulsion subsystems. This report is submitted to the George C. Marshall Space Flight Center, National Aeronautics and Space Administration, in compliance with Report Requirement d of Contract NAS8-26196.

The overall objective of this study program was to select optimum methods for orbital resupply, maintenance, and repair of a hybrid attitude control propulsion subsystem for a large orbiting Space Station. Hybrid rockets were studied because they appear to offer significant benefits for the attitude control of manned space stations. United Technology Center served as a subcontractor to Martin Marietta Corporation to provide assistance in satisfying the overall program objective.

Tasks conducted during this program included: establishing candidate methods; analyzing their impact on Space Station systems; selecting preferred system/methods; developing conceptual design; and analyzing demands on Space Station systems. This report describes the activities for these tasks, and is submitted in two volumes:

Volume I - Program Summary;

Volume II - Technical Study.

ACKNOWLEDGEMENTS

The leadership of NASA, under the program sponsorship of Mr. Lee W. Jones, S&E-ASTN-PPC, was instrumental in establishing the constraints employed in this study and in providing guidance. United Technology Center, under the lead of their program manager, R. L. Taylor, provided assistance in the area of the thrust chamber assembly.

The following individuals have made significant contributions to this report:

M. C. Emanuel - UTC
D. G. Green - Martin Marietta Corporation
J. M. Humphrey - UTC
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CONTENTS

ABSTRACT

The National Aeronautics and Space Administration (NASA) is investigating the possibility of launching a large manned earth orbital space station. The nominal operational lifetime of this base would be a minimum of 10 years with a 180-day resupply period.

A 10-year mission in space dictates new approaches to the design of propulsion subsystems. Previous and current space efforts have satisfied the lifetime requirements with component redundancy and rigorous testing of the components. This approach is acceptable for relatively short missions. For long missions, critical subsystems, such as propulsion, must be designed so that the crew can perform resupply, maintenance, and repair operations to maintain the subsystem's original integrity. This requires a different approach: one that minimizes the impact on the workload of the crew and maximizes the probability of successfully accomplishing the mission.

This volume summarizes the results of a study to determine optimum methods for orbital resupply, maintenance, and repair of a hybrid attitude propulsion subsystem (APS)* for a large orbiting Space Station. An overall goal of this program was to develop the information needed to compare the hybrid APS with other candidate propulsion subsystems.

The hybrid rocket is an attractive candidate for the Space Station APS because the use of a solid fuel and a liquid oxidizer removes the failure modes associated with mixing propellants together at the wrong time, in the wrong place, or in the wrong quantity. In addition, the selected propellants are completely nontoxic and nonhypergolic. In other words, this propulsion approach is the safest of those considered. In addition, the hybrid combustion process is insensitive to grain imperfections and chamber pressure variations. This approach also minimizes the propellant logistics because of its commonality with other Space Station subsystems. Finally, the hybrid APS combines the simplicity of a monopropellant engine with the performance of a bipropellant engine.

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*The hybrid APS consists of the attitude control system (ACS) motors and spin/despin motors.

A combination of polymethylmethacrylate and polybutadiene was selected as the baseline fuel, and liquid oxygen was chosen as the oxidizer. Helium gas was the selected pressurant for the blowdown stored gas system. Capillary screen propellant acquisition devices were selected. Long life was obtained in the thrust chamber assembly by using radiation cooling and permitting the fuel-rich boundary gases to flow directly into the nozzle. This not only significantly reduces the thermal load and the chemical corrosivity of the hybrid chamber and nozzle, but it also extends the operating life beyond 10,000 sec. The radiation cooling of the hybrid thrust chamber assembly provided an exhaust gas species environment that was similar to the environment of the bipropellant liquid engine.

The study indicated that the hybrid APS is capable of satisfying the 10-year life capability. An evaluation was conducted to determine which combination of the 18 candidate oxidizer feed systems, four ignition concepts, three grain design concepts, five grain resupply concepts, nine oxidizer resupply concepts, and five pressurant concepts will provide the optimum APS from resupply, maintenance, and repair considerations while satisfying mission success criteria. The study also showed that, to obtain the 10-year lifetime for the propulsion subsystem, it is necessary to have both redundant critical subsystems and inflight maintenance.

Areas studied in detail included: reliability; failure modes; malfunction detection and repair during APS operation, standby, and refurbishment; estimates of unscheduled maintenance time to correct random failures; and onboard servicing and repair concepts.

Many of the concepts, findings, and conclusions presented in this study are equally adaptable to other mechanical and fluid subsystems for the Space Station.

I. INTRODUCTION

The National Aeronautics and Space Administration (NASA) is investigating the possibility of launching a large manned earth orbital space station. The nominal operational lifetime of this base would be a minimum of 10 years with a 180-day resupply period.

This type of long-duration manned space mission requires drastic improvements in the capabilities of the propulsion subsystem, as well as other subsystems, to attain satisfactory probabilities of mission accomplishment. Increasing the reliability of the parts and assemblies of the propulsion subsystem, although mandatory, will not be sufficient in itself to achieve the overall levels of assurance that are sought. The realization of the 10-year mission in space dictates new approaches to the design of the propulsion subsystem. These approaches must include appropriate onboard resources to augment or maintain, throughout the mission, the initial integrity of the propulsion subsystem. This can be accomplished by providing redundancy, performing fault correction, or incorporating a combination of the first two and resupplying expendables. The selected approach must minimize the impact on the work load of the crew and maximize the probability of successfully accomplishing the mission.

A. STUDY OBJECTIVES

The objective of this study was to select optimum methods for the orbital resupply, maintenance, and repair of a hybrid* attitude propulsion subsystem (APS) for a large orbiting Space Station. An overall goal of this program was to develop the information needed to compare the hybrid attitude propulsion subsystem with other candidate propulsion subsystems.

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*The hybrid rocket considered in this study uses a liquid or gaseous oxidizer with a solid fuel.

Secondary objectives were to:

1) Determine the effect of selected approach/methods on Space Station systems, and
2) Identify propulsion areas that require further immediate technology investigation and/or development to meet an operational date of the late 1970s.

B. PROGRAM OVERVIEW

The present study is one of three such study contracts awarded by the Marshall Space Flight Center (MSFC) to provide the necessary data to support the definition study being conducted by the McDonnell Douglas Astronautics Company (MDAC), one of the two prime contractors for the Phase B Space Station study. Other candidate propulsion subsystems are the bipropellant subsystem (studied by the Martin Marietta Corporation, Denver Division) and the monopropellant hydrazine APS (studied by Hamilton Standard). MDAC is presently basing its Space Station APS design approach on the monopropellant hydrazine subsystem. The other Space Station prime contractor, the North American Rockwell Corporation (NAR), has a cryogenic bipropellant subsystem as the baseline for its APS.

The hybrid rocket was selected as a candidate for the Space Station APS because: (1) it is safe (due to its lack of toxicity and explosive hazards); (2) it can combine the simplicity of a monopropellant with the performance of a bipropellant; and (3) it provides on-off operation that cannot be satisfactorily obtained with a solid rocket.

This study was made with the baseline Space Station defined in the MDAC Phase B Study.* This configuration, shown in Fig. I-1, has a 10-m (33-ft) diameter "common" module; the Saturn S-II stage is used as the counterweight for the artificial-g experiments. The "common" module contains two decks. Two of these modules make up the main work and living areas. Two of the decks are devoted to

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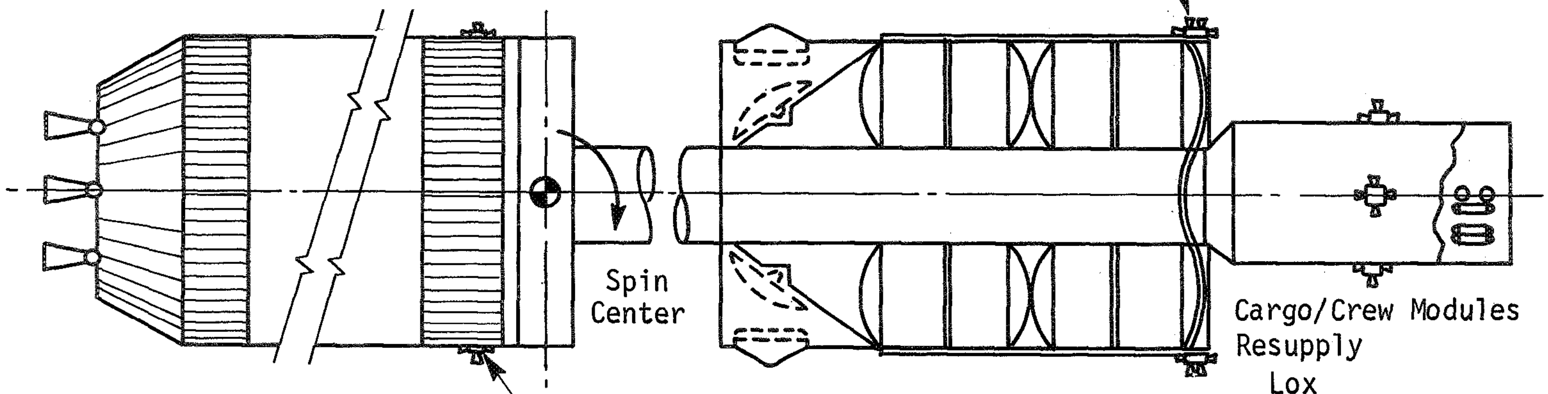
* *Space Station Preliminary Design - Utility Services.* MSFC-DRL-160-Line Item 13, Vol I, Book 4, Preliminary Systems Design Data, Contract NAS8-25140. McDonnell Douglas Astronautics Co, July 1970.



Note:
1. S-II and tunnel section are jettisoned after the last artificial-g experiment.
2. S-II is shown in the zero-g (undeployed) position.
3. Attached experiment modules arrive after S-II is jettisoned.

Fig. II-1 Space Station Configuration

general purpose laboratories that support the experimental program. Each of the remaining two decks houses an operations and living quarters for six men. Either living area could accommodate the entire 12-man crew indefinitely, should the need arise. Access between decks is furnished by a central tunnel 3.048 m (10 ft) in diameter that provides emergency shelter. Zero gravity, which is desirable for the conduct of experiments, is the normal mode of operation, although the Space Station has an artificial-g capability provided by using the spent Saturn S-II stage as a counterweight.

Trade studies of MDAC indicated the desirability of satisfying the propulsion requirements by using both a high thrust and a low thrust propulsion subsystem. The low thrust requirements were satisfied by a Resistojet subsystem, which performed drag makeup and the CMG desaturation function. Only the high-thrust requirements were considered; the baseline thrust was 222 N $\left(50\ \mathrm{lb}_f\right)$.

II. CONCEPTUAL DESIGN

This chapter describes the conceptual design of the hybrid APS that resulted from this program. Details on the evolution of this concept are presented in Volume II.

A. REQUIREMENTS

Several functions for the APS involve positioning, stationkeeping, attitude control, pulsing, thrust vector alignment, thrust vectoring, and plume impingement. In this study, the uses for the hybrid APS are limited to high-torque, high-thrust functions only for the Space Station. These functions are:

1) Providing attitude control, maneuvers, and docking functions before activation of the control moment gyros (CMGs):
2) Performing spin/despin maneuvers for the five artificial-g experiments;
3) Providing attitude control (wobble damping) during the artificial-g experiment periods;
4) Providing control during the docking maneuvers;
5) Providing backup attitude control.

The high-thrust subsystem is located on the outboard aft end of the Space Station. With the thruster orientation shown in Fig. II-1, it provides the capability to perform both attitude control and spin/despin for artificial-g experiments. Separate thrusters are used for spin/despin and attitude control. The thrusters, installed in two thruster module groupings, are located aft on the Y-axis (in the spin plane). A cluster of spin thrusters is located in the module, oriented normal to the vehicle surface; a corresponding cluster of thrusters on the opposite module provides despin. The multiple thrusters provide the reliability and redundancy necessary to complete the spin/despin operations safely. Redundant attitude control thrusters are also provided. By limiting the locations and orientation of the thrusters, plume impingement is minimized on attached experiment modules and thruster module installation weight is reduced; i.e., there are only two, instead of four, modules.

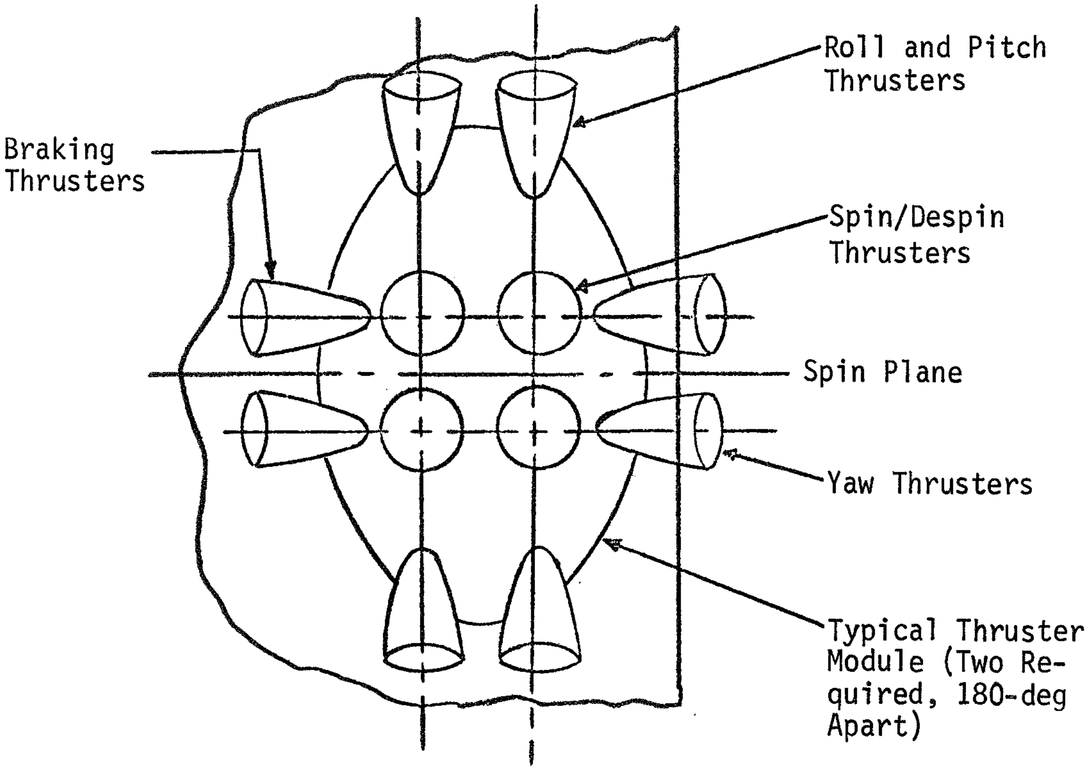


Fig. II-1 Thruster Location

The impulse requirements, based upon the MDAC Phase B study, are presented in Table II-1. These requirements are further defined in terms of the sixteen 222-N $\left(50\text{-lb}_f\right)$ attitude control motors and the three 1114-N $\left(250\text{-lb}_f\right)$ spin/despin motors in Table II-2.

B. SELECTED APPROACH

The selected concept (Fig. II-2) employs separate thrust chamber assemblies (TCAs) for the attitude control functions and the spin/despin requirements. Separate oxidizer feed systems are also used to satisfy both requirements. Details of the selected approach are presented in Table II-3.

Conceptual thrust chamber assembly designs are presented for both the ACS motors and the spin/despin motors. Conceptual motor refurbishment assembly designs are also discussed for both systems using the selected movable tube approach. The resupply techniques for the pressurant and oxidizer are presented. Two integrated thruster pads were designed, each to mount eight ACS motors and two spin/despin motors, along with the required oxidizer feedlines and instrumentation cables. Two auxiliary propulsion system rooms (one for each thruster pad) were designed to provide facilities for all hybrid propulsion maintenance and repair functions, as well as storage space for spare propulsion components and replacement fuel grains. Propulsion characteristics were defined to establish component and overall system weights; reliability, maintenance, repair, and resupply requirements; and complete motor performance information.

The overall reliability for the complete attitude control system for the 10-year period was 0.9671. The spin/despin system had an overall reliability of 0.9913.

1. ACS Thrust Chamber Assembly

An early consideration of mission requirements and constraints led to the selection of two separate hybrid TCA propulsion units to satisfy, in an optimum manner, the impulse profiled necessary for Station attitude control and the discrete spinup/despin functions.

Table II-1 High-Thrust Impulse Requirements

MISSION PHASE	FUNCTION	IMPULSE N-sec	IMPULSE lb_f-sec
Initial Boost thru Space Station Operation (7-10 days)	Maneuver to Gravity Gradient Orientation	154,000	34,500
	Attitude Control (Roll) While in Gravity Gradient Operation		
	Control during Docking of Initial Crew/Cargo Module (ALS Hard Dock)		
	Attitude Control until CMGs Are Operating		
	Space Station Turnaround and Docking		
	Control Attitude during S-II Safing and Arming	204,000	46,000
Space Station Operation (10-90 days)	Attitude Control (if CMGs Are Inoperative)	51,000	11,500
	Control during Docking Disturbances	87,000	19,550
Artificial-g Experiment Period (15 months) Five Experiments	Spin/Despin	6,200,000	1,396,100*
	Attitude Control while Spinning	184,000	41,400*
	Control during Cargo Module or ALS Docking Disturbances	87,000	19,550*
	Attitude Control if CMGs Are Inoperative	51,000	11,500*
Zero-g Space Station (8½ years)	Control during Docking Maneuvers (every 90 days)	87,000	19,550†
	Miscellaneous Maneuvers (every 90 days)	51,000	11,500†
	TOTAL	38,000,000	8,509,500

*Per experiment.

†Per event.

Table II-2 Impulse Summary for Hybrid Propulsion Subsystem

FUNCTION	IMPULSE	
	N-sec	lb_f-sec
Attitude Control		
0-90 Days	498,000	111,550
3-18 Months	1,632,000	362,250
18 Months-10 Years [138,000 N-sec ($31,050\ lb_f$-sec)/90 days]	4,770,000	1,055,700
Total Attitude Control Requirements	6,900,000	1,529,500
Spin/Despin		
3-6 Months	6,200,000	1,396,100
6-9 Months	6,200,000	1,396,100
9-12 Months	6,200,000	1,396,100
12-15 Months	6,200,000	1,396,100
15-18 Months	6,200,000	1,396,100
Total Spin/Despin Requirements	31,100,000	6,980,000
TOTAL APS REQUIREMENTS	38,000,000	8,509,500

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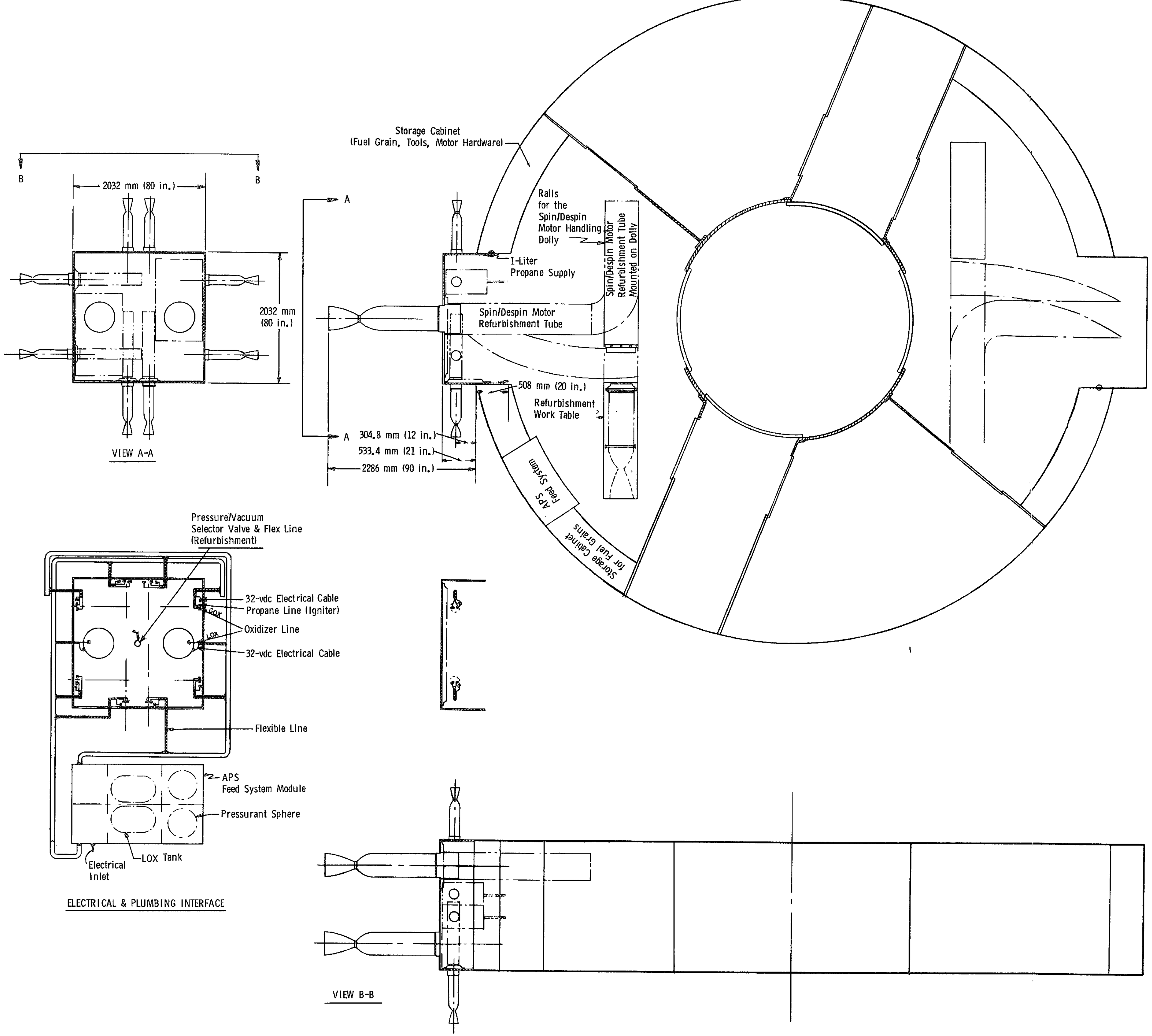


Fig. II-2 APS Pads and Refurbishment Compartment

Table II-3 Conceptual Hybrid APS Characteristics

PROPELLANTS	
Oxidizer	Gaseous oxygen
Fuel	Polymethyl methacrylate/polybutadiene
Steady-State Specific Impulse (sec)	323
Exhaust Products ($99^+\%$)	CO, CO_2, H_2O, H_2
Density of LOX at -297°F (456°K)	1,104 kg/m^3 (71.2 lb/cu ft)
Freezing Point of LOX at 1.03 kg/cm^2 (14.7 psi)	55.2°K (-362°F)
Boiling Point of LOX at 1.03 kg/cm^2 (14.7 psi)	90.2°K (-297°F)
Shock Sensitivity	Stable
Health Hazards	Nontoxic
Fire Hazard	Nonflammable
THRUSTER MODULES (Two Required)	
Impulse of Primary System	222 N $(50\ lb_f)$
Number of Redundant Thrusters	
Attitude Control Thrusters	16
Braking Thrusters	4
Thruster Size, mm (in.)	172 (6.80) diameter by 940 (37.0) long
Weight (Less Structure) of Two Modules, kg (lb_m)	168 (371)
SPIN/DESPIN SYSTEM	
Number of Thrusters	3
Thruster Size, mm (in.)	394 (15.5) diameter by 2032 (80.0) long
Weight (Less Structure) of Two Modules, kg (lb_m)	232 (522)
PROPELLANT TANKAGE ASSEMBLIES	
Minimum Total Propellant Capacity, kg (lb_m)	454.3 (1000)
Fuel	161 (355)
Oxidizer	293 (645)
Total Oxidizer Volume, m^3 (ft^3)	0.27 (9.22)
Typical Size of Capillary Screen Tank Assembly, mm (in.)	419 (16.5) diameter by 69.9 (27.50) long
Total Weight, kg (lb_m)	38.8 (85.72)
HIGH-PRESSURE STORAGE ASSEMBLIES AND PRESSURE CONTROL ASSEMBLY	
Pressurant	He at 35.15 kg/cm^2 (500 psi)
Total Pressurant Capacity, kg (lb_m)	7.4 kg $(16.32\ lb_m)$
Total Pressurant Volume, m^3 (ft^3)	0.20 (7.08)
Number of Titanium Spheres	4
Typical Size of Titanium Spheres, mm (in.)	45.7 (18) diameter
Pressure Control Assembly	Regulated
Total Weight, kg (lb_m)	17.1 (37.68)
RESUPPLY	
Method	Blowdown Fluid Flow Transfer
Transfer Efficiency (%)	98
Total Weight of Distribution/Manifolds/Umbilicals, kg (lb_m)	31.7 (70)
TOTAL SUBSYSTEM INERT WEIGHT (Less Structure), kg (lb_m)	491.6 (1086.48)

Sixteen 222-N $\left(50\text{-lb}_f\right)$ thrusters were selected to supply attitude control impulse, while three 1114-N $\left(250\text{-lb}_f\right)$ units were selected for the large impulse requirements of spinup/despin.

The selection of two similar, but differently sized thrusters, is dictated to achieve a simple and reasonably sized motor for attitude control, while providing a unit of sufficient size to limit required maintenance (refueling) during station spinup operation. A maximum of commonality is maintained between the two units to permit simplified development.

In designing both thrusters, long-duration and low-maintenance requirements led to the selection of a radiation-cooled molybdenum thrust chamber operating at relatively low pressure (80 psi, or 558 kN/m^2). A radiation-cooled nozzle of the same material, lined with an $MoSi_2$ coating, is also used. The nozzle expansion area ratio is limited by a restriction that the exit diameter be no larger than the diameter of the case to facilitate withdrawal into the Space Station for routine maintenance.

The nozzle selected operates at a maximum temperature of 2900°F (1867°K) with essentially zero erosion and minimum maintenance requirements.

Based on an evaluation of the performance and handling characteristics of potential propellants, we selected a gaseous oxygen/(PMM/PBD) propellant combination for the attitude control thrusters. Liquid oxygen is used for the spin/despin thrusters. This propellant system is safe to handle, nontoxic, and results in minimum impact on the Space Station. In addition, these propellants provide satisfactory performance at oxygen-to-fuel mixture ratios, which results in acceptable exhaust gas temperature and chemistry, and reasonable refurbishment (refueling) intervals.

For the larger spinup motor, solid fuel grains are loaded in easily handled segments. The smaller attitude control motor uses monolithic grains.

Ignition system differences between the multipulse operation of the attitude control thrusters and the single long burn of the spinup motors resulted in the selection of alternative systems. The multipulse ignition is obtained with an oxygen/propane spark-initiated preburner that has proven safety and reliability. The simpler single-pulse motor ignition is accomplished with a squib-initiated pyrogen system similar to those used with solid rocket motors.

Both motors share a common malfunction detection system (MDS) philosophy and sensing techniques. In particular, a helical sensing wire system is buried in the replaceable fuel cartridge near the outer diameter. As the fuel grains burn back to the cartridge wall, they cause a break in the sensing wire, which signals oxidizer flow shutdown. If oxidizer continues to flow after the fuel grains burn back to the cartridge wall, an off-mixture ratio operating condition will occur, with an accompanying performance loss and potential for nozzle/case damage.

Except for minor variations associated with dimensional differences, essentially common construction, mounting, and handling philosophies are employed in both motors. Motor closure joints use shear pin fasteners with strap retainers that are at once simple and reliable, and which impose minimum work load on the crew during routine maintenance operations. Motor joints are so located as to eliminate the possibility of having hot gas leak into the Space Station in the event of seal failure.

Reliability goals of the APS are met through use of high-reliability components and redundancy in the area of critical subsystems. Main oxidizer pressure regulation and valving, for example, will be accomplished using redundant systems. Malfunction sensing also includes redundant sensing techniques, and all primary pressure seals use redundant O-rings.

A detailed discussion of selected motor configuration is presented in Volume II. The attitude control motor TCA is shown in Fig. II-3 and described in the performance, design, and weight summaries shown in Table II-4. The ACS motor has an overall length of 940 mm (37.0 in.), a loaded mass of 21.0 kg $\left(46.3\ lb_m\right)$, and delivers 225 N $\left(50.5\ lb_f\right)$ of average thrust for 386 sec, at an average chamber pressure of 558 kN/m^2 (81.0 psia). The average delivered specific impulse is 323 sec, and the total impulse per fuel grain is 86,630 N-sec $\left(19,480\ lb_f\text{-sec}\right)$.

The ACS motor TCA is shown schematically in Fig. II-4. The gaseous oxygen line is connected to the motor via a double poppet screw disconnect. Opening the oxidizer control valve allows GOX to energize the fluidic injection system, which mixes a measured amount of propane with GOX in a precombustor. A timed spark ignites the mixture and starts the motor. Chamber pressure, thrust, and fuel depletion measurements are monitored by the MDS.

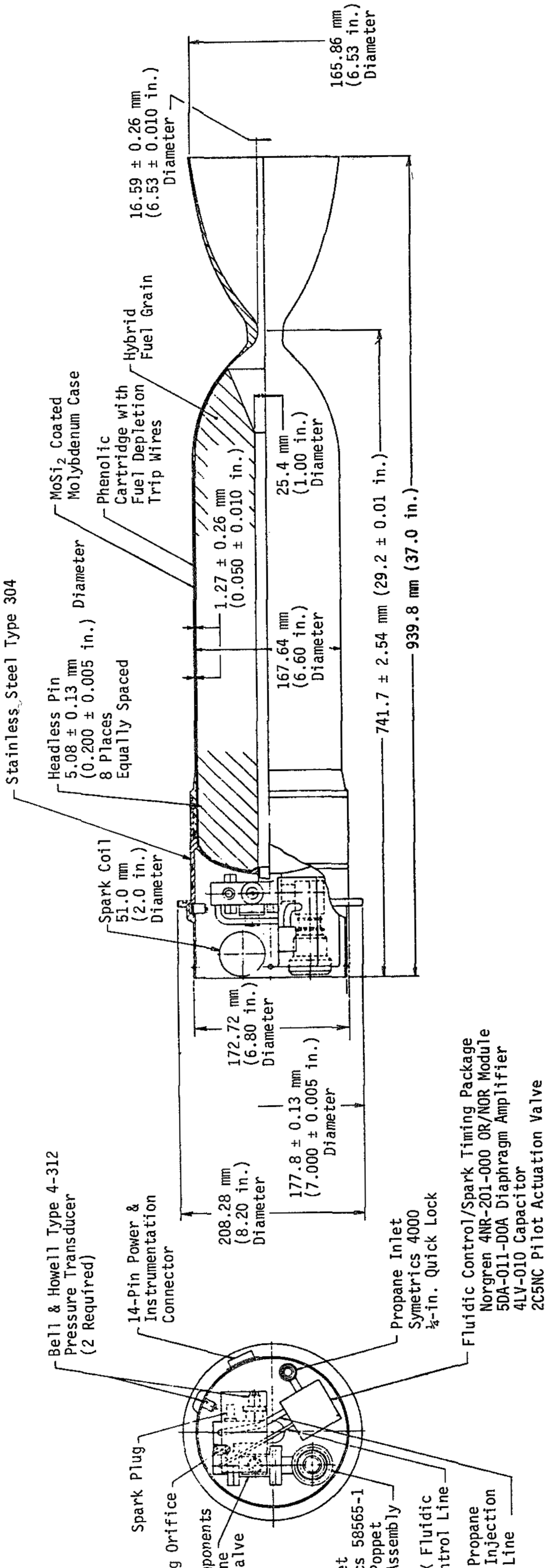

165.86 mm (6.53 in.) Diameter
16.59 ± 0.26 mm (6.53 ± 0.010 in.) Diameter
Hybrid Fuel Grain
$MoSi_2$ Coated Molybdenum Case
Phenolic Cartridge with Fuel Depletion Trip Wires
25.4 mm (1.00 in.) Diameter
1.27 ± 0.26 mm (0.050 ± 0.010 in.) Diameter
741.7 ± 2.54 mm (29.2 ± 0.01 in.)
939.8 mm (37.0 in.)
167.64 mm (6.60 in.) Diameter
Stainless Steel Type 304
Headless Pin 5.08 ± 0.13 mm (0.200 ± 0.005 in.) 8 Places Equally Spaced
Spark Coil 51.0 mm (2.0 in.) Diameter
172.72 mm (6.80 in.) Diameter
177.8 ± 0.13 mm (7.000 ± 0.005 in.) Diameter
208.28 mm (8.20 in.) Diameter
Bell & Howell Type 4-312 Pressure Transducer (2 Required)
14-Pin Power & Instrumentation Connector
Propane Inlet Symetrics 4000 ¼-in. Quick Lock
Fluidic Control/Spark Timing Package Norgren 4NR-201-000 OR/NOR Module 5DA-011-D0A Diaphragm Amplifier 4LV-010 Capacitor 2C5NC Pilot Actuation Valve
Spark Plug
Metering Orifice
Wright Components 15027 Inline Solenoid Valve
GOX Inlet Symetrics 58565-1 Double-Poppet Socket Assembly
GOX Fluidic Control Line
Propane Injection Line

Table II-4 Conceptual Attitude Control Motor TCA

PERFORMANCE SUMMARY	
Propellants	Gaseous Oxygen/(20% Polymethylmethacrylate-80% Polybutadiene)
Average Oxidizer/Fuel	1.815
Average Chamber Pressure, kN/m^2 (psia)	558 (81)
Nozzle Expansion Ratio	100
Average Specific Impulse, sec	323
Average Thrust, N (lb$_f$)	225 (50.5)
Total Impulse, N-sec (lb$_f$-sec)	86,630 (19,480)
Duration (sec)	386
DESIGN SUMMARY	
Motor Design	
Ignition	Fluidic-Controlled, Sparked Propane Ignition System
Oxidizer Flow Control	Inline Solenoid Valve with Double-Poppet Screw Line Disconnect
Forward Closure	304 Stainless Steel Forward Closure Attached
Motor Case and Nozzle	Radiation-Cooled, MoSi$_2$-coated Molybdenum
Grain Design	Monolithic, Single-Port Fuel Grain Cast into a Phenolic Cartridge. Trip Wires Embedded in the Cartridge Signal Fuel Depletion
Motor Refurbishment	Movable Tube Approach
Grain Diameter, mm (in.)	160 (6.30)
Grain Length, mm (in.)	564 (22.2)
Throat Diameter, mm (in.)	16.6 (0.653)
Overall Length, mm (in.)	940 (37.0)
WEIGHT SUMMARY	
Thrust Chamber Assembly	kg (lb$_m$)
Motor Case/Nozzle	5.32 (11.72)
Forward Closure	3.82 (8.42)
Oxidizer Flow Control Instrumentation	1.41 (3.10)
Reusable TCA Mass	10.6 (23.2)
Phenolic Fuel Cartridge	0.38 (0.83)
Useful Hybrid Fuel	9.71 (21.42)
Residual Hybrid Fuel	0.37 (0.81)
Expended TCA Mass	10.5 (23.1)
Loaded Motor Mass	21.0 (46.3)
Useful Propellant Mass	
Oxidizer	17.63 (38.87)
Useful Fuel	9.71 (21.42)
Total Propellant Mass	27.3 (60.3)

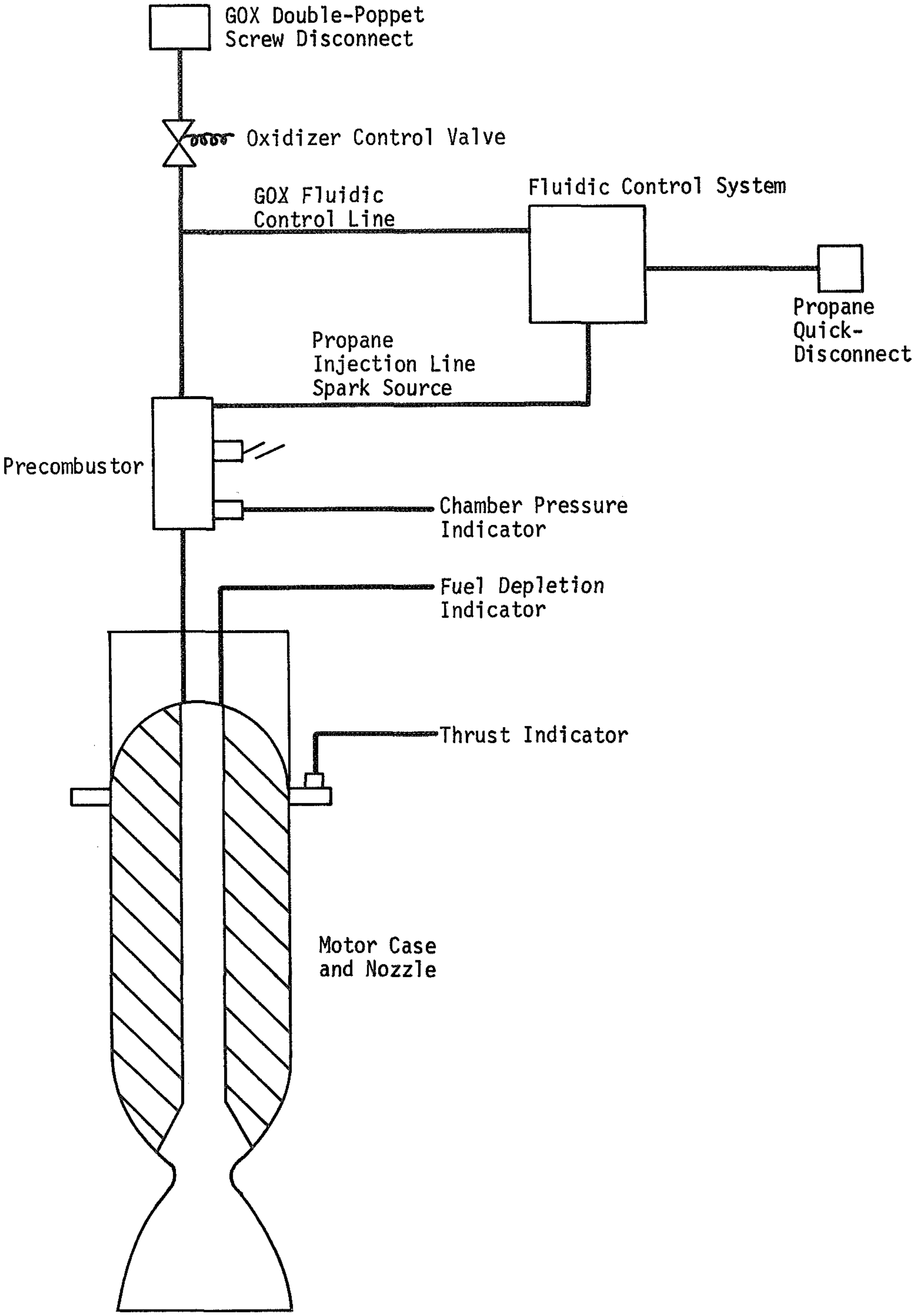


Fig. II-4 ACS Motor Schematic

The complete hybrid APS system uses two thruster pads with a total of 16 ACS motors and three spin/despin motors (located in four possible firing locations). A hybrid APS thruster pad is shown schematically in Fig. II-5. The eight ACS motors are arranged into two redundant sets of four motors. Each set is connected to a backup shutdown valve. Each ACS motor has separate GOX, propane, and electrical lines. The two spin/despin motors are attached to redundant LOX valves via vacuum-jacketed flex lines.

The motors are located on raised thruster pads inside two hybrid APS rooms on the bottom deck of the proposed Space Station, as shown in Fig. II-2. All motors are stored inside during launch and extended once the Space Station is in orbit. The APS rooms provide all the facilities required for maintenance, repair, and resupply of the hybrid APS.

Refurbishing/refueling of the thrusters, shown in Fig. II-6, is accomplished by mounting a vacuum-tight work chamber within the Station's pressure hull, leak-checking the inner chamber, withdrawing the thruster back into the work chamber, sealing off the opening that is left, leak-checking the hull seal, and removing the work chamber. The motor is then refueled by inserting a fuel grain cartridge complete with MDS sensors. All oxidizer and command/instrumentation umbilicals are equipped with quick-disconnect couplings to facilitate handling. Following checkout of the assembled system, the thruster motor is returned to firing position by essentially reversing the motor withdrawal procedure.

The hybrid thrusters have minimum impact on the operation and function of the Space Station. This concept also offers a safe and reliable means of satisfying long-term attitude control requirements, as well as special propulsion demands such as spinup/despin.

Storage of the inert, nontoxic fuel cartridges within the Space Station presents no crew hazard or special handling problems. The oxidizer system potentially could serve in a backup capacity to life support systems should such an arrangement be attractive.

Operation of the APS also presents no crew or hardware hazard, inasmuch as all potential motor hot gas leakage paths are external to the Space Station hull, and the inherent safety characteristics of the hybrid motor eliminate the potential for destructive pressure spikes or propellant detonations that exist in monopropellant, bipropellant, and solid rocket motor systems.

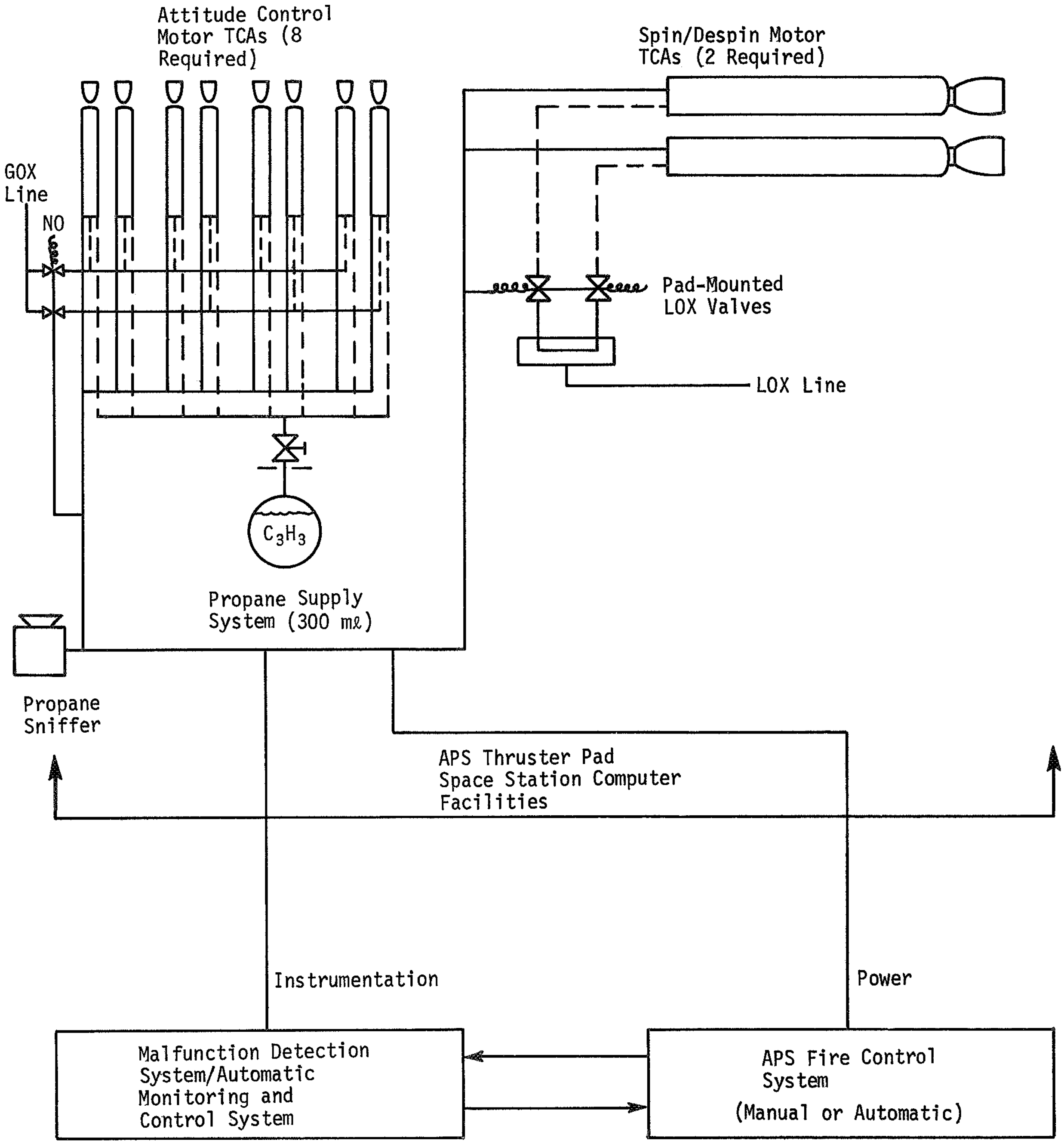


Fig. II-5 APS Thruster Pad Schematic

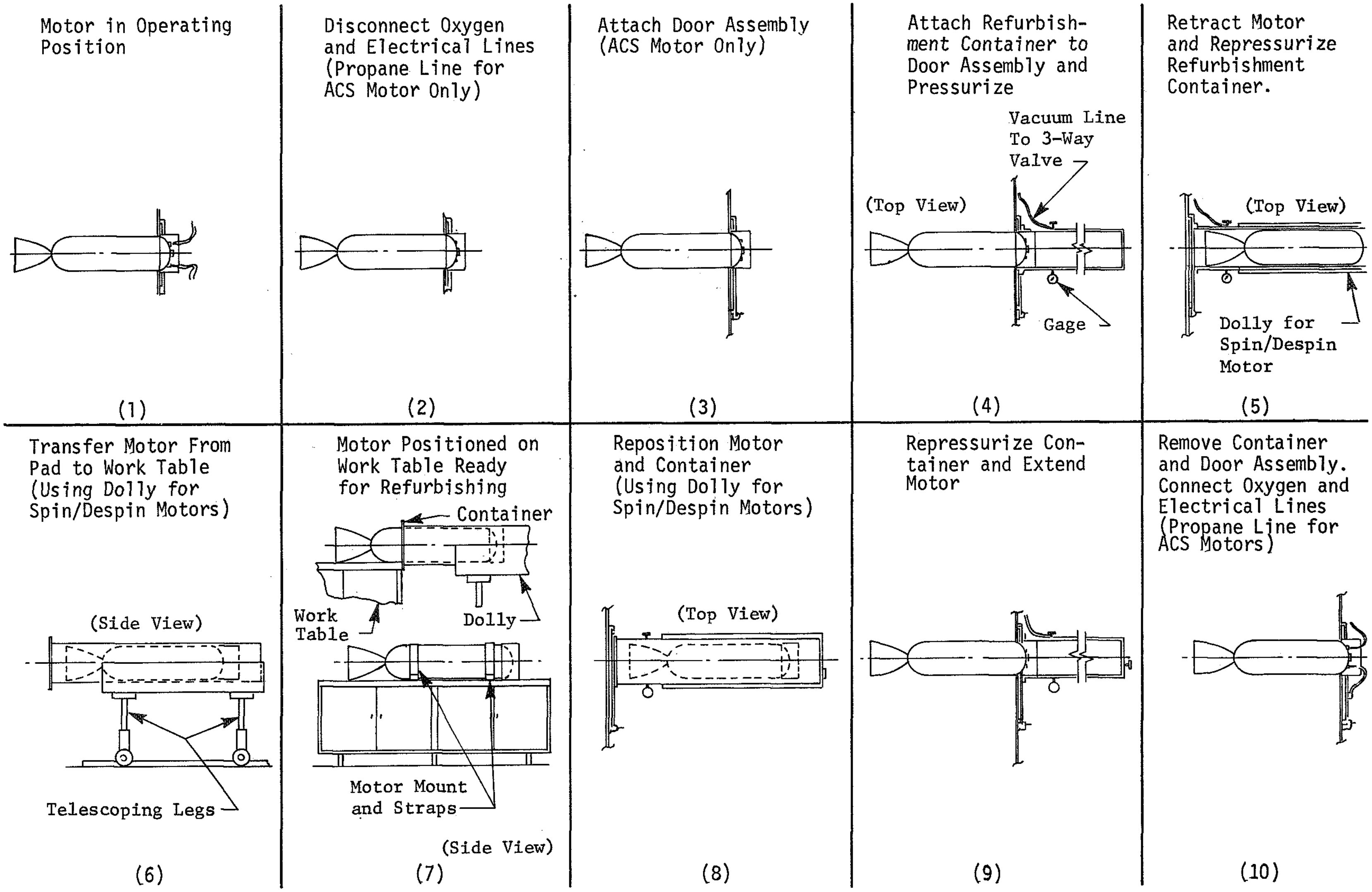


Fig. II-6 Refurbishment of Thrust Chamber Assemblies

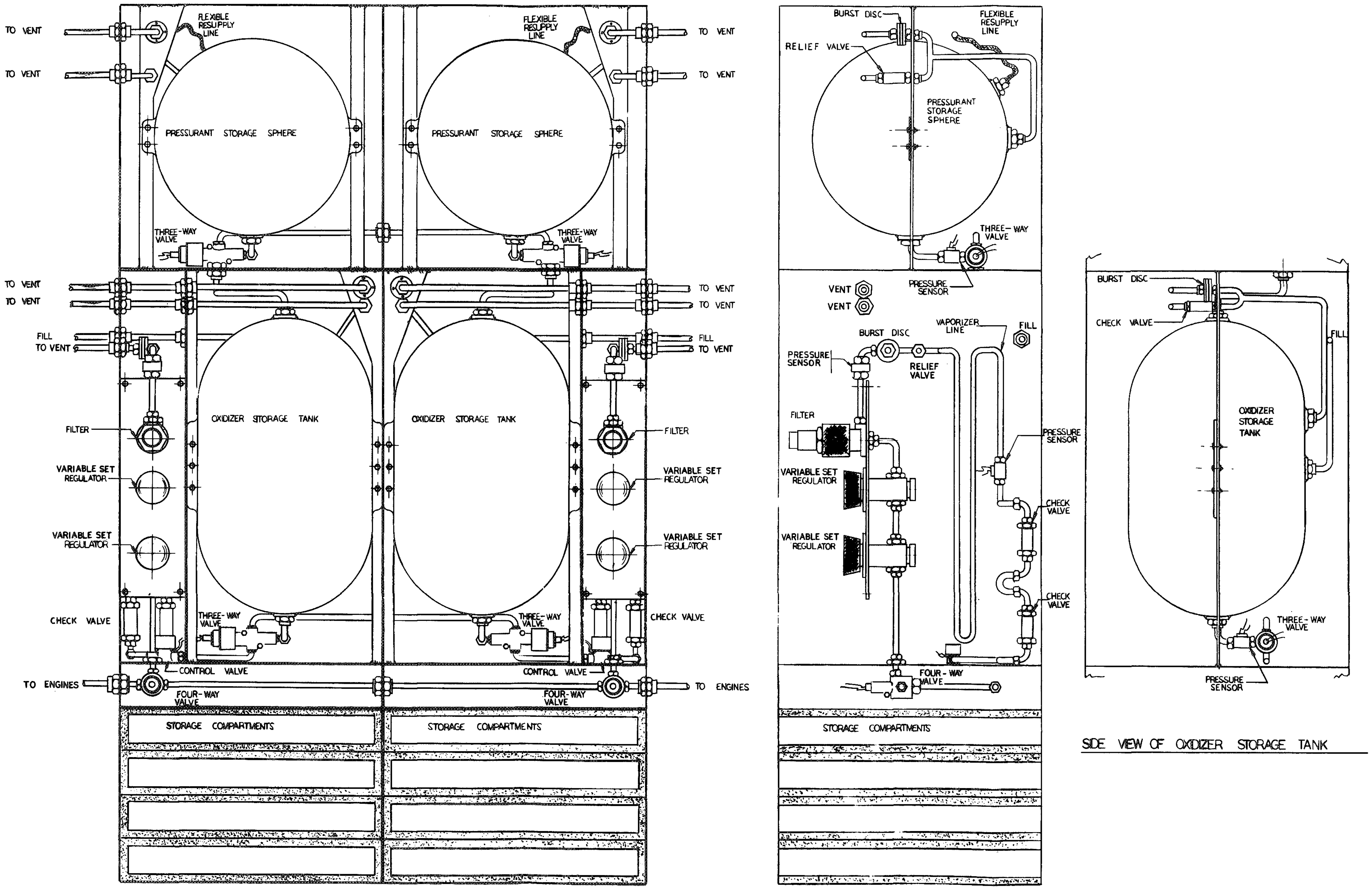
2. Oxidizer Feed Assembly

The conceptual oxidizer feed assembly shown in Fig. II-7, was designed to minimize maintenance, repair, and resupply time while maximizing safety, reliability, and performance. The assembly was designed to operate with the ACS thrusters. The assembly fits in a cabinet 203 mm by 122 mm by 61 mm (80 in. by 48 in. by 24 in.) with a volume of 1.51 m^3 (533 ft^3).

The oxidizer assembly is a pressurized feed system that uses helium as the pressurant gas in a blowdown manner. The titanium oxidizer tank is a capillary-screen type chosen to provide oxidizer positioning and expulsion capabilities during zero-g or low-g operation.

The 10-year life requirement dictates that the oxidizer feed assembly be reparable and contain a degree of redundancy. Thus, each propulsion module is designed to have two interconnected oxidizer feed systems that are virtually independent. In addition, the oxidizer feed assemblies for each module are interconnected. Furthermore, each system has sufficient redundancy among its components to eliminate single-point failures. Each system contains an assembly of quad check valves. A potential failure on one side of the quad valve is eliminated by flow through the redundant side. This also permits replacement of the failed side of the quad valve without hindering the operation of the propulsion system. The system employs a two-stage pressure and flow regulation assembly. In this manner, coarse regulation is obtained, followed by fine regulation. Use is made of interconnections (crossover valves) between the two systems making up a propulsion module. Interconnections are located downstream of the pressurant tank, downstream of the oxidizer tank, and just upstream of the TCA units. This provides interaction between the two systems of the propulsion module, if required. Each system also contains relief valves and burst discs at locations where unrelieved pressure buildup could result in catastrophic failure.

The components are designed for quick removal with a minimum of physical effort. Since a group of components (one side of the quad valve assembly, for example) or a section of the oxidizer feed assembly may become defective, modularization is used when possible.



SIDE VIEW OF OXIDIZER STORAGE TANK

Fig. II-7 Conceptual Oxidizer Feed Assembly

Finally, it is recognized that the system fluids should be isolated during repair. These fluids should be removed during component repair or replacement. This requirement is satisfied by venting all fluid storage containers and transfer lines to vacuum and by using cold traps to reclaim the fluid. This permits storing the fluid, as well as isolating the system fluid if it becomes contaminated.

Resupply of the oxidizer feed assembly will be made with a blowdown system using capiallary screens for propellant orientation and acquisition. A blowdown system will be used for pressurant resupply. The pressurant bottle onboard the logistics craft will be sized so that the residual gas from the pressurant resupply will be used as the pressurant for oxidizer resupply.

Self-sealing disconnects will be used to prevent spillage. The pressurant level will be determined by a pressure gage on Space Station storage tank. The oxidizer level will be predetermined on the logistics craft, and the whole bulk of fluid will be transferred.

The interface between the logistics craft and the Space Station is the hand-operated quick disconnect. This could be converted to a "hard-dock" operation with additional development. This would eliminate crew commitment and completely automate the system.

The feed system for the spin/despin experiments will be contained onboard the cargo module. This is necessitated by the large quantities of consumables required. This approach was used rather than a separate, larger feed system onboard the Space Station for the spin/despin motors. In this manner the feed system for spin/despin is removed when it is not required. This will also simplify the resupply requirements. All other functions -- including fault detection and compensation -- will remain the same.

The Space Station oxygen feed assembly will be capable of two modes of operation, automatic and manual. For normal conditions, attitude correction will be initiated by the onboard computer operating on the automatic mode. This system will also automatically compensate for component failures by actuating proper crossover valves to operate the standby redundant system. System condition will be indicated on the control panel (Fig. II-8). The panel will consist of a system schematic with warning lights for all major portions or modules of the system. Three lights will be provided for each module: green for operating path, white for standby, and red for a failed module.

If the crew wishes to perform experiments or emergency attitude corrections, they can switch the toggle switch on the control panel from automatic to manual operation. After the control valve is opened, engine control is accomplished with isolation switches on the control panel. The control panel will also include a pressure gage and selector switch that can be used to check pressure readings at various points along the system to isolate possible future failures. The onboard computer will be programmed to indicate component failure and necessary compensation requirements.

C. DEMAND ON SPACE STATION

This section presents the demand on Space Station systems imposed by the hybrid propulsion subsystem. Items presented include onboard spares, scheduled maintenance, special equipment, and resupply.

All maintenance, repair, and spares storage for the oxidizer feed assemblies and the thrusters take place in two auxiliary propulsion subsystem rooms located on the bottom deck of the Space Station. This lower deck also contains two docking ports with 1.52-m (5.0-ft) passageways leading to a 3.04-m (10-ft) diameter central tunnel.

The auxiliary propulsion subsystem rooms are designed around the thruster pads and refurbishment table. This table is the primary APS maintenance and repair station. Storage space underneath the table and in cabinets holds spare and replacement parts, replacement fuel grains, and refurbishment equipment. Recessed cradles and straps are available to hold motors and feed system tanks during repair or refurbishment.

The selection of onboard spares was based on the following criteria:

1) Components whose failure would adversely affect crew safety. No components are required to meet this criterion;

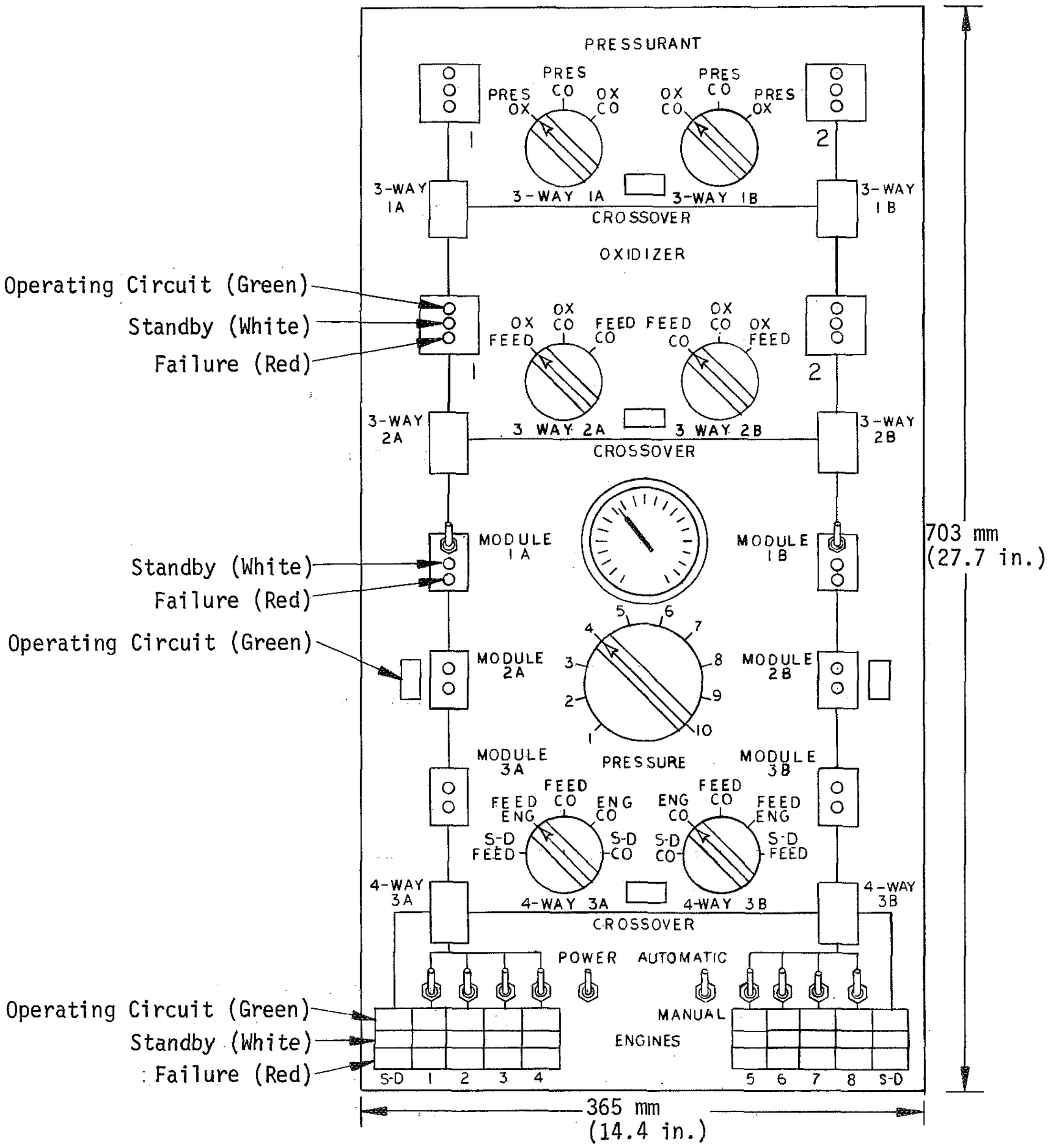


Fig. II-8 Oxidizer Feed System Control Panel

2) Components whose failure would degrade mission success;
3) Components with a high failure probability.

Because each piece of hardware and each designed piece of equipment was selected with reliability as one of the important criteria, spares were kept to a minimum. Motor replacement parts will include complete modular assemblies, such as igniters, fluidic assemblies, and sparking assemblies, in addition to O-rings, shear pins, and fuel grains. Oxidizer feed assembly replacement parts include three-way valves, control valves, relief valves, control regulators, and filters. Whenever an item is replaced or refurbished, the older stocked item will be used first, so the spare and reserve parts will always be fresh.

Refurbishment of each ACS thruster requires approximately 41 minutes, and each spin/despin motor, 43 minutes. The total crew time per year for the scheduled maintenance of the feed assembly, including resupply periods, is 286 minutes.

Special tools required include container assemblies for the thrusters, a dolly, a fluid decontamination tool, and the normal hand tools.

The instrumentation and computer facilities requirements were designed to satisfy four primary objectives:

1) Ensure mission success;
2) Promote safe propulsion subsystem operation;
3) Minimize propulsion maintenance and increase propulsion reliability;
4) Provide minimum impact on Space Station activities.

Malfunction detection devices on the thrusters include pressure and thrust transducers and fuel trip wires. The operation of the oxidizer feed assembly is monitored by a series of pressure readings. The conceptual hybrid APS can achieve high reliability and safety with extensive computer facilities.

Resupply of the APS encompasses all activities from terrestrial storage, inventory control, and ground handling to inflight refurbishment of the subsystem.

At launch, all necessary equipment and tooling will be onboard the Space Station to perform the planned attitude control and spin/despin maneuvers. Items that will be resupplied during the 10-year Station orbit will be as follows:

1) Consumables:
    a) Liquid oxygen,
    b) Helium pressurant,
    c) ACS and spin/despin motor fuel grains,
    d) Propane gas for igniting ACS motors,
    e) Spin/despin motor igniter assemblies;
2) Items that Age or Wear Out with Time and Use:
    a) Valves,
    b) Filters,
    c) O-rings,
    d) Seals.

A schedule for resupply is shown in Table II-5. Resupply quantities of the consumable items were determined from the total impulse requirements presented in Table II-2. The resupply schedule assumes a Shuttle flight every 6 months, except during the artificial-g maneuvers when a cargo module is docked to supply LOX. The first Shuttle flight would be flown 3 months after launch, and the last resupply flight would be flown 9 years and 6 months after launch. A total of 21 resupply Shuttle flights would be made during the 10-year Space Station mission.

Table II-5 Scheduled Resupply (6-Month Shuttle)

	Units																						Total
ACS MOTOR																							
Fuel Grain			3		3		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	36
Propane Bottle			1		1			1	1	1		1	1	1		1		1		1	1	1	7
O-Rings																							
Motor								10				10				10				10			82
Motor-to-Pad								10				10				10				10			82
Seals																							
Motor-to-Pad																							18
Door Assembly								10				10				10				10			10
Refurbishment Container								6				6				6				6			6
SPIN/DESPIN MOTOR																							
Fuel Grain																							
Forward Segment			12		12																		7
Cylindrical Segment			48		48																		28
Aft Segment			12		12																		7
Igniter Assembly			12		12																		7
O-Rings and Seals																							
Motor																							14
Motor-to-Pad																							8
Door Assembly																							10
Refurbishment Container																							4
OXIDIZER FEED ASSEMBLY																							
LOX & Helium Cargo Module		1	1	1	1	1																	5
LOX							1				1				1				1				4
Helium							1				1				1				1				4
Valves																							
Solenoid							4			4			4			4			4				20
Check							4			4			4			4			4				20
Three-Way							4			4			4			4			4				20
Relief							4			4			4			4			4				20
Regulators					2			2		2		2		2		2		2		2			16
Quick-Disconnects					2			2		2		2		2		2		2		2			16
Months after Launch	LAUNCH 0	3	6	9	12	15	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	
Shuttle Flight Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	

III. RECOMMENDATIONS

This study has shown that the hybrid propulsion subsystem is an attractive candidate for attitude propulsion on the Space Station. However, the changing status of the Space Station concept means that additional study programs are required. Recommended study programs include:

1) Use of the hybrid rocket to satisfy low-thrust, as well as high-thrust requirements;
2) A system's study investigation of the use of trash generated onboard the Space Station to supply the fuel for the hybrid-grain;
3) An evaluation of the candidate propulsion subsystems for attitude control of the Space Station. The candidate propulsion subsystems include hybrid, monopropellant, and cryogenic bipropellant systems.

We also recommended that NASA initiate propulsion programs that emphasize inflight maintenance and commonality. Previous programs have emphasized propulsion performance which, in itself, is not sufficient for long-life systems. These programs should not only emphasize the design of these systems, but also demonstrate their inflight maintenance capability.

It is also apparent in this study that inflight maintenance for propulsion must interface with other subsystems to provide the most effective concept. Therefore, one central integrator is required to define, implement, and coordinate the inflight maintenance program for the Space Station.

New technology requirements identified during the performance of this study and recommended for further effort are:

1) Development of three-way valves;
2) Development of electromechanical and mechanical bellows systems;
3) Inflight maintenance experiment;
4) Zero-g fluid transfer;
5) Capillary screen development for cryogens;
6) Component design and test for maintainability;
7) Design and test fluid fittings;
8) Long-life test program;

9) Low-pressure, radiation-cooled hybrid motor;
10) Low oxidizer mass flux regression characteristics with GOX/(PMM/PBD);
11) Advanced low-maintenance ignition concepts.

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