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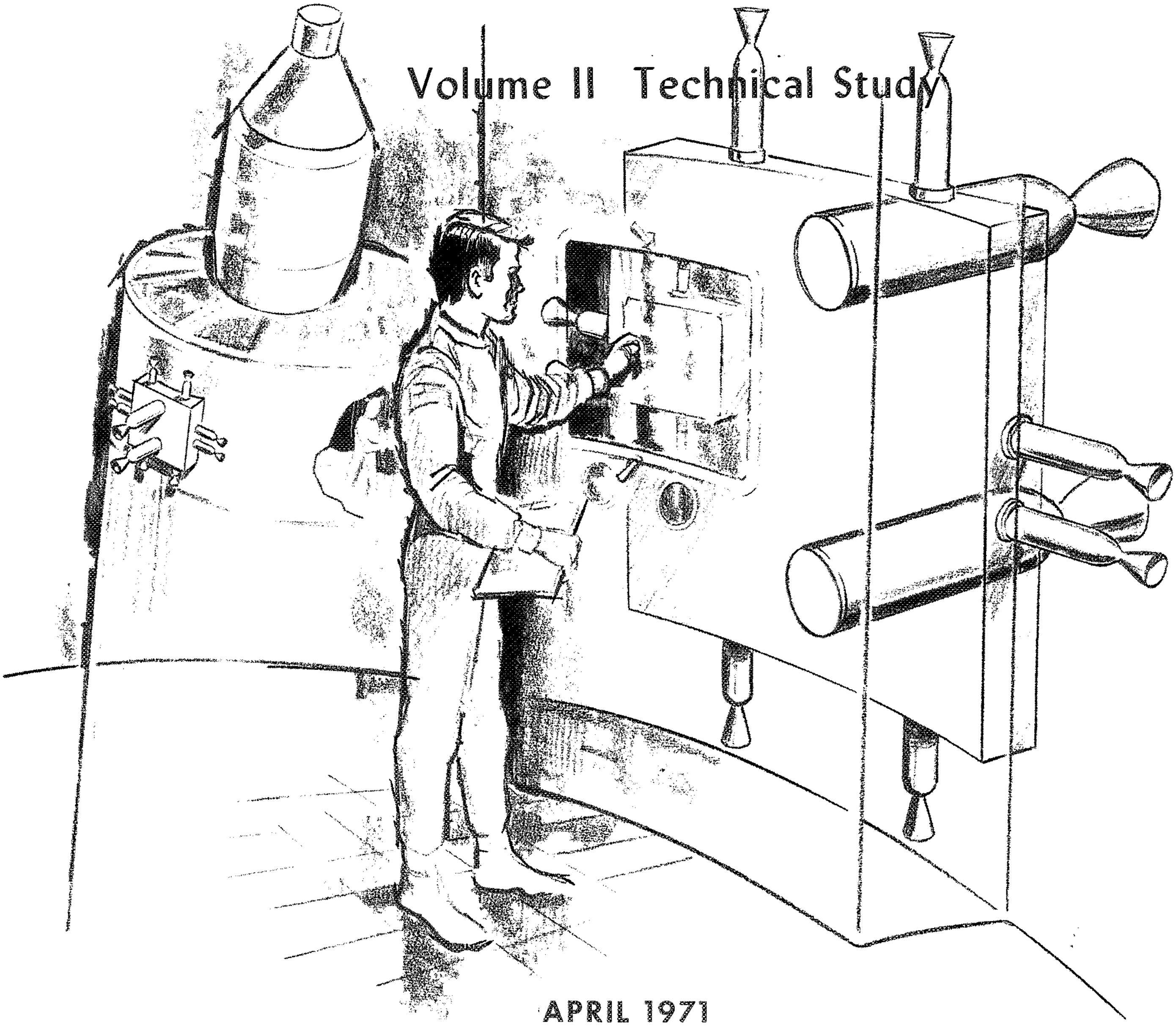
Resupply/Repair of Solid or Hybrid Attitude Propulsion Subsystems

Final Report

Volume II Technical Study



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MARTIN MARIETTA
DENVER DIVISION

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

Volume II
Technical Study

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.

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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 presents the details 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: (1) it is safest due to its lack of toxicity and explosion hazards); (2) it can combine the simplicity of a monopropellant with the performance of a bipropellant; and (3) it provides on-off and throttled operation that cannot be satisfactorily obtained with a solid rocket.

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 that expels the oxidizer from the capillary screen storage tank. Long life was obtained in the thrust chamber

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

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.

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

Section A summarizes the significant findings and conclusions derived from this 6-month study. Details and supporting data are presented in the body of the report. The recommendations presented in Section B must be accomplished if the hybrid APS is to become a reality.

A. SUMMARY

This study has shown that the hybrid APS has many exceptional characteristics for use aboard a manned Space Station. The selected hybrid APS:

1) Is the safest high-thrust propulsion system in use today;
2) Offers high reliability;
3) Requires little inflight maintenance;
4) Offers high performance;
5) Achieves a low total system weight;
6) Requires minimum crew time.

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

Sixteen 223-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.

Two similar, but differently sized thrusters, were selected 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 case diameter 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 an oxygen/(PMM/PBD) propellant combination for both 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. The spinup motor uses liquid oxygen as the oxidizer, inasmuch as any start transient effects are insignificant with regard to the magnitude of the impulse bits involved. For attitude control, reproducible impulse management with small impulse bits is necessary for attitude control, and start transient variations become important; consequently, gaseous oxygen was selected as the oxidizer.

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 grain burns back to the cartridge wall, the heat causes the sensing wire to break, which signals oxidizer flow shutdown. If oxidizer continues to flow after the fuel grain burns 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 hybrid thrust chamber assemblies (TCAs) are met by using high-reliability components and redundancy in the area of critical subsytems. 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 the selected motor configuration is presented in Chapter VI of this volume. The ACS motor has an overall length of 940 mm (37.0 in.), a loaded mass of 21.0 kg $\left(46.3\ \text{lb}_m\right)$, and delivers 225-N $\left(50.5\ \text{lb}_f\right)$ 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 $\left(19{,}480\ \text{lb}_f\text{-sec}\right)$.

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.

The complete hybrid APS uses two thruster pads with a total of 16 ACS motors and three spin/despin motors (located in four possible firing locations). 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. All motors are stored inside during launch and extended once the Space

Station is in orbit. The propulsion refurbishment rooms provide all the facilities required for maintenance, repair, and resupply of the hybrid APS.

Refurbishing/refueling of the thrusters 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 its firing position by essentially reversing the motor withdrawal procedure.

The oxidizer feed assembly selected for the conceptual hybrid APS was designed to operate with the attitude control thrusters. The cargo module must be docked to the Space Station to store and supply the liquid oxidizer and pressurant for the spin/despin motors.

The conceptual oxidizer feed assembly was designed to minimize maintenance, repair, and resupply while maximizing safety, reliability, and performance. This led to the selection of a helium blowdown pressurization system using capilliary screens. This is based on a launch date in the late 1970's. An early launch date would necessitate the use of a bellows system, as was recommended in an earlier Martin Marietta study.*

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.

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*V. A. DesCamp *et al.*: *Study of Space Station System Resupply and Repair, Final Report*. MCR-70-150, Contract NAS8-25067. Martin Marietta Corporation, Denver, Colorado, June 1970.

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.

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.

The oxygen is stored in the liquid phase to minimize space requirements, and is vaporized using the heat rejected by the Space Station systems before being injected into the TCAs.

Resupply of the oxidizer feed assembly will be made with a blowdown screen arrangement. 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 will be used as the pressurant for oxidizer resupply. An earlier Martin Marietta study recommended modular replacement for the pressurant; the present study placed a premium on crew time, which resulted in the blowdown approach.

Self-sealing disconnects will be used to prevent spillage. The pressurant level will be determined by pressure gases on the 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.

A cargo module feed system will also be used for the spin/despin experiments, thereby eliminating a separate system for this operation. Engine selection would take place at the control panel, along with pressure regulator setting.

The consumable demand for the spin/despin experiments required the use of the cargo module to supply the feed system. All other functions -- including fault detection and compensation -- will remain the same.

The overall reliability of the attitude control thruster pads is 0.9671. The overall reliability of the spin/despin thrusters is 0.9913.

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;
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) Insure 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.

Resupply quantities of the consumable items were determined from the total impulse requirements, and assume 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.

As shown in previous studies and confirmed in this study, long-life components can not, by themselves, satisfy the long-life operational requirements for auxiliary propulsion systems for manned space missions. Even standby redundancy, although it improves system reliability, cannot satisfy the long-life requirement. Inflight maintenance is a must if the system has a long-life operational requirement.

B. RECOMMENDATIONS

This study has shown that the hybrid propulsion subsystem is an attractive concept for attitude propulsion on the Space Station. This really should not be surprising, inasmuch as the USSR arrived at the same conclusion earlier. However, the changing status of the Space Station concept means that the present results are limited specifically to the McDonnell Douglas Phase B "common module" Space Station concept. We recommend that additional study programs be considered to account for new concepts. These study programs should include:

1) Use of the hybrid rocket to satisfy low-thrust, as well as high-thrust, requirements (the hybrid rocket is also a likely candidate for drag makeup);
2) A system's study investigation of the use of trash generated onboard the Space Station to supply the fuel for the hybrid grain. Results of this study could indicate what materials should be used for items that become trash;
3) An evaluation of hybrid, monopropellant, and cryogenic bipropellant systems as candidate propulsion subsystems for attitude control of the Space Station.

We also recommended that NASA initiate propulsion programs that emphasize inflight maintenance, long life, and commonality with other subsystems. The propulsion community presently emphasizes one factor -- performance. This, of course, is not sufficient to satisfy long life requirements for either manned or unmanned applications. The propulsion programs should not only emphasize the design of these systems, but also demonstrate their inflight maintenance capability.

It is also apparent from 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 complex applications like 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.

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* 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.

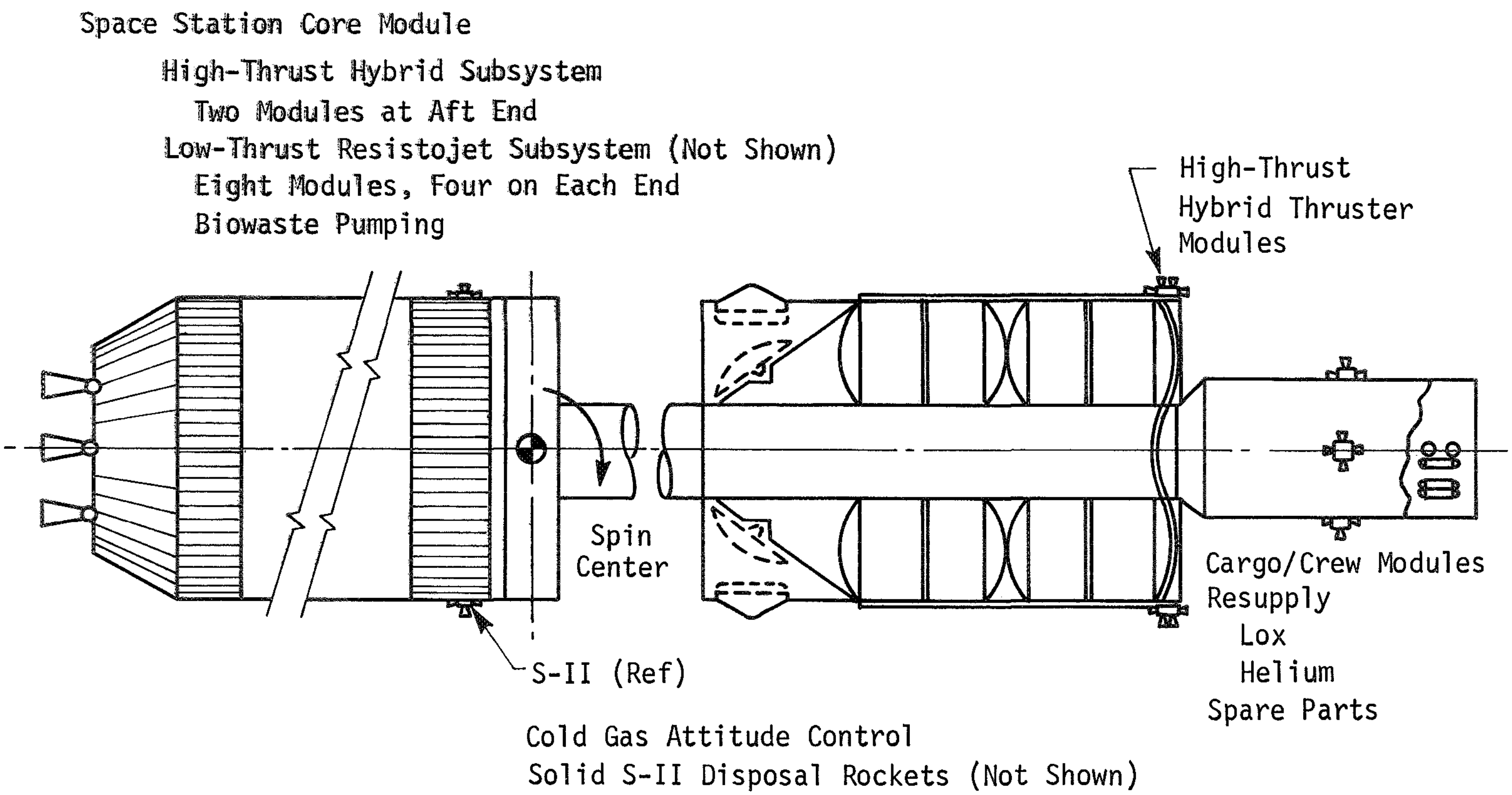
C. STUDY GROUND RULES

The ground rules for this study were selected to provide a scope of work compatible with a reasonable investigation of the application of hybrid rocket propulsion to the attitude control of an earth-orbiting Space Station.

This study was made with the baseline Space Station defined in the MDAC Phase B study.* This configuration, shown in Fig. II-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 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 also 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. Other pertinent study ground rules were:

1) Only the high-thrust requirements are to be considered; the baseline thrust is 222 N $\left(50\ lb_f\right)$;
2) The propulsion subsystem design is not constrained to a pod-type mount on the vehicle skin;
3) The study will be limited to the mechanical portion of the system and associated instrumentation. The electrical control circuitry will not be defined;
4) The thermal requirements will be considered, but no detailed thermal analysis will be undertaken;
5) Repair or resupply concepts should minimize the requirement for extravehicular activity (EVA);
6) The only requirement for the APS is in orbit, not during boost;
7) The resupply/repair requirements imposed on the logistics craft will be established, rather than optimizing the type and size of the craft;
8) All replaced hardware must be collected and placed inside the logistics craft for return to earth;

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, 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

9) The study will assume that there is no continuous ground monitoring of the attitude control system;

10) Safety shall be a prime consideration in system selection;

11) Alternative concepts will be limited to technology available for operational use by the late 1970s.

Other evaluation criteria used to compare alternative hybrid APS approaches included:

1) Supply requirements;
2) Maintainability and repair;
3) Crew requirements;
4) Commonality
5) Onboard equipment requirements;
6) Reliability;
7) Space Station interfaces;
8) Performance;
9) Weight;
10) Growth potential;
11) Cost.

D. 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-2, 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 functions safely. Redundant attitude control thrusters are also provided. By limiting the locations and orientation of the thrusters, plume impingement is minimized on the attached experiment modules and the installation weight of the thruster modules is reduced; i.e., there are only two, instead of four, modules.

The impulse requirements for the hybrid APS, 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.

E. APPROACH

The approach followed to determine the optimum resupply, maintenance, and repair methods for a hybrid APS to serve a 10-year life as part of the Space Station is shown in Fig. II-3. The study was divided into five tasks:

Task	Description
I	Establish Candidate Methods
II	Analyze Impact on Space Station Systems
III	Select Preferred System/Methods
IV	Develop Conceptual Design
V	Determine Effect on Space Station Systems

Initially in Task I, requirements and constraints were agreed upon. This was followed by preliminary analyses of the hybrid thrust chamber assembly (TCA) and the oxidizer feed system.

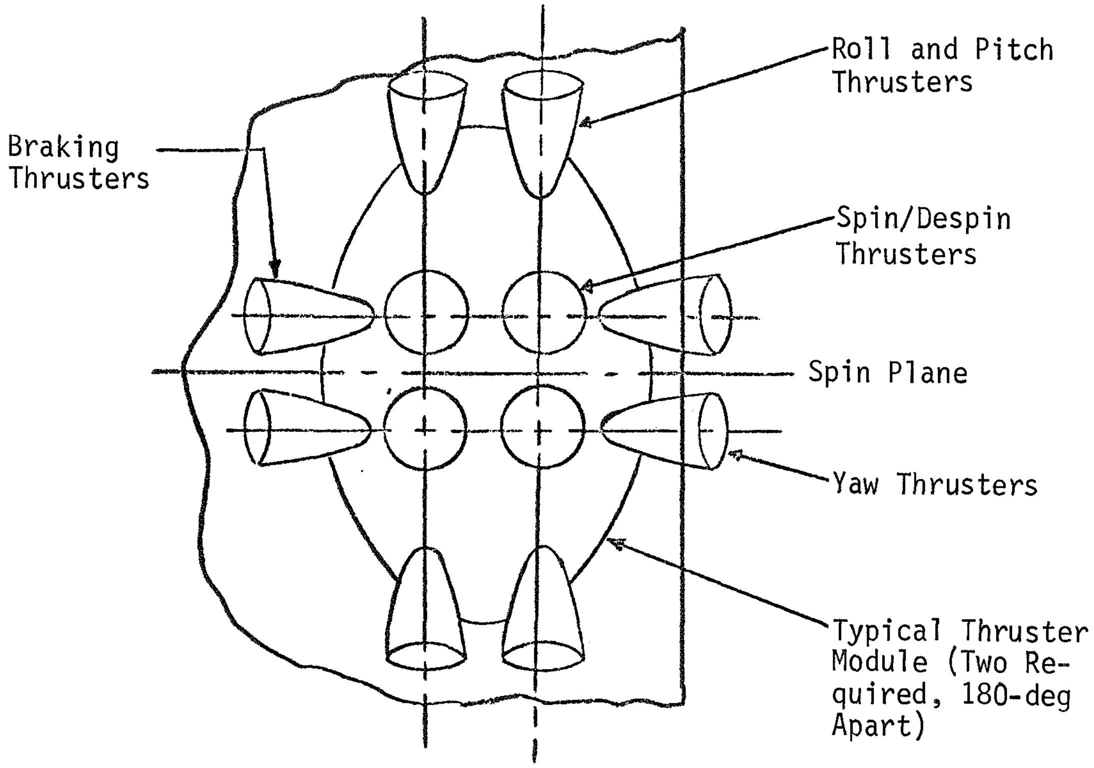


Fig. II-2 Thruster Location

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

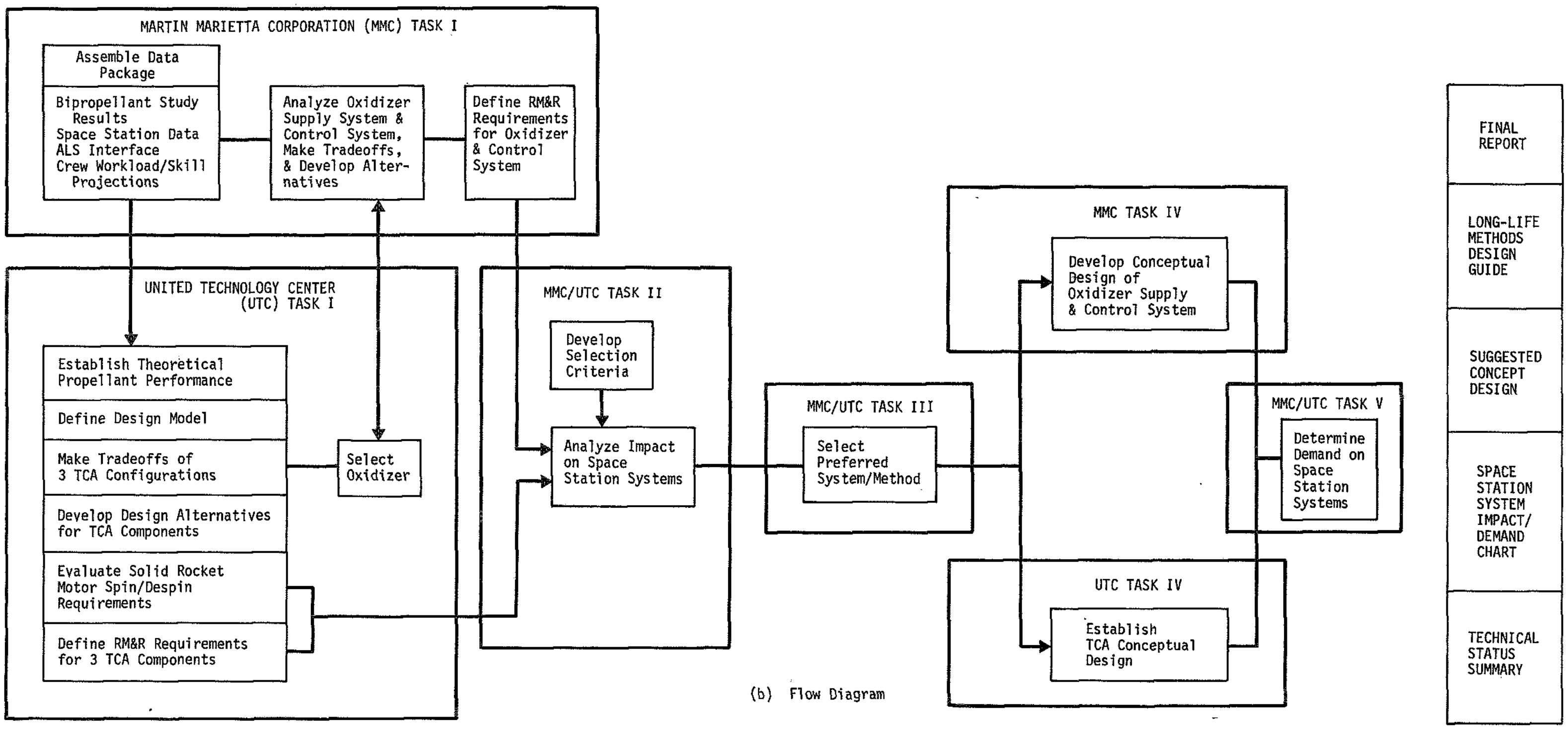
*Per experiment.

†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

(a) Task Breakdown



(b) Flow Diagram

Fig. II-3 Technical Approach

Task II resulted in the development of selection criteria, as well as a Space Station systems impact analysis. This analysis considered 18 candidate oxidizer feed systems, three grain design concepts, four ignition concepts, five grain resupply concepts, nine oxidizer resupply concepts, and five pressurant resupply concepts and how they interface with other subsystems of the Space Station.

Task III consisted of an analysis to select the optimum APS from resupply, maintenance, and repair considerations while satisfying mission success criteria.

Task IV developed the conceptual design of the selected APS that incorporated the selected methods of maintenance, resupply, and repair.

During Task V, the characteristics of the conceptually designed APS were factored against the requirements of the Space Station. Details of the study results in each of these areas are discussed in Chapters III thru VII.

The studies performed in Task 1 were under the following subtasks.

Subtask No.	Description
1	Theoretical Propellant Performance
2	Design Model Thrust Chamber Assembly (TCA)
3	Parametric TCA Tradeoffs
4	Candidate Motor Component Designs
5	Spin/Despin Requirements
6	Oxidizer and Pressurant Considerations
7	Candidate Oxidizer Feed Systems

A. THEORETICAL PROPELLANT PERFORMANCE

Seven candidate hybrid propellant systems were analyzed using a shifting-equilibrium propellant performance computer program. Theoretical values of specific impulse, flame temperature, characteristic exhaust velocity, and chemical composition were calculated for expansion ratios of 20, 40, and 60 at a baseline chamber pressure of 689 kN/m^2 (100 psia). Table III-1 lists the seven candidate propellant systems that were examined and briefly outlines the reasons for their consideration. The theoretical performance curves for these seven candidate propellant systems are shown in Fig. III-1 thru III-3 for an expansion ratio of 60 and a chamber pressure, P_c, of 689 kN/m^2 (100 psia).

The gaseous oxygen (GOX) propellant systems have similar characteristics, with flame temperature increasing with higher performance. The polymethyl methacrylate (PMM) fuel system has the lowest optimum oxidizer/fuel (O/F) ratio (1.6), and has a peak performance $\left(I_{sp} = 343 \text{ sec at } \varepsilon = 60\right)$ that is about 20 sec lower than the other fuels investigated. The three other candidate fuels -- TFTA/polybutadiene (PBD),* 50-50 by weight; PMM/PBD, 20-80 by

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*TFTA = tetraformal trisazine; PBD = hydroxy terminated polybutadiene.

Table III-1 Hybrid APS Candidate Propellants

PROPELLANT SYSTEM		REASON FOR CONSIDERATION
OXIDIZER	FUEL	
GOX	PMM	UTC has a great deal of experience with this propellant system. GOX is safe & nontoxic. PMM has a low minimum regression rate $\leq$ 0.127 mm/sec (0.005 in./sec) & decomposes to a monomer, leaving a clean, char-free surface on shutdown.
GOX	20% PMM/80% PBD	Fuel formulation yields higher performance than GOX/PMM at a higher mixture ratio, & with a less corrosive exhaust. Fuel is similar to the formulation currently in use in UTC's hybrid target drone & has an extremely low minimum regression rate, 0.074 mm/sec (0.003 in./sec).
GOX	50% TFTA/50% PBD	TFTA also increases fuel density.
GOX	PE	Relatively high regression rate & moderately high mixture ratio.
90% H_2O_2/10% H_2O	PE	Low flame temperature system with extremely high mixture ratio. Storable, noncryogenic oxidizer.
NTO	20% PMM/80% PBD	Storable, noncryogenic oxidizer. Fuel yields good performance. Propellant similar to formulation currently used in UTC's target drone.
75% CPF/25% PF	25% Li/25% LiH/50% PBD	High-I_{sp}, maximum-density impulse propellant system with storable, noncryogenic oxidizer.

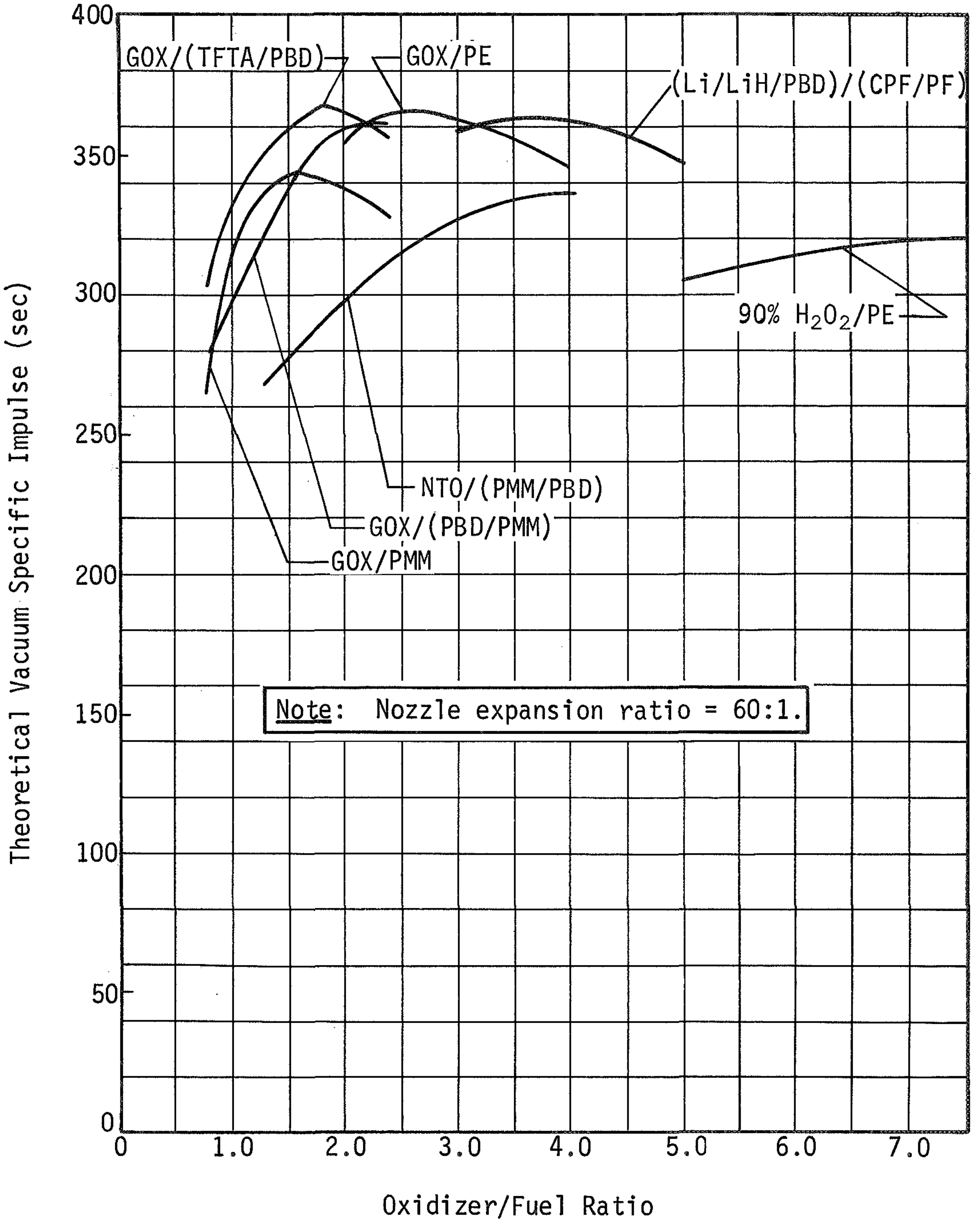

Fig. III-1 Theoretical Vacuum Specific Impulse vs Oxidizer/Fuel Ratio

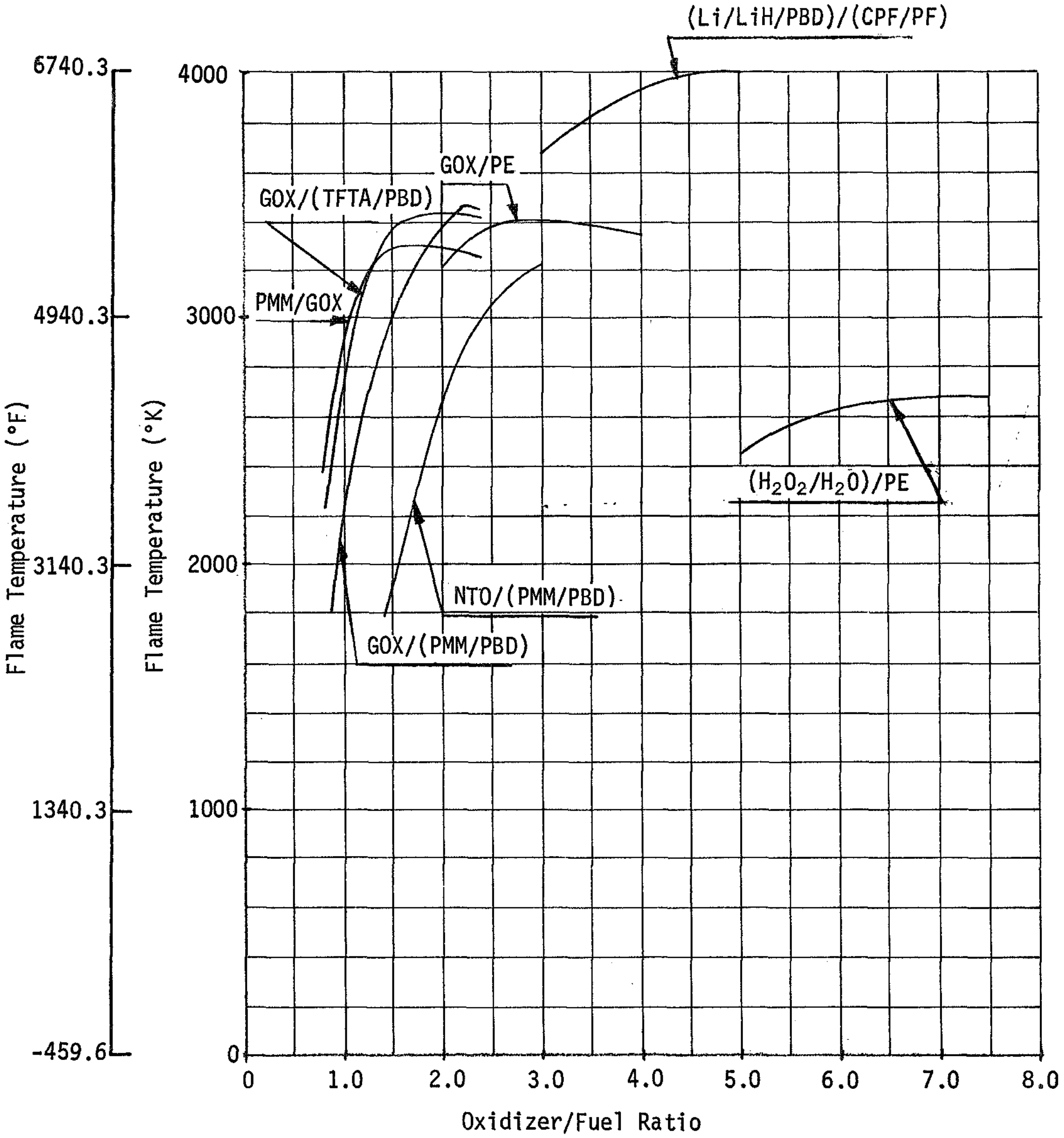

Fig. III-2 Flame Temperature vs Oxidizer/Fuel Ratio

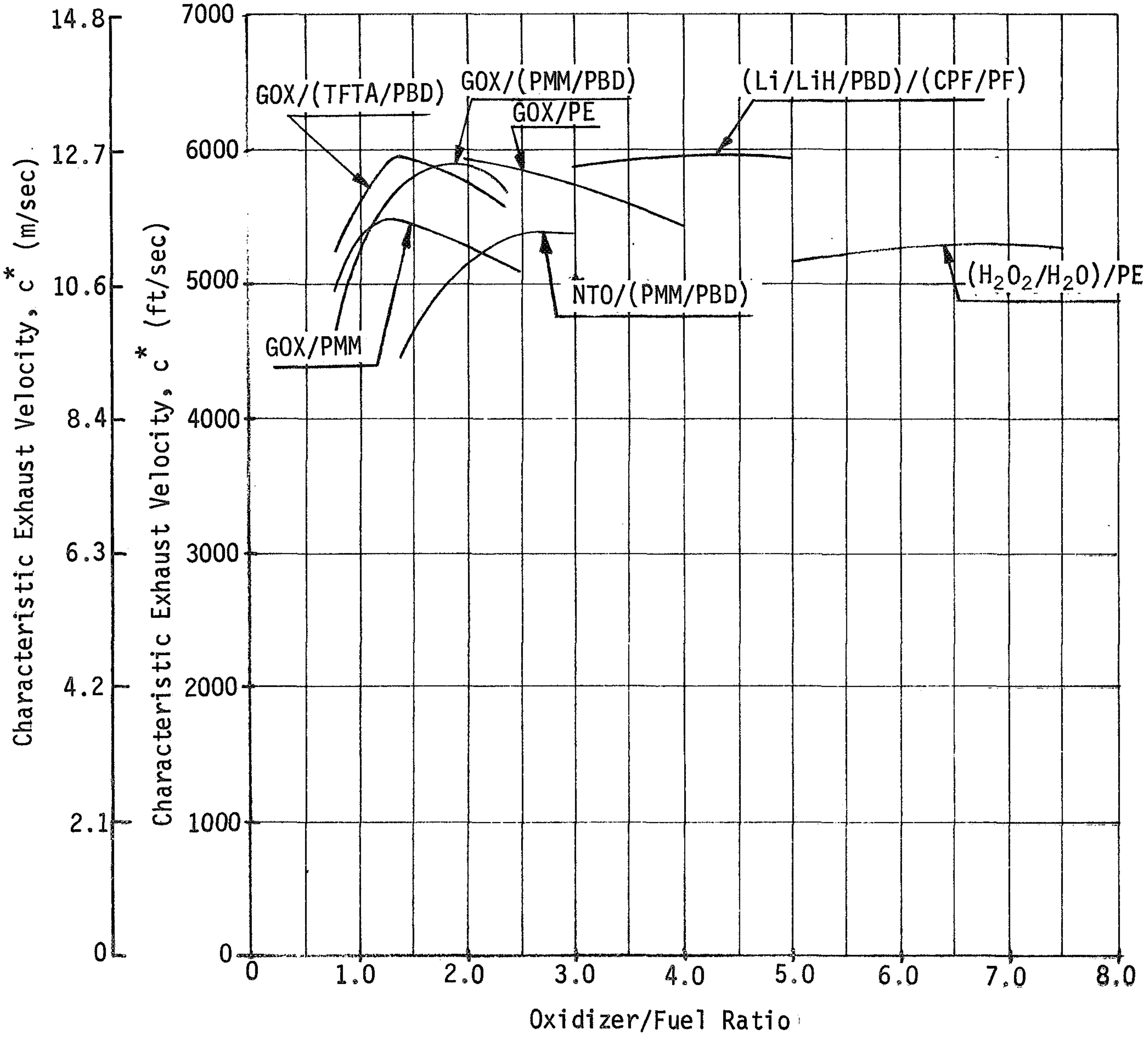

Fig. III-3 Characteristic Exhaust Velocity vs Oxidizer/Fuel Ratio weight; and polyethylene (PE) -- have optimum O/F ratios of 1.8, 2.25, and 2.6, respectively, with optimum performance at $\varepsilon = 60$ from 361 to 366 sec. Peak flame temperatures vary from 3300°K (5480°F) for PMM to 3460°K (5770°F) for the PMM/PBD combination.

Nitrogen tetroxide (NTO) with the PMM/PBD combination offers good performance at a relatively high mixture ratio, and has the advantages of a noncryogenic oxidizer. These features are very attractive in many applications and led to the selection of a mixture of NTO and nitrous oxide (MON-25) and PMM/PBD for UTC's hybrid target vehicle. However, the toxicity problems associated with NTO* make this propellant system unattractive for a manned Space Station.

A chlorine pentafluoride (CPF)/perchloryl fluoride (PF) oxidizer with a lithium fuel system was included to compare a high-performance, maximum-density impulse propellant with the other candidate systems. The CPF/PF system has about the same specific impulse as the GOX system, but its flame temperature, 4000°K (6740°F), is significantly higher. In addition, this CPF/PF oxidizer is even more toxic than NTO and is difficult to seal. Furthermore, the fuel grains present storage and handling problems because they react mildly with water vapor at room temperature and must therefore be sealed from cabin air during storage and handling.

The hydrogen peroxide (H_2O_2)/PE propellant system was included to evaluate a high-performance system with a very high O/F ratio (88% oxidizer by weight at O/F = 7.5). Ninety percent H_2O_2 is storable, provided special tank passivation and clean room procedures are used. H_2O_2 is also nontoxic. Although its theoretical I_{sp} at 320 sec is some 40 sec lower than other systems, its flame temperature, 2690°K (4380°F), is substantially lower than other candidate systems, which simplifies the TCA cooling problem.

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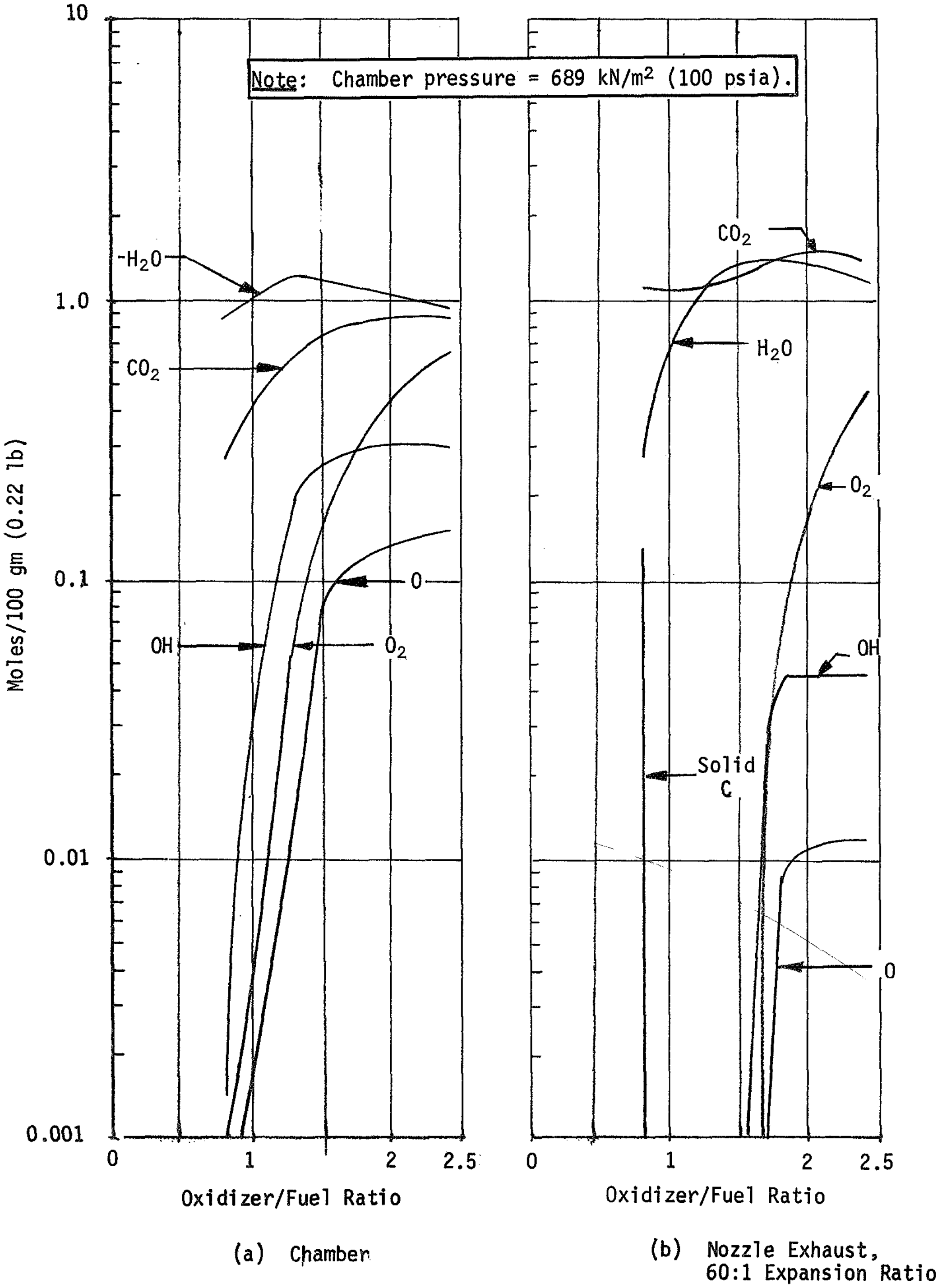
*V. A. Deschamp *et al.*: *Study of Space Station Propulsion System Resupply and Repair, Final Report.* MCR-70-150, NASA Contract NAS8-25067, Martin Marietta Corporation, Denver, Colorado, June 1970.

The selection of a mixture ratio presents some unique considerations for the candidate hybrid propellants. Slightly oxidizer-rich operation offers several performance and ballistic advantages for the hybrid attitude control system (ACS). Operation at higher O/F ratios increases the permissible maximum fuel grain diameter and reduces the fuel grain length, thereby increasing maximum total impulse and operating time between fuel changes. However, oxidizer-rich TCA operation increases the corrosivity and the flame temperature of the combustion products. Therefore, it was necessary to determine the limiting oxidizer-rich mixture ratio that would permit the required long-term operation of the motor chamber and nozzle assembly.

The chemical composition of the combustion products for three candidate propellant formulations [GOX/PMM, GOX/(PMM/PBD), and (90% H_2O_2/PBD] is shown in Fig. III-4 thru III-6 for P_c = 689 kN/m^2 (100 psia) and $\varepsilon = 60$. At peak performance, the H_2O_2 system has the lowest concentration of oxidizer species, the GOX/(PMM/PBD) system has the next lowest, and the GOX/PMM system, the highest. Slightly fuel-rich operation can dramatically reduce both the concentration of oxidizer species and the flame temperature, causing only a 10-15 sec loss in specific impulse. This can be achieved without entering the region where solid carbon begins to form in the exhaust. Any deposition of solid carbon on the Space Station or associated experiments would be unacceptable.

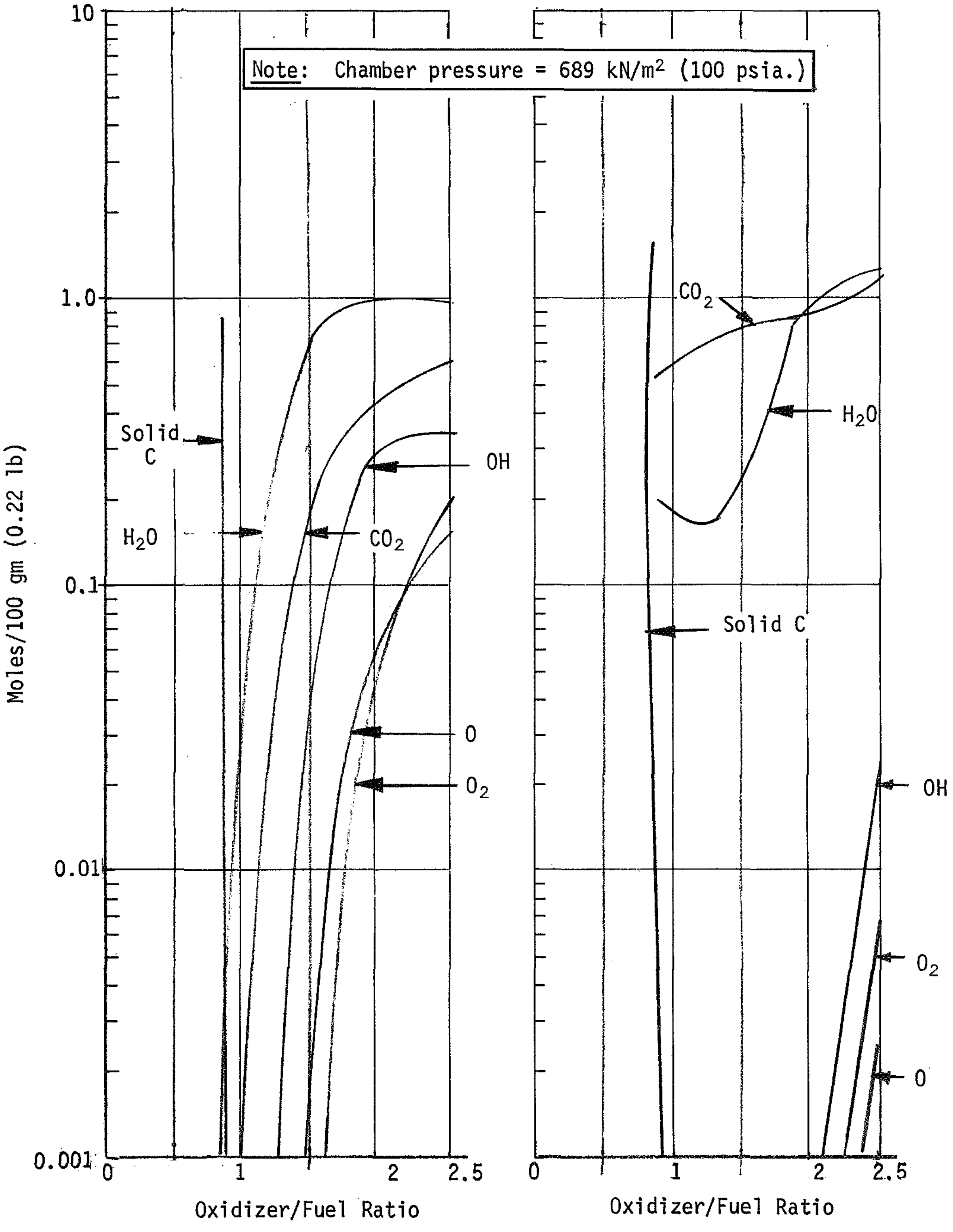
Preliminary fuel regression rate characteristics have been determined for the seven candidate propellant formulations. A relatively simple analytical model widely used for preliminary design relates the fuel regression rate ($\dot{r}$) a constant times the square root of the oxidizer mass flux $\left(\dot{r} = A_o \sqrt{G_o}\right)$. A semiempirical relationship, where A_o = semiempirical regression constant and G_o = oxidizer mass flowrate/grain port area = lb_m/sec-in.^{2}, was developed that relates the regression coefficient A_o to the driving enthalpy, the fuel heat of vaporization, and the fuel density. Because the driving enthalpy can be calculated from a theoretical thermochemical propellant combustion analysis, this approach provides both a convenient preliminary value of A_o and a comparison of the effects of pressure and O/F ratio on the regression rate. Table III-2 lists the values of A_o predicted by this theory for the seven candidate propellant formulations at the baseline chamber pressure of 689 kN/m^2 (100 psia). Most of the



(a) Chamber

(b) Nozzle Exhaust, 60:1 Expansion Ratio

Fig. III-4 Chemical Composition vs Oxidizer/Fuel Ratio, GOX/PMM

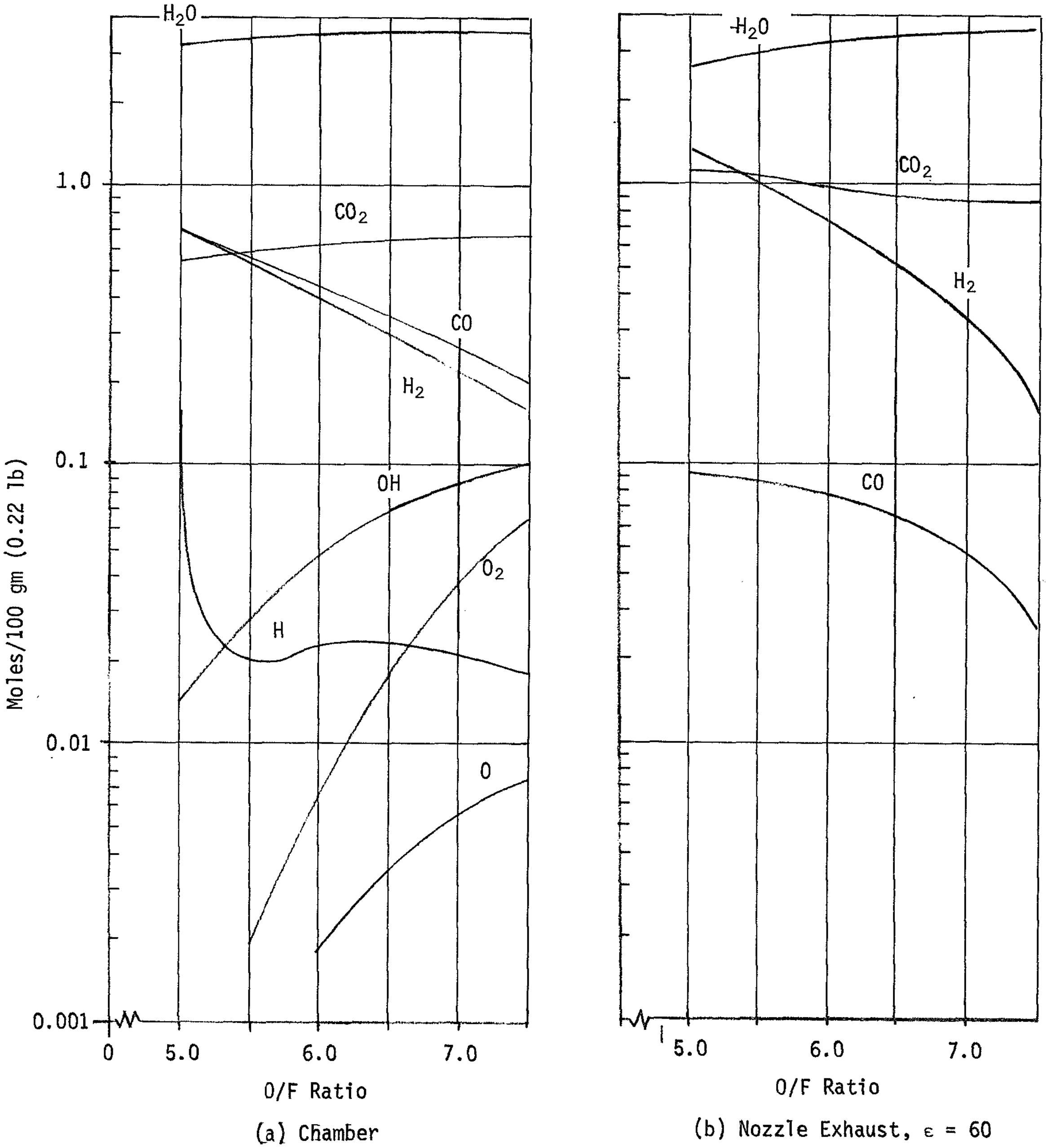


(a) Chamber

(b) Nozzle exhaust,
60:1 Expansion Ratio

Fig. III-5 Chemical Composition vs Oxidizer/Fuel Ratio, GOX/(PMM/PBD)

Note: Chamber pressure = 689 kN/m^2 (100 psia.)



(a) Chamber

(b) Nozzle Exhaust, ε = 60

Fig. III-6 Chemical Composition vs Oxidizer/Fuel Ratio (90% H_2O_2 - 10% H_2O)/PE

Table III-2 Theoretical Regression Rate Coefficients*

PROPELLANT SYSTEM	O/F RATIO	FLAME TEMPERATURE		THEORETICAL REGRESSION RATE COEFFICIENT	
		°F	°K	ENGLISH UNITS†	METRIC UNITS (x 10^{-3})
GOX/PMM	1.8	5469.5	3294	0.064	0.0604
GOX/(PMM/PBD)	2.4	5737.7	3443	0.079	0.0745
GOX/(TFTA/PBD)	1.8	5703.5	3424	0.079	0.0745
GOX/PE	2.5	5622.5	3379	0.086	0.0811
H_2O_2/PE	7.5	4378.7	2688	0.078	0.0736
NTO/(PMM/PBD)	3.0	5325.5	3214	0.081	0.0764
(Li/LiH/PBD)/(CPF/PF)	4.0	6628.7	3938	0.171	0.1613

* Chamber pressure = 689 kN/m^2 (100 psia).

† Correlates with approximate regression rate relationship:

$$\dot{r} = A_o \sqrt{G_o}$$

where $\dot{r}$ is in m/sec (in./sec) and

G_o = oxidizer mass flux in kg/m^2-sec $\left(lb_m / in.^2\text{-sec}\right)$.

propellants considered have fuel regression coefficients between 0.06 and 0.08. The lithium fuel propellant system has a considerably higher regression coefficient, primarily due to a higher flame temperature, a low propellant density, and a low effective heat of vaporization.

B. DESIGN MODEL TCA

A design model hybrid TCA (Fig. III-7 and Table III-3) was developed to indicate the relative size, weight, and performance of a 222-N (50-lb_f) hybrid thruster. The design model TCA used gaseous oxygen and PMM at a baseline chamber pressure of 689 kN/m^2 (100 psia) and delivered 49,553 N-sec $(11{,}140\ \text{lb}_f\text{-sec})$ of total impulse between grain changes with a specific impulse of 302 sec at an expansion ratio of 60. The overall motor length was 818 mm (32.2 in.) with a 122-mm (4.8-in.) motor case diameter.

The TCA used LOX from the oxidizer feed system to regeneratively cool the nozzle throat area. The resulting LOX temperature increase raised the vapor pressure above the GOX injection pressure (but below the line pressure). The LOX was then passed through a phase compensator that throttled the pressure to about 894 kN/m^2 (130 psia) and flashed the LOX to GOX. The GOX then passed through an oxidizer control valve into a precombustion chamber, where it was mixed during an 0.050-sec ignition period with a measured amount of gaseous butane and sparked. During the ignition transient, the hot, oxygen-rich precombustor gases flowed into the primary combustion where they initiated the hybrid combustion process. After ignition, the GOX was injected directly into a cylindrical port fuel grain tailored to provide a fuel flowrate of 0.0250 kg/sec $(0.0552\ \text{lb}_m/\text{sec})$ for a period of 223 sec.

The design model TCA was designed to operate slightly oxidizer-rich at a mixture ratio of 2.0. This significantly improved the hybrid fuel grain configuration and increased the maximum total impulse. The fuel grain was designed to provide a mixing chamber in the aft closure to increase combustion efficienty. without using a submerged nozzle. An unsubmerged nozzle benefits from fuel boundary-layer cooling that significantly reduces the aft closure and nozzle heating problem. The motor case and nozzle assembly were constructed of molybdenum disilicide-coated molybdenum, and were radiatively cooled.

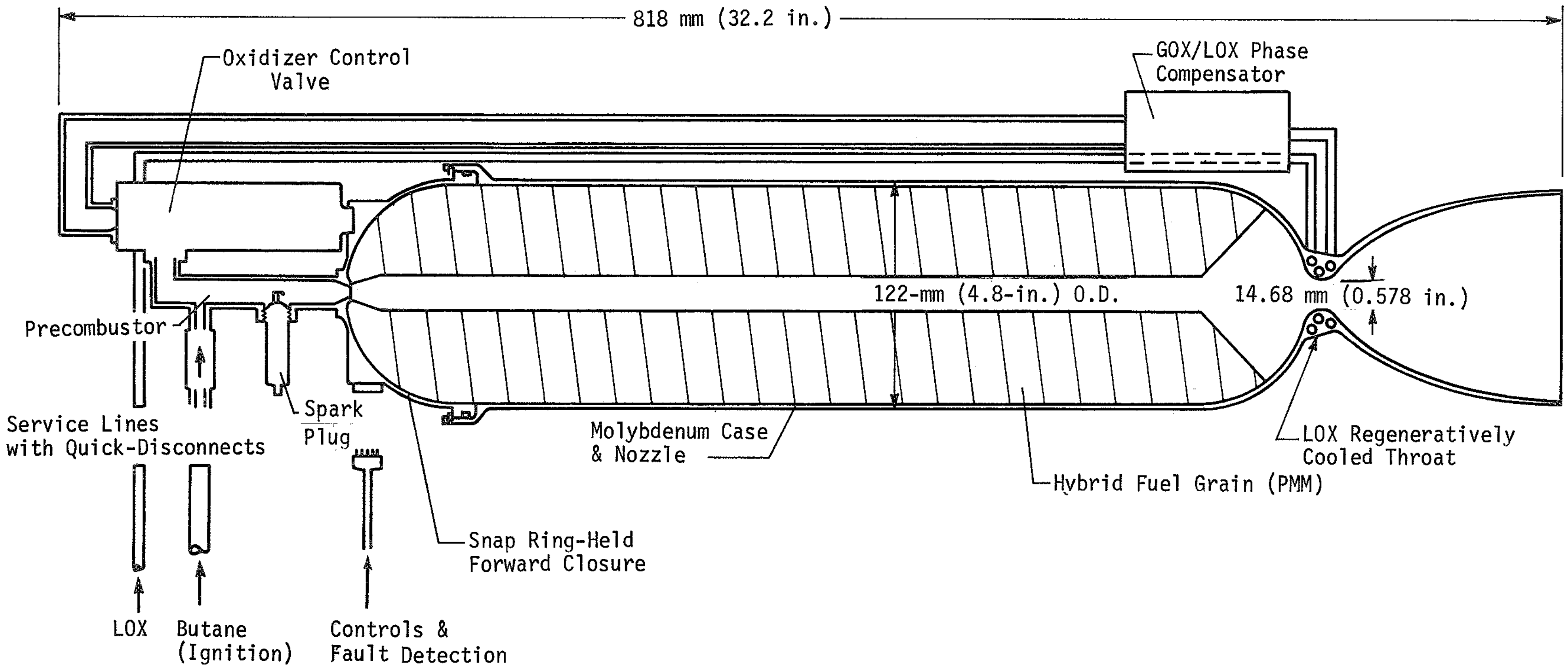


Fig. III-7 Design Model of Hybrid TCA

Table III-3 Design Model of Hybrid TCA

PERFORMANCE SUMMARY	
Propellants	GOX/PMM
O/F Ratio	2.0
Chamber Pressure, kN/m^2 (psia)	689 (100.0)
Nozzle Expansion Ratio	60.0
Vacuum Specific Impulse, sec	302
Thrust, N (lb_f)	222 (50)
Total Impulse, N-sec (lb_f-sec)	49,553 (11,140)
Duration, sec	223
DESIGN SUMMARY	
Motor Diameter, mm (in.)	122 (4.80)
Throat Diameter, mm (in.)	14.7 (0.578)
Overall Length, mm (in.)	818 (32.2)
Grain Design	Single Central Port
Case & Nozzle Design	Radiatively-Cooled Molybdenum Case with LOX Regeneratively-Cooled Throat
Ignition System	Sparked-Butane Precombustor
WEIGHT SUMMARY, kg (lb_m)	
Thrust Chamber Assembly	
Forward Closure, Ignition, & Oxidizer Control Assembly	29.4 (6.5)
Motor Case & Nozzle Assembly	60.3 (13.3)
Reusable TCA Weight	89.7 (19.8)
Expendables	
Useful Fuel	55.7 (12.3)
Residual Fuel	2.7 (0.6)
Loaded TCA	148.1 (32.7)
Gaseous Oxygen	117 (25.8)
Butane (used for ignition - weight for 100 restarts)	1.4 (0.3)
Total Expended Weight	176.8 (39.0)

The design model TCA was constructed to facilitate the replacement and maintenance of the fuel grain. The LOX, butane, and electrical lines all used quick-disconnects. The oxidizer control assembly was attached to a snap ring-held forward closure that could be easily removed by bending or detaching the flexible GOX line. The fuel cartridges had several loops of thin wire imbedded in the grain. During motor operation, an electrical current flowed through a relay in this wire, which supplied power to the oxidizer control valve in the closed position. When the fuel surface reached these wires, the electrical current ceased, which opened the relay and automatically shut down the motor for grain replacement.

C. PARAMETRIC TCA TRADEOFFS

1. Objective

Using the equations in Appendix B of the Quarterly Report,* three propellant systems were evaluated to determine the effects of chamber pressure, mixture ratio, and thrust on performance, total impulse, duration, motor size, and fuel weight. Although several simplifying assumptions were made to make a parametric analysis possible, the results are sufficiently accurate for preliminary design and for a comparison of propellant systems.

2. Ground Rules and Assumptions

a. Propellant Systems - The following three nontoxic hybrid propellant systems were selected for parametric analysis:

1) GOX/PMM;
2) GOX/(PMM/PBD);
3) H_2O_2/PE.

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*J. M. Murphy: *Resupply/Repair of Solid or Hybrid Attitude Propulsion Subsystems, Quarterly Report.* MCR-70-375. Martin Marietta Corporation, Denver, Colorado, October 15, 1970.

The GOX/plexiglas, polybutadiene systems were selected for their high performance, safety, and excellent fuel-regression characteristics. The 90% H_2O_2/PE system was selected for its storability, low flame temperature, and high mixture ratio. The other four candidate propellant systems either offered no advantages to the three that were selected or had serious drawbacks for this mission (e.g., toxicity or handling problems), and were not evaluated further.

b. Performance - The theoretical performance values calculated in Section III-A were applied to the partial boundary layer-cooled design model TCA presented in Section III-B. The estimated delivered performance with this design should be a 95% theoretical characteristic velocity, c*, and a 90% I_{sp} efficiency at $\varepsilon = 60$ and $P_c = 689\ kN/m^2$ (100 psia). The nozzle exit diameter was set equal to the maximum grain diameter for ease in handling.

c. Regression Characteristics - The regression rate relationship $\dot{r} = A_o\sqrt{G_o}$ was used with the values of A_o at 689 kN/m^2 (100 psia) determined theoretically in Section III-A. Data for the GOX systems indicate that there is a flattening of the regression curves at values of G_o below 6.98 kg/m^2-sec $\left(0.01\ lb_m/in.^2\text{-sec}\right)$. Therefore, this analysis is conservative and probably underpredicts the maximum total impulse. The pressure sensitivity of the two oxygen propellants should be very similar and can be matched by $\dot{r} \propto \left(P_c\right)^{0.25}$, where $P_c \leq 1379\ kN/m^2$ (200 psia). The H_2O_2 system will also be matched by this relation, although the lower reactivity of the oxidizer may increase the pressure sensitivity. Furthermore, because the effect of the mass flux on the pressure sensitivity has not been completely characterized, a constant pressure exponent of 0.25 will be used in this analysis. Therefore, $\dot{r} = A_o\ (P/100)^{0.25}$, where $P_c \leq 1379\ kN/m^2$ (200 psia).

d. Critical Regression Rate - The critical regression rate for PMM was ∿0.127 mm/sec (0.005 in./sec) for the proposed Space Station ACS application. Tests with PMM/PBD indicated that minimum regression rates as low as 0.076 mm/sec (0.003 in./sec) may be possible, but a value of 0.1016 mm/sec (0.004 in./sec) will be used in this analysis to account for pulsed operation and to minimize transient effects. Polyethylene has a low melting temperature and a rather high critical regression rate; thus, a minimum regression rate of 0.254 mm/sec (0.010 in./sec) would be required to prevent melting of the surface during pulsed operation.

3. Results of Parametric Motor Analysis

Specific impulse depends on the chamber pressure and O/F ratio, and is independent of thrust level. Figure III-8 shows the maximum nozzle expansion ratio vs chamber pressure for three propellant systems, based on propellant ballistic characteristics and the constant $D'_{exit} = D_{grain_{max}}$. The GOX/(PMM/PBD) system can be designed for $\varepsilon = 100$ (the highest expansion ratio considered) down to a chamber pressure of 517 kN/m^2 (75 psia), due to the extremely low critical regression rate and relatively high regression coefficient of this propellant system. On the other hand, the GOX/PMM system is expansion ratio-limited at low pressure, and the H_2O_2/PE system is limited to comparatively low expansion ratios due to a high $\dot{r}_{crit}$ of 0.254 mm/sec (0.010 in./sec).

Figure III-9 shows the effect of the mixture ratio on the maximum expansion ratio at 689 kN/m^2 (100 psia). Because $\varepsilon_{max} \propto O/F/(O/F + 1)$, the GOX/PMM system is more sensitive to the O/F ratio than the H_2O_2/PE system, which operates at a significantly higher mixture ratio. The GOX/(PMM/PBD) system, whose curve was off the graph, had an intermediate sensitivity to the O/F ratio.

Figure III-10 shows the delivered specific impulse vs chamber pressure of the three propellants. The GOX/(PMM/PBD) system delivers over 330 sec at chamber pressures greater than 448 kN/m^2 (65 psia). The performance of the GOX/PMM system is 20 to 30 sec lower, and that of the H_2O_2/PE system is lower by another 20 to 30 sec. All three propellants suffer significant performance losses at chamber pressures below 414 kN/m^2 (60 psia).

Using 222 N $(50\ lb_f)$ of thrust as a baseline, Fig. III-11 shows the variation in fuel grain length with chamber pressure. The grain length decreases with increasing chamber pressure due to the increase in the regression coefficient. Operating fuel-rich increases the grain length and its sensitivity to chamber pressure, but the opposite is true for oxidizer-rich operation. The GOX/PMM system has the longest fuel grain, due to a low O/F ratio and a low regression coefficient. Conversely, the H_2O_2/PE system offers a very short grain length, due to a very high O/F ratio.

The maximum port area (Fig. III-12) is a strong function of the critical regression rate and is less sensitive to the O/F ratio. The low critical regression rate and relatively high

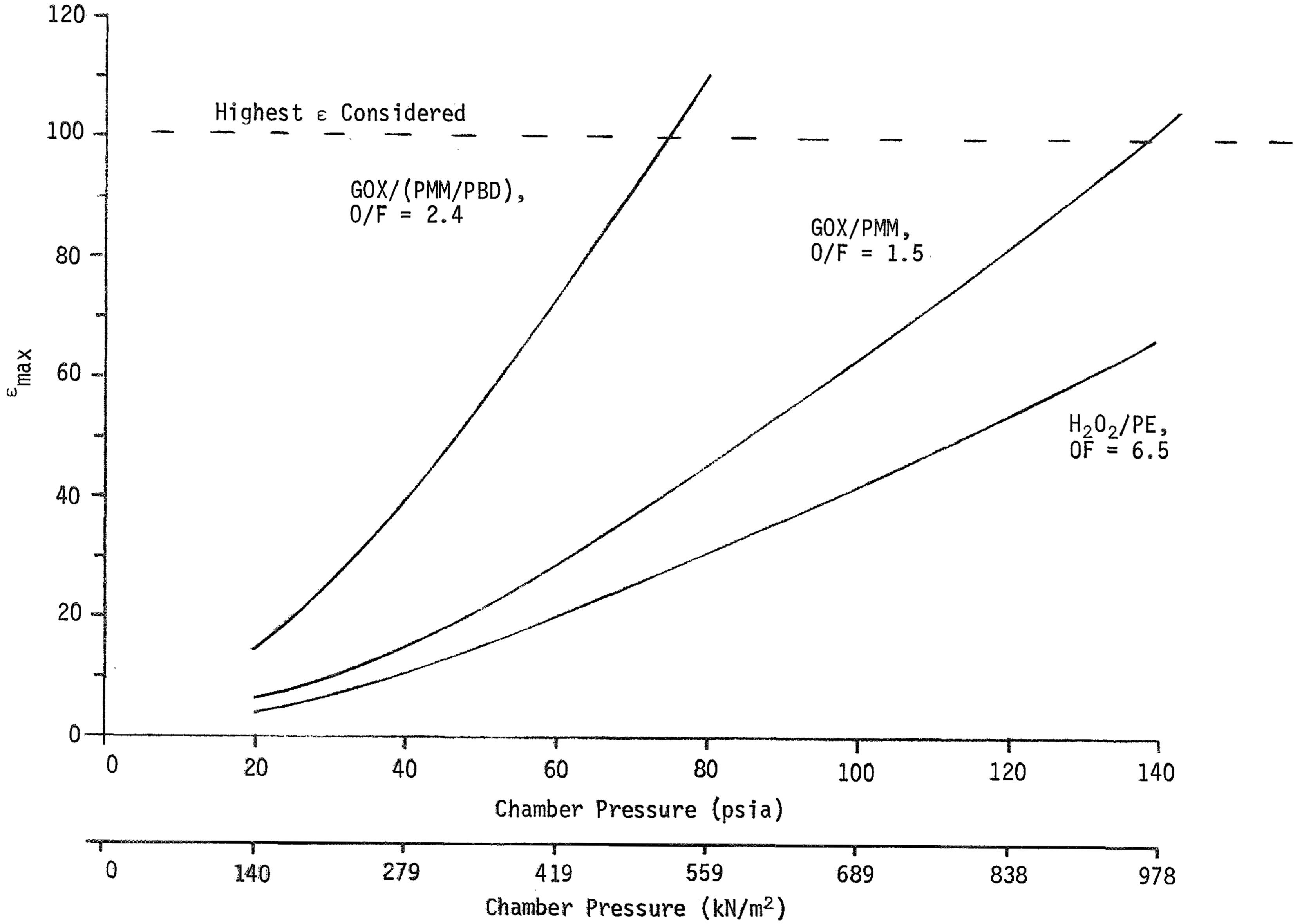
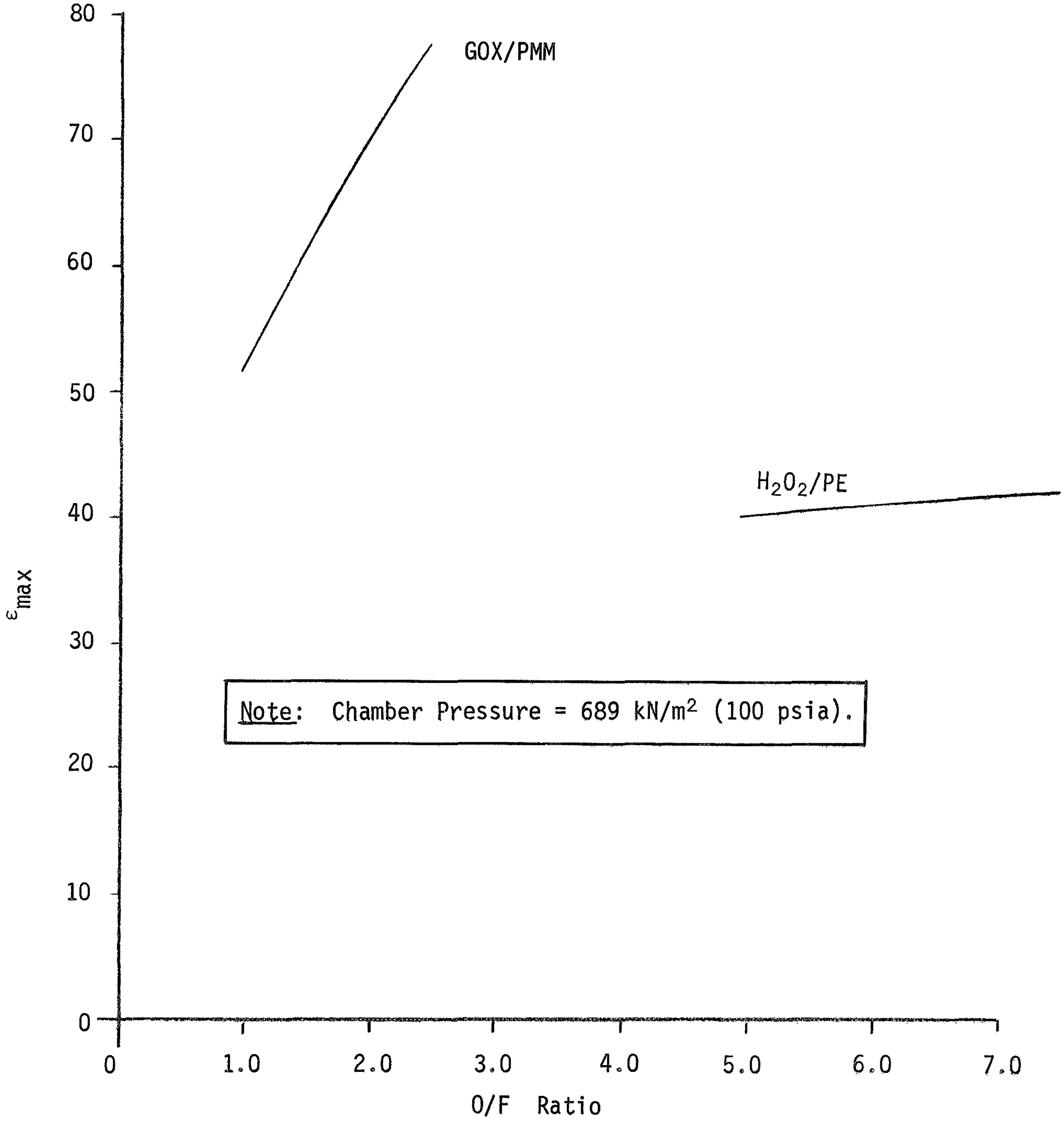


Fig. III-8 Maximum Nozzle Expansion Ratio vs Chamber Pressure



Note: Chamber Pressure = 689 kN/m^2 (100 psia).

Fig. III-9 Maximum Expansion Ratio vs Oxidizer/Fuel Ratio

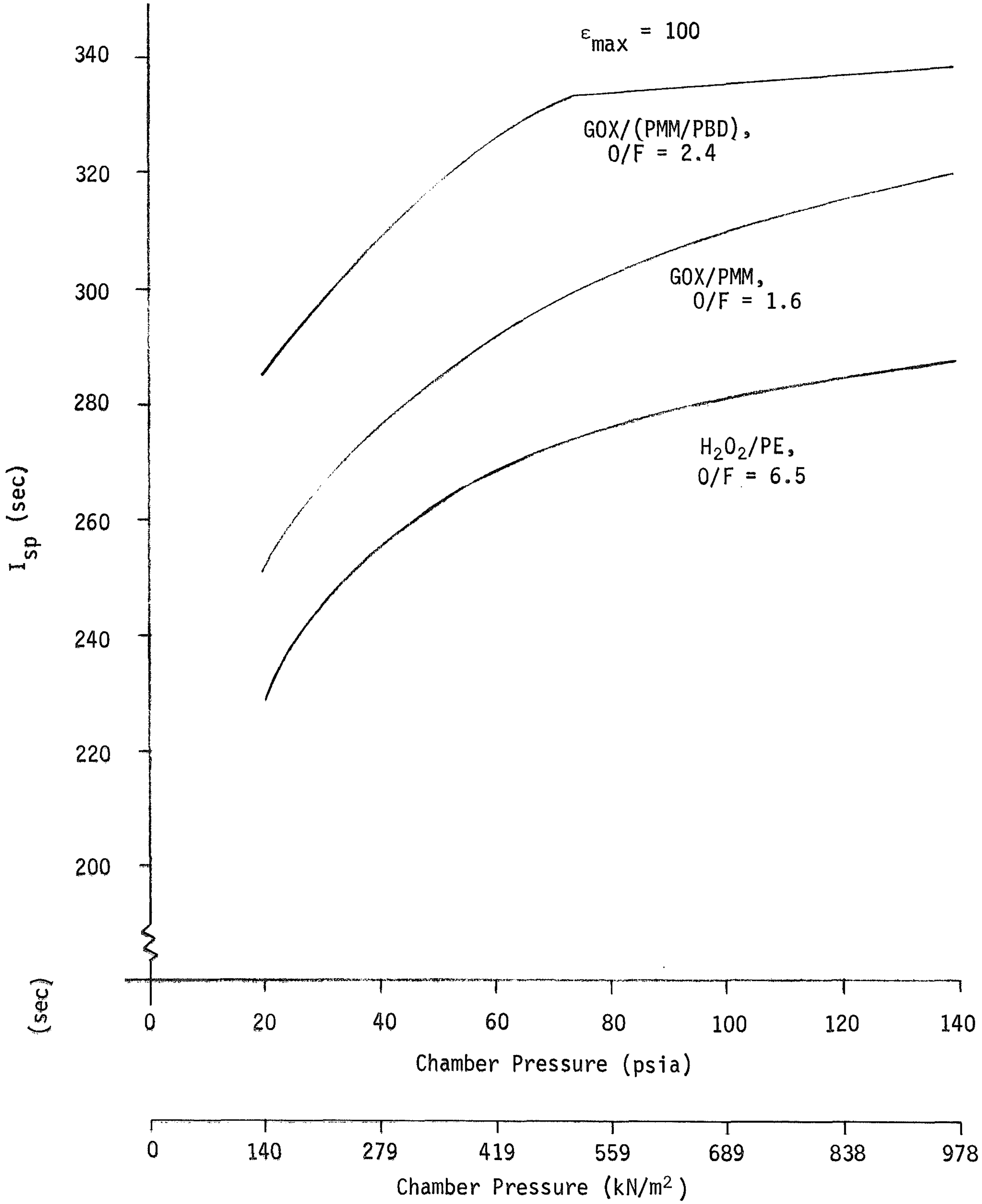


Fig. III-10 Delivered Vacuum Specific Impulse vs Motor Chamber Pressure

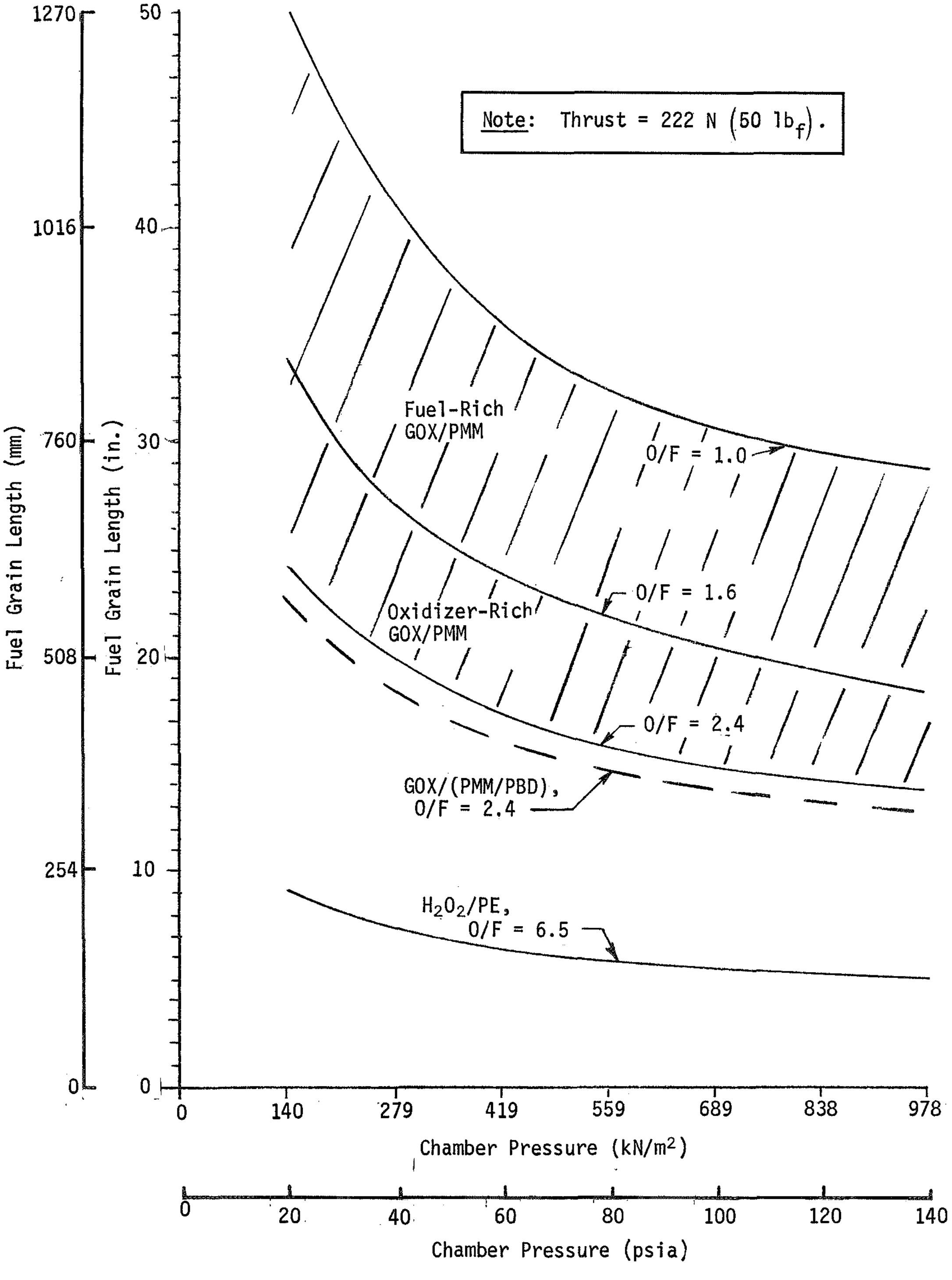


Fig. III-11 Fuel Grain Length for Single-Port Hybrid APS vs Chamber Pressure and Oxidizer/Fuel Ratio

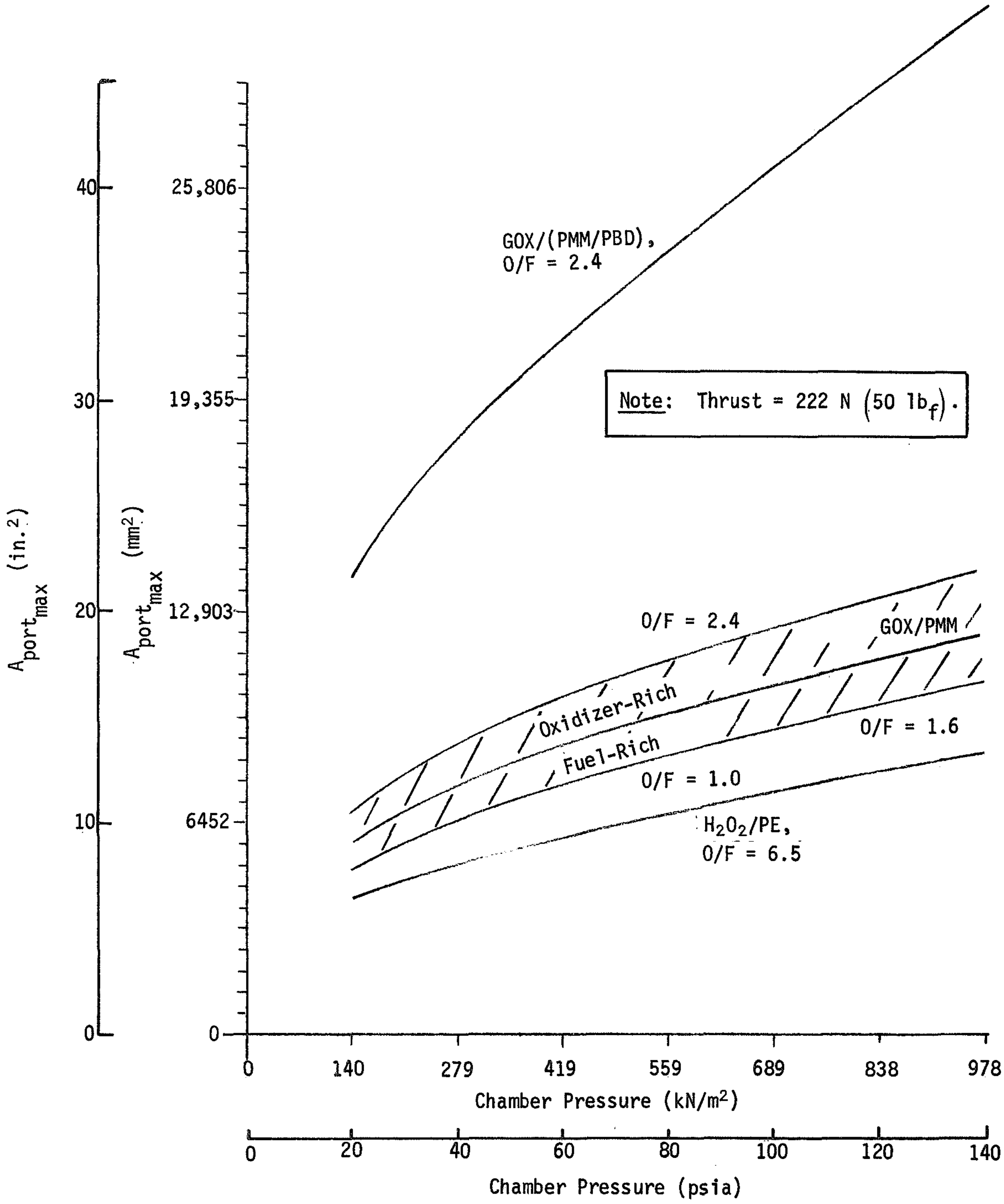


Fig. III-12 Maximum Port Area vs Chamber Pressure and Oxidizer/Fuel Ratio regression coefficient of the GOX/(PMM/PBD) system allows a much larger maximum port area than the other two propellants. Polyethylene's high critical regression rate offsets its high regression coefficient and results in a small maximum port area.

At a low chamber pressure and a high O/F ratio, the minimum port area is determined by Mach number effects; but at high pressures and low O/F ratios, boundary-layer constraints are more important. Figure III-13 shows the minimum port area vs pressure and O/F ratio for the GOX/PMM system. At O/F = 1.0, the longer grain length restricts the initial port diameter, due to boundary layer effects; at O/F = 2.4, the grain is significantly shorter, and Mach number constraints limit the initial port diameter until $P_c > 978$ kN/m^2 (140 psia). Figure III-14 shows the minimum port area for the other two propellant systems, both of which are Mach number-limited for $P_c < 689$ kN/m^2 (100 psia).

The usable fuel-grain weight for a 222-N $\left(50\text{-lb}_f\right)$ motor is shown in Fig. III-15. The values shown in this figure do not include the weight of residual fuel, which would add 3 to 6% to these weights, depending on the grain. The fuel-grain weights for the GOX propellants are around 4.54 to 9.07 kg $\left(10 \text{ to } 20\ \text{lb}_m\right)$. Hybrid grains can easily be segmented to facilitate handling and storage. However, a man would be able to handle 1.34 to 18.14 kg $\left(25 \text{ to } 40\ \text{lb}_m\right)$ grains in the 0 to 0.7-g Space Station environment, and segmentation would not be necessary for a 222-N $\left(50\text{-lb}_f\right)$ thruster. The H_2O_2/PE grains are extremely small and only weigh about 0.9 kg $\left(2\ \text{lb}_m\right)$.

The maximum total impulse capability of the three propellants is shown in Fig. III-16. At a thrust of 222 N $\left(50\ \text{lb}_f\right)$, the GOX/(PMM/PBD) system can deliver 80,000 to 97,860 N-sec $\left(18{,}000 \text{ to } 22{,}000\ \text{lb}_f\text{-sec}\right)$ between grain replacements, but the GOX/PMM system can only deliver about half this much. The H_2O_2/PE system delivers less than 22,240 N-sec $\left(5000\ \text{lb}_f\text{-sec}\right)$ and would, therefore, require more frequent grain replacement than either GOX system. Figure III-17 shows the motor firing time between grain replacements. At 689 kN/m^2 (100 psia), this varies from 442 sec for GOX/(PMM/PBD) to only 92 sec for H_2O_2/PE.

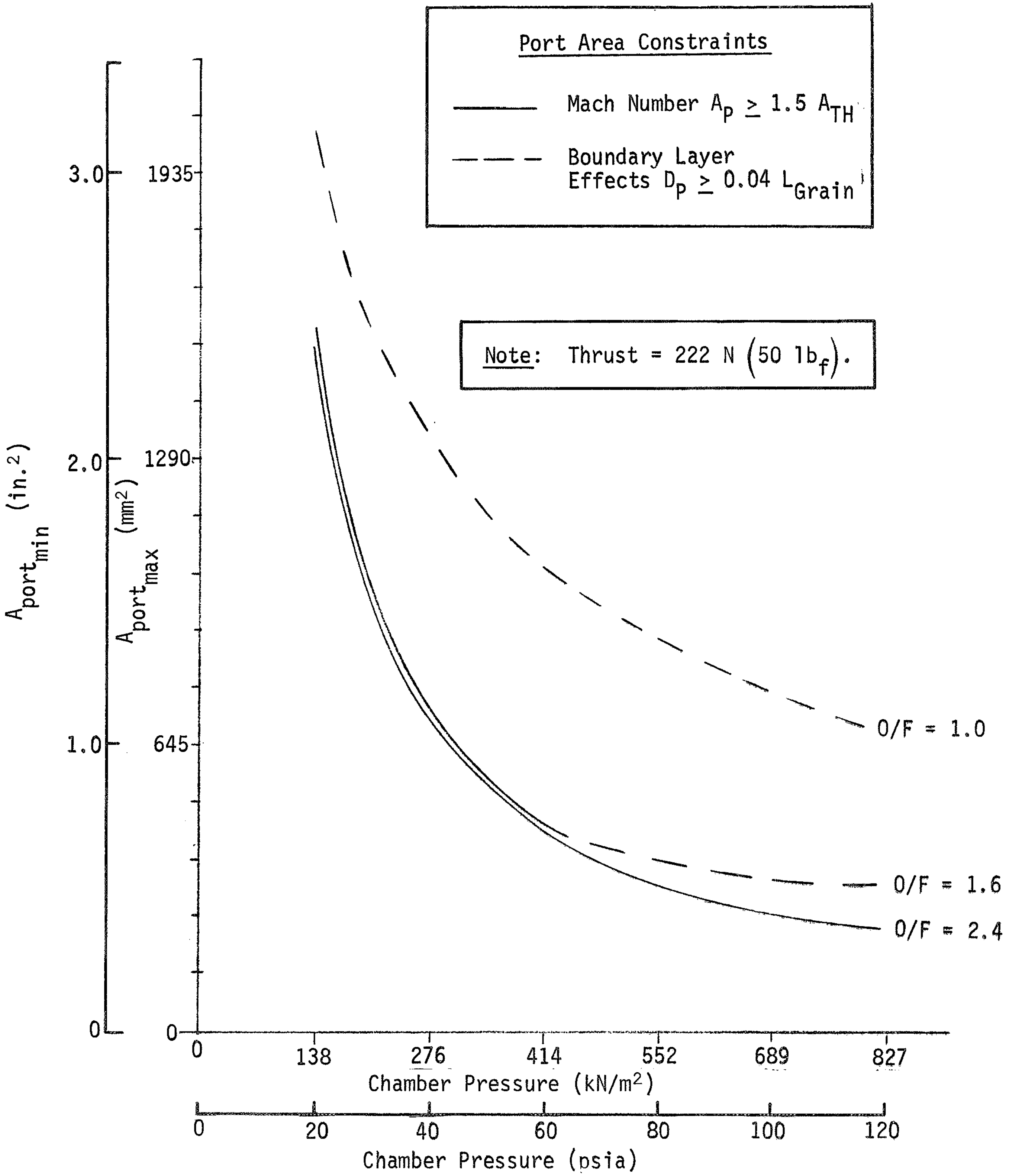


Fig. III-13 Minimum Port Area vs Chamber Pressure and Oxidizer/Fuel Ratio for GOX/PMM

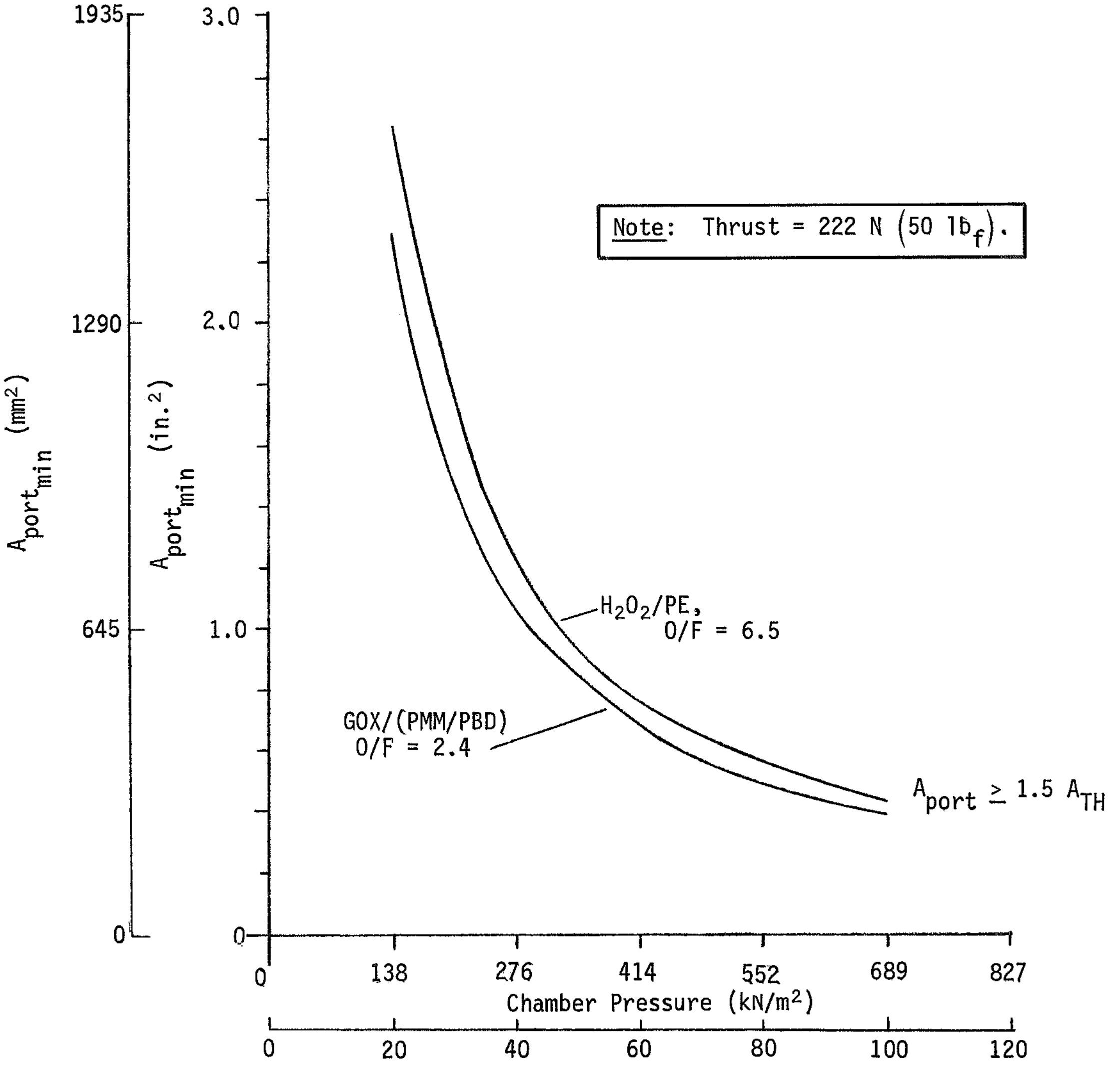


Fig. III-14 Minimum Port Area vs Chamber Pressure

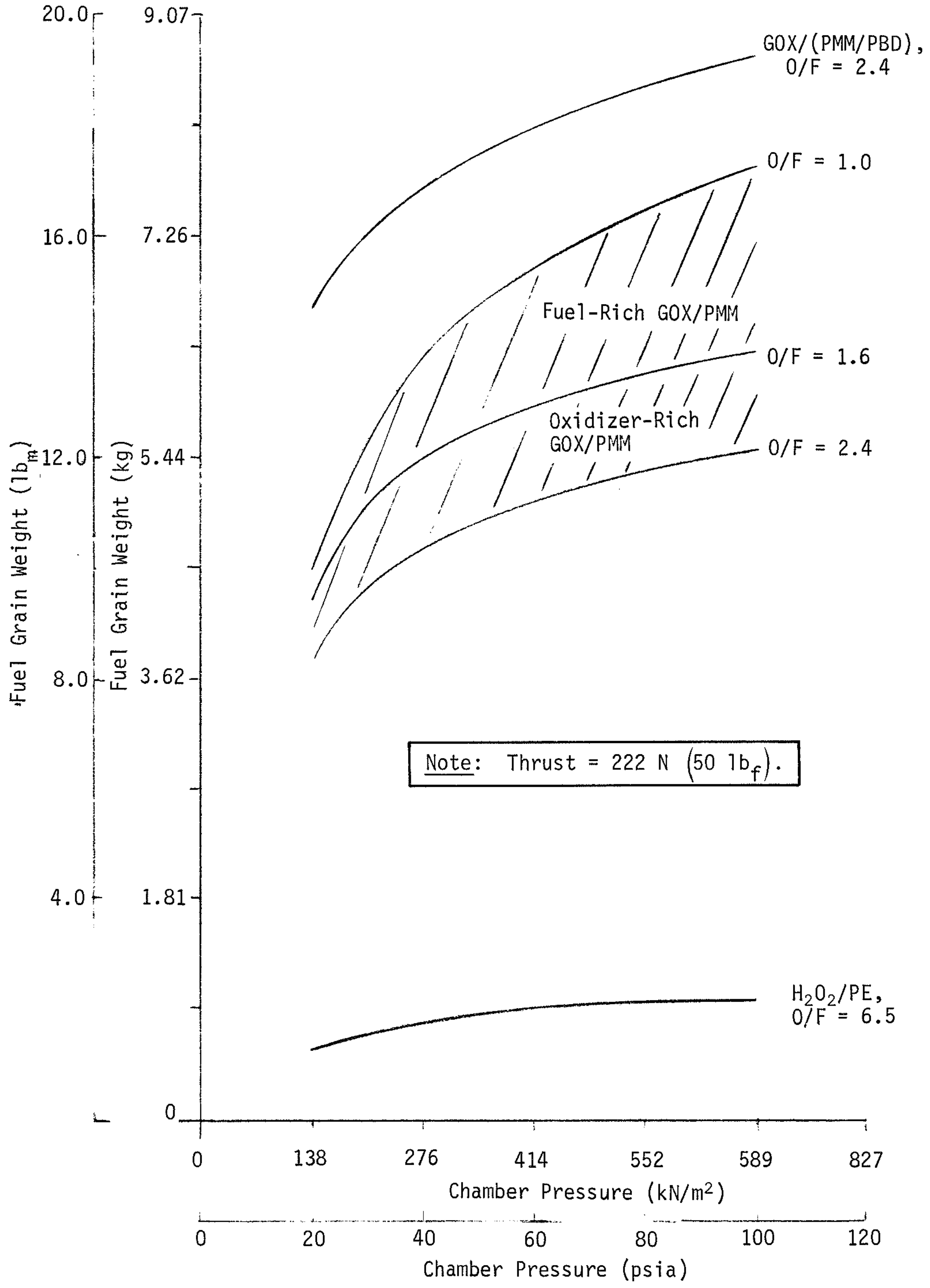


Fig. III-15 Fuel Grain Weight for Single-Port Hybrid APS vs Chamber Pressure and Oxidizer/Fuel Ratio

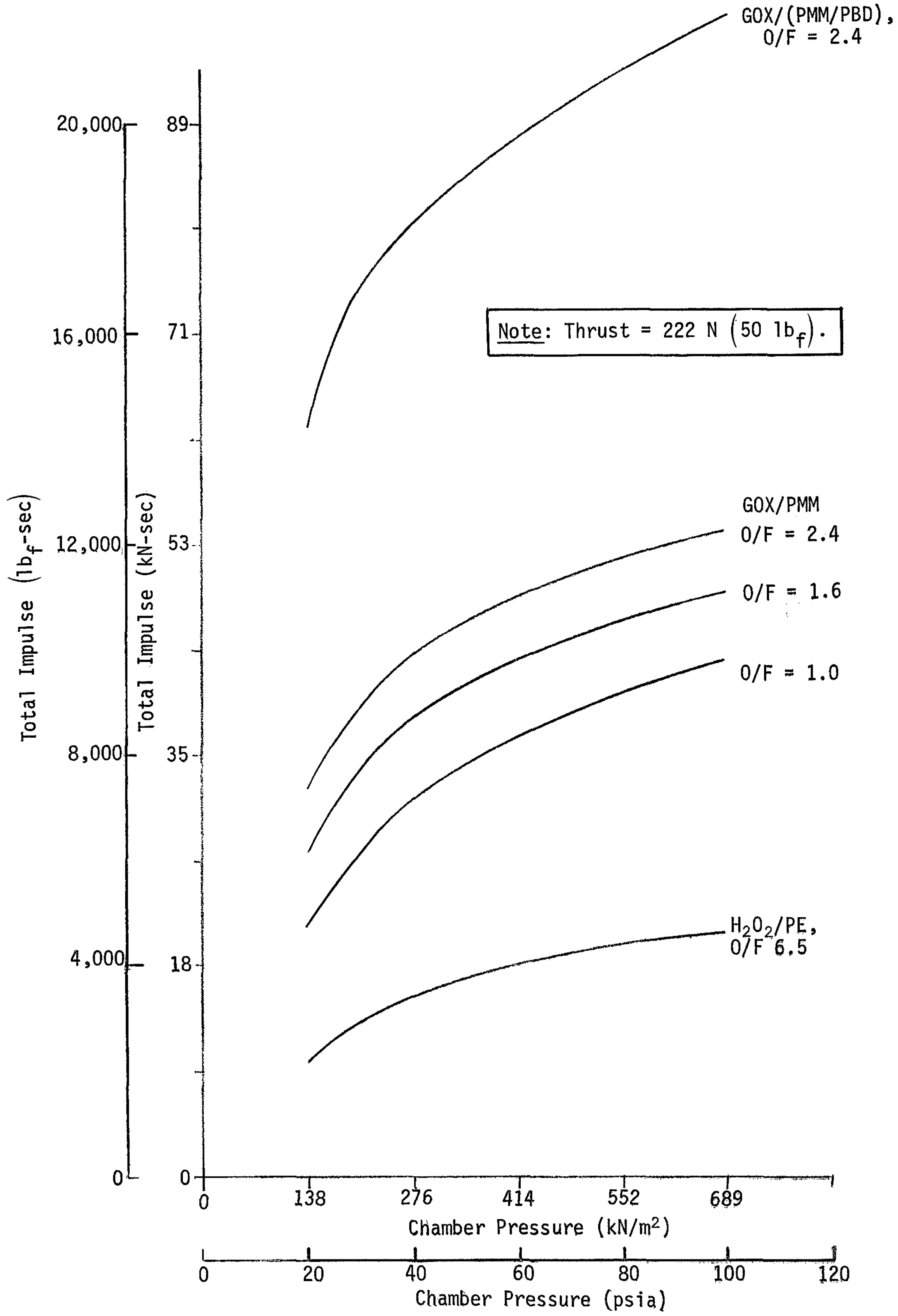


Fig. III-16 Total Impulse vs Chamber Pressure and Oxidizer/Fuel Ratio

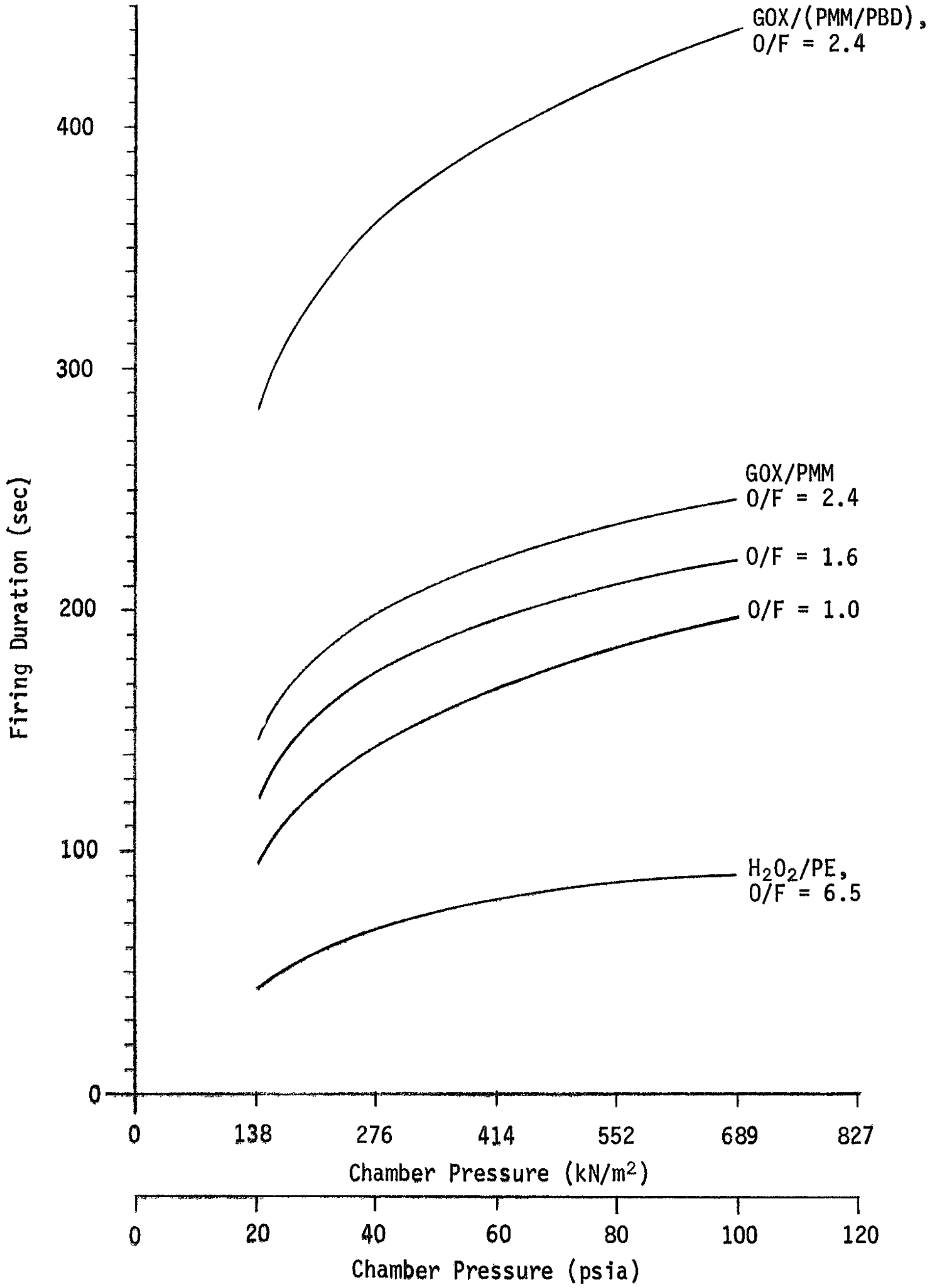


Fig. III-17 Firing Time at 222 N (50 lb_f) vs Chamber Pressure and Oxidizer/Fuel Ratio

The effect of the motor thrust level has been evaluated for a baseline motor using GOX/(PMM/PBD) at O/F = 2.4 and P_c = 689 kN/m^2 (100 psia). Figure III-18 shows the maximum total impulse and fuel-grain weight vs thrust. This curve shows that varying the thrust level is a good approach to tailoring the motor impulse to mission requirements. Motors up to about 667 N (150 lb_f) and delivering 448,822 N-sec (100,000 lb_f-sec) of total impulse could use monolithic grains, which weigh 45.4 kg (100 lb_m) and are handled by one man.* Motors in the 1000 to 1334 N (225 to 300 lb_f) size can deliver 889,644 to 1,334,466 N-sec (200,000 to 300,000 lb_f-sec) of total impulse with fuel grains segmented into 2 to 3 maximum-weight [45.4-kg (100-lb_m)] segments, or into 5 or 8 segments weighing 18 kg (40 lb_m) each.

Figure III-19 shows the grain length and maximum grain diameter vs thrust. Both these dimensions increase with thrust. Therefore, a 1334-N (300-lb_f) motor [L_G = 856 mm (33.7 in.), D_G = 447 mm (17.6 in.)] is similar to and 2.5 times the size of a 222-N (50-lb_f) motor. The maximum grain diameter of 457 mm (18 in.) is well within the 111-mm (25 in.) limit defined in the study by Nelsen.*

4. Thermal Analysis of Radiation-Cooled Nozzle

A preliminary thermal analysis was made of the design model TCA motor nozzle to determine the feasibility of a design using radiation cooling. The configuration that was analyzed is shown in Fig. III-20. It consisted of an aft closure, throat, and exit cone made of a single piece of molybdenum coated with molybdenum disilicide. A satisfactory design must be capable of radiating sufficient energy to space to maintain temperatures below an appropriate operating maximum. This maximum operating temperature will depend on

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*C. B. Nelsen: "Simulation of Package Transfer Concepts for Saturn I Orbital Workshop". *Proceedings of the Second National Conference on Space Maintenance and Extra-Vehicular Activities*, Las Vegas, Nevada, August 1968.

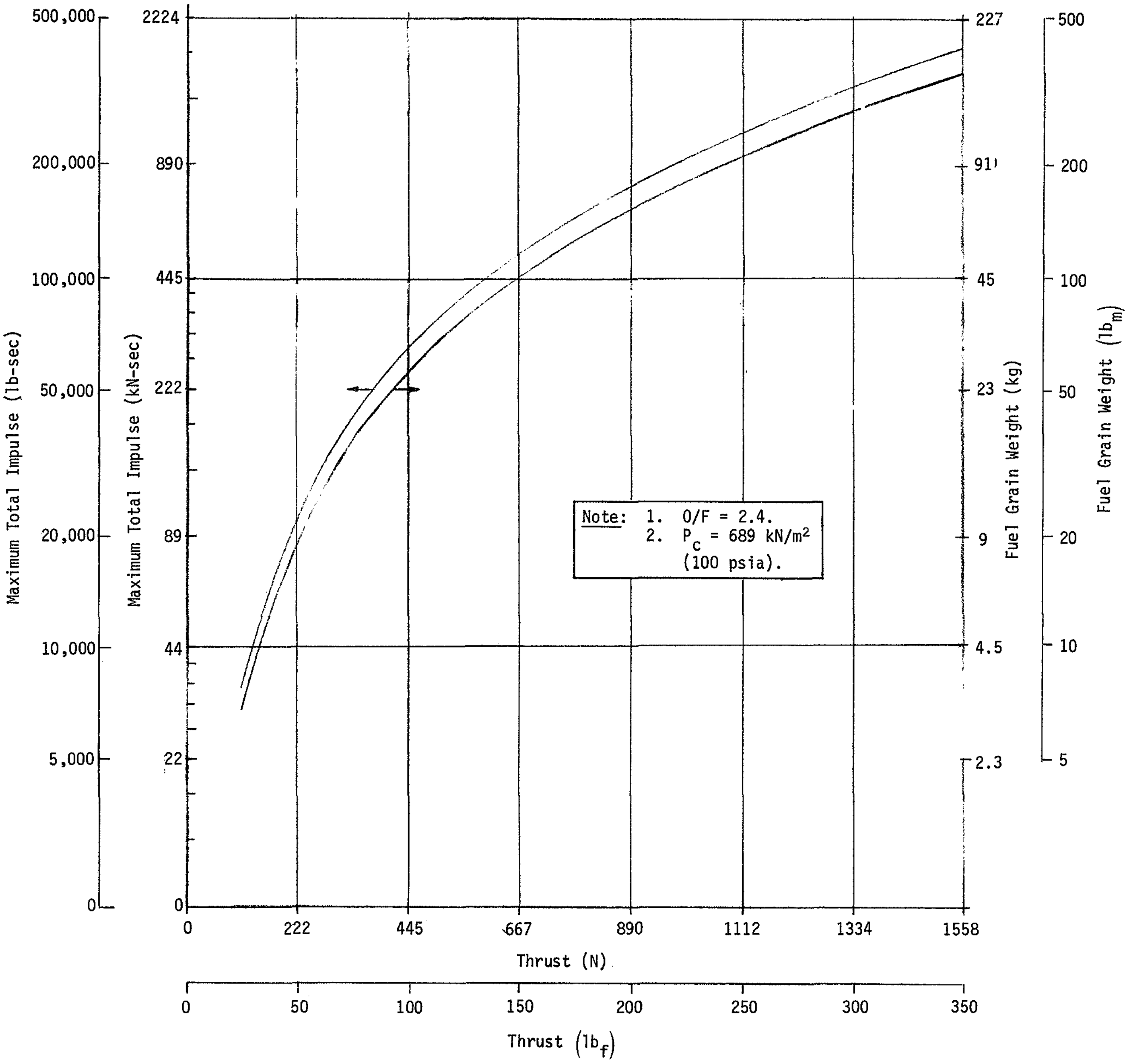


Fig. III-18 Maximum Total Impulse and Fuel Grain Weight vs Motor Thrust Level for GOX/(PMM/PBD)

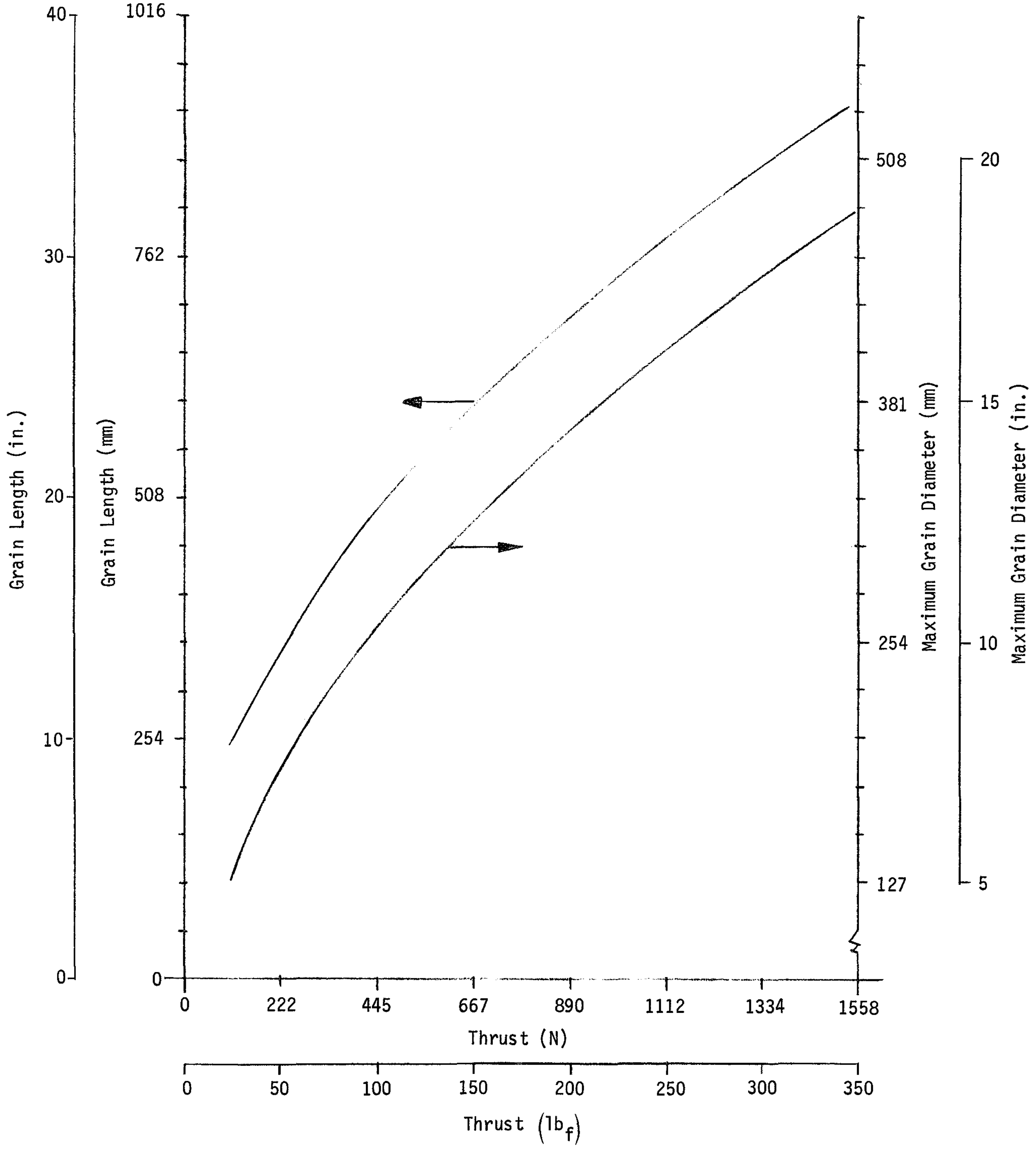


Fig. III-19 Grain Length and Maximum Grain Diameter vs Thrust

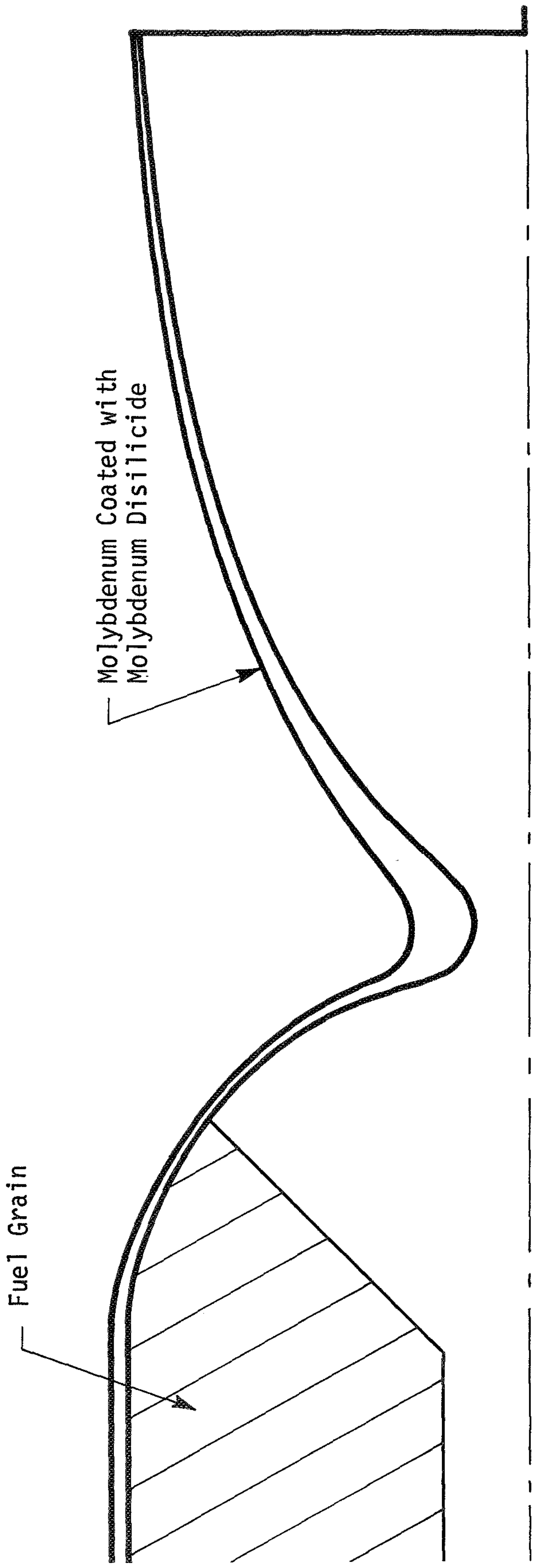


Fig. III-20 Nozzle Design

the structural properties of the molybdenum (or other metal used) and the ability of the coating to withstand high temperatures. The analysis was performed for the GOX/(PMM/PBD) propellant system because it has the highest peak flame temperature of the propellant systems most likely to be adopted.

The design model nozzle operates by conducting heat away from the throat area, where maximum heat transfer from the exhaust gases occurs, to the exit cone, where there is more radiating surface and lower heat transfer from the gases. Furthermore, by making the nozzle exit cone considerably thicker than the aft closure of the case, heat in the throat region tends to be conducted toward the exit cone, rather than toward the aft motor closure, where high temperatures may damage the fuel grain.

A thermal analysis was made to determine the wall temperature under a variety of operating conditions. This analysis was performed using a heat-conduction computer program that allows for one-dimensional conduction along a structure where radiative and convective boundary conditions depend on the location on the structure. Using a finite-difference technique, the program solves the heat-transfer equations for a structure divided into discrete nodes. A convective boundary condition is specified for each node, representing the transfer of heat from the exhaust gases, and a radiative boundary condition is specified, which represents the ability of the nodes to radiate energy to space. The thermal gradient through the nozzle wall was assumed to be negligible.

Convective heat transfer is strongly dependent on the exhaust gas properties near the nozzle wall. Because of the constant addition of fuel species to the boundary layer along the burning grain, the composition of the gas in the region near the surface can be expected to differ considerably from that in the free stream. Marxman* has shown that both theory and data indicate the oxidizer/fuel mixture ratio at the flame in an oxygen/PMM system approaches about 75% of the stoichiometric mixture ratio.

***Final Technical Report, Investigation of Fundamental Phenomena in Hybrid Propulsion.* UTC 2097-FR. United Technology Center, Sunnyvale, California, November 1965.

Between the flame and the grain surface, the gases can be expected to be even more fuel-rich. For the heat-transfer analysis, it has been assumed that the effective mixture ratio along the nozzle surface is 75% of the free-stream mixture ratio.

Convective heat-transfer coefficients were calculated using a simplified Bartz equation. These heat-transfer coefficients are strongly dependent upon the oxidizer/fuel mixture ratio, due to changes in the influential Bartz equation parameters with changes in the mixture ratio; specifically, the stagnation temperature, characteristic velocity, molecular weight, and ratio of specific heats vary widely, as shown in Fig. III-21. The chamber pressure also has a direct influence on convective heat transfer. Figure III-22 shows the calculated heat-transfer coefficients as a function of nozzle station for a boundary-layer mixture ratio of 1.33 and chamber pressure equal to 689 kN/m^2 (100 psia).

The radiation view factor to space from each point on the nozzle was found by subtracting from 1.0 the value obtained for the view factor to the rest of the nozzle. Points in the exit cone have a view factor made up of two contributions: one for the radiation from the external surface, and one for radiation out the exit plane. An emissivity of 0.85 was used for the molybdenum disilicide coating. View factors as a function of location on the nozzle are shown in Fig. III-23.

These convective and radiative boundary conditions were input to the heat-conduction computer program, along with a description of the nozzle geometry and the material properties. The results are shown graphically in Fig. III-24 thru III-26.

A typical temperature distribution in the nozzle after 10 sec is shown in Fig. III-24. Because the convective heat transfer is highest at the throat and the radiative view factor is lowest, the throat has the maximum temperature. Figure III-25 shows a typical temperature history at the throat.

The throat temperature as a function of mixture ratio and chamber pressure is shown in Fig. III-26. As can be seen, the mixture ratio is the primary parameter determining nozzle temperatures.

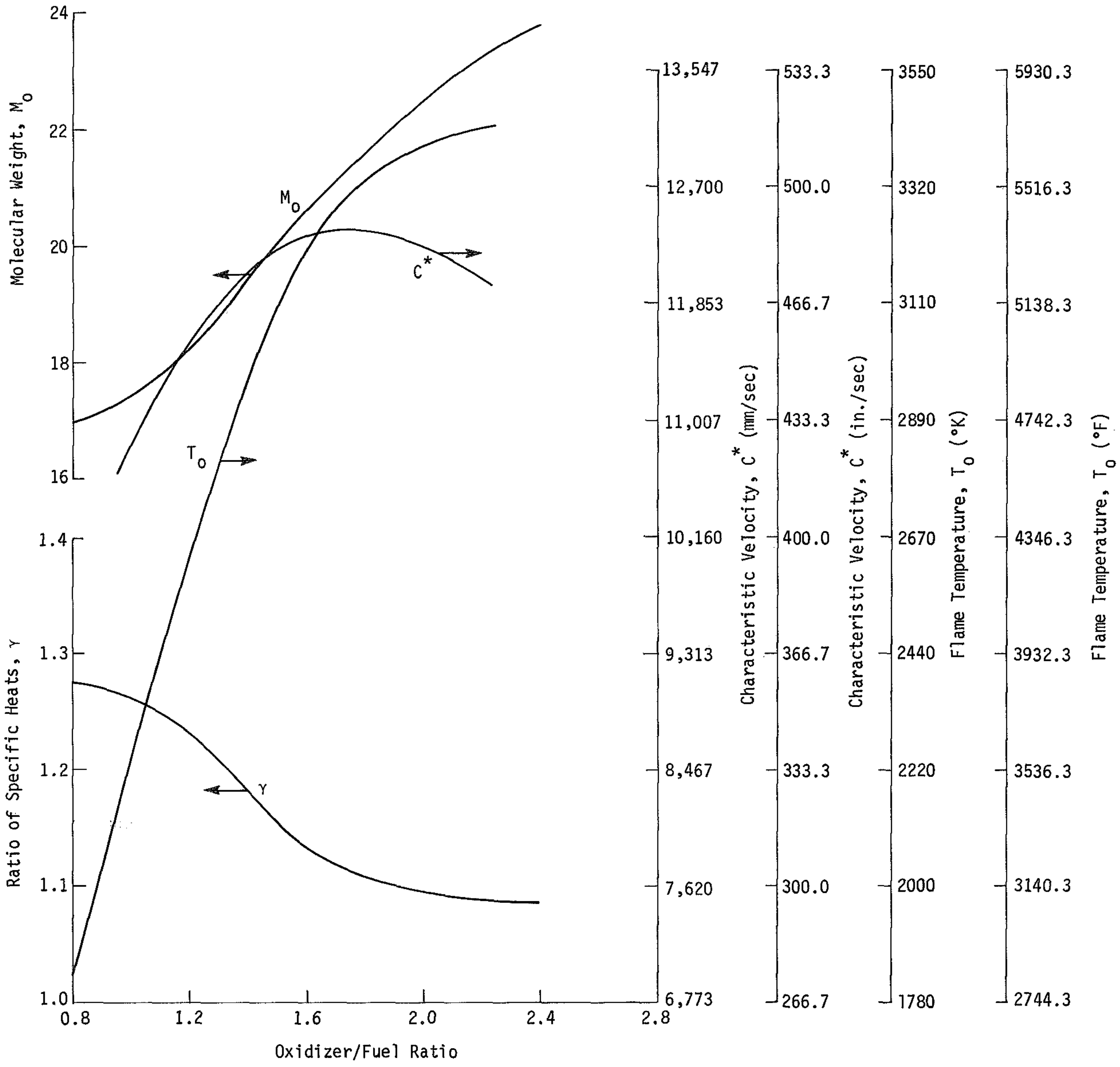
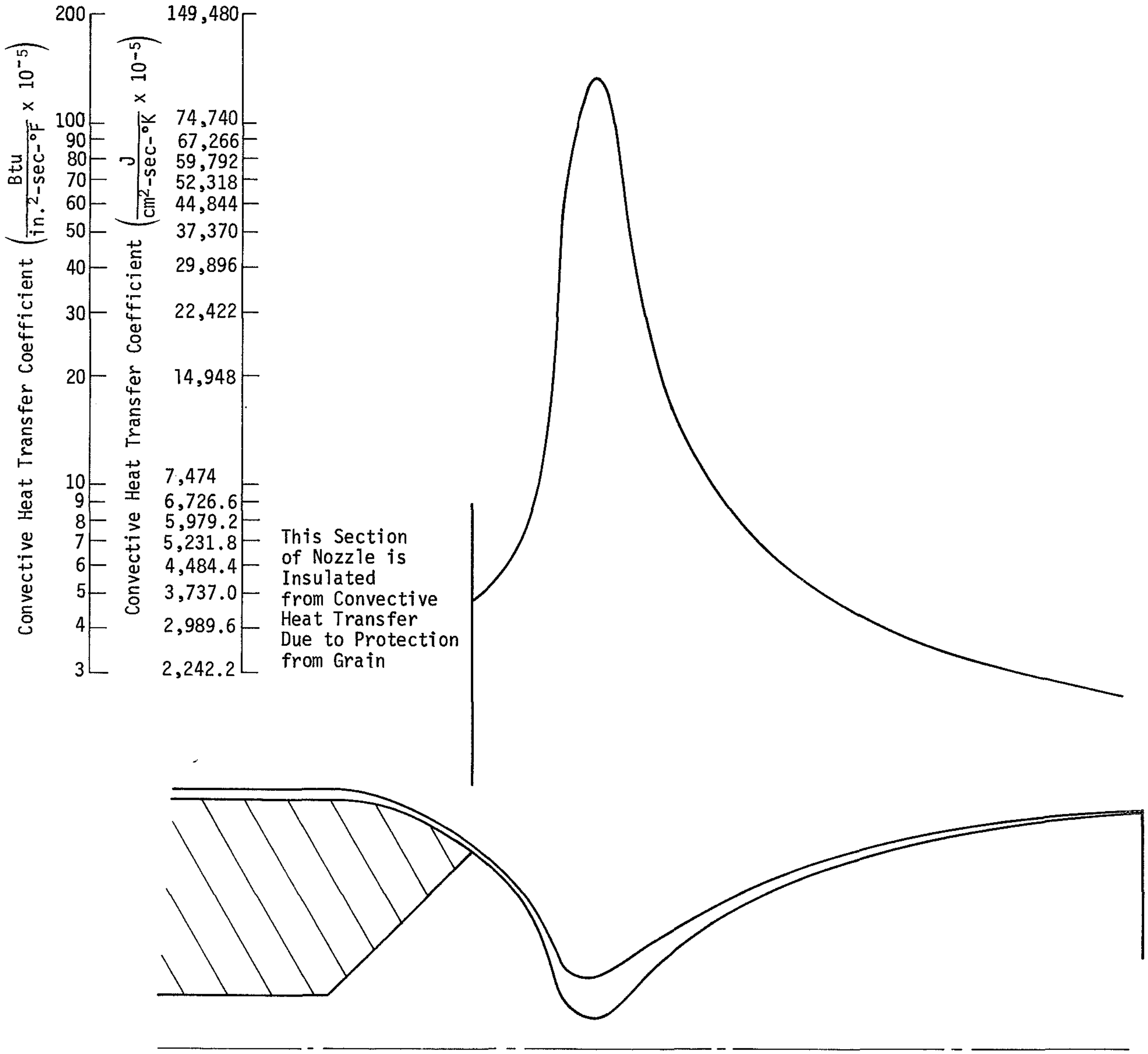


Fig. III-21 Exhaust Gas Properties vs Oxidizer/Fuel Ratio



This Section of Nozzle is Insulated from Convective Heat Transfer Due to Protection from Grain

Fig. III-22 Convection Heat Transfer Coefficient vs Location in Nozzle

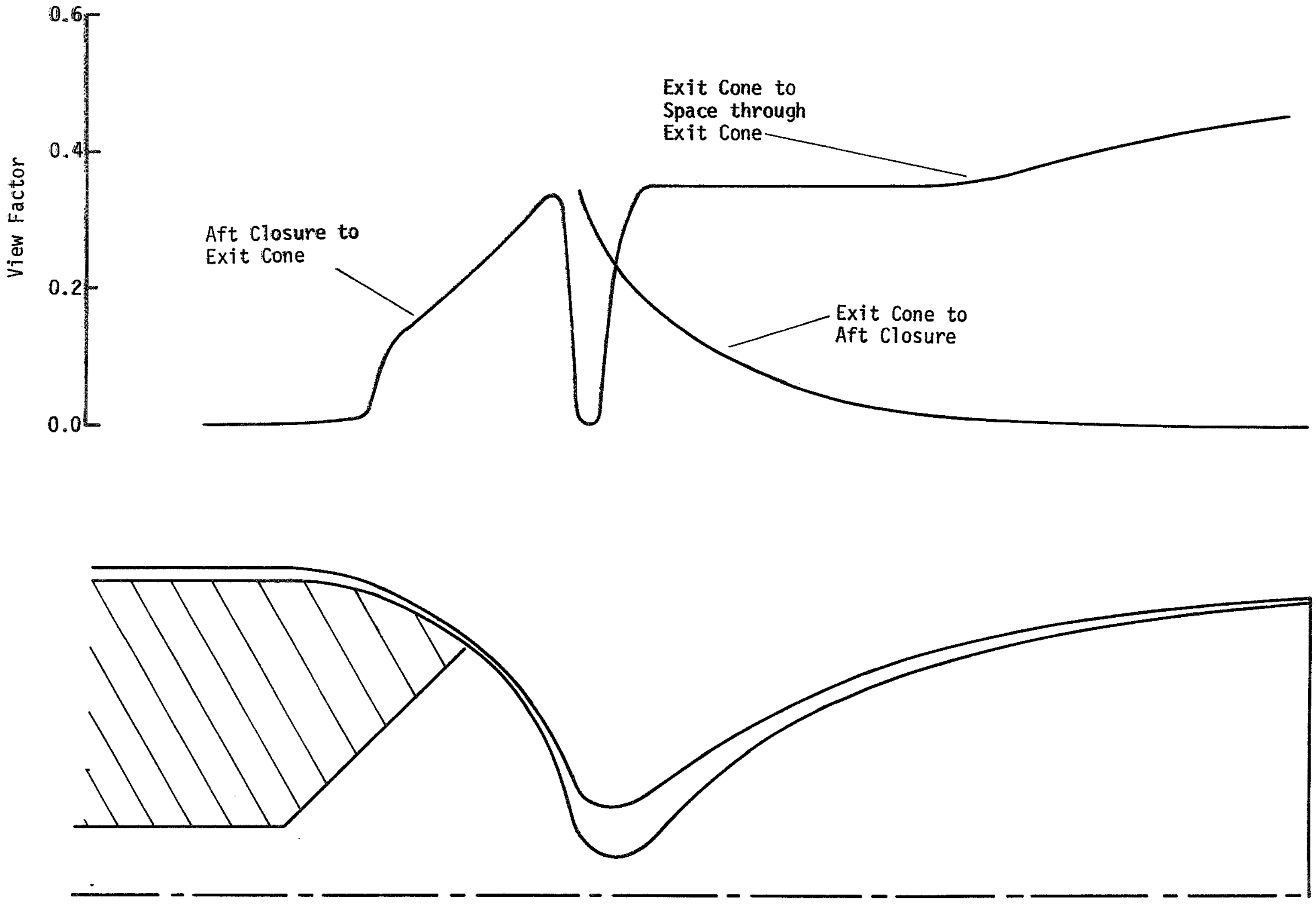
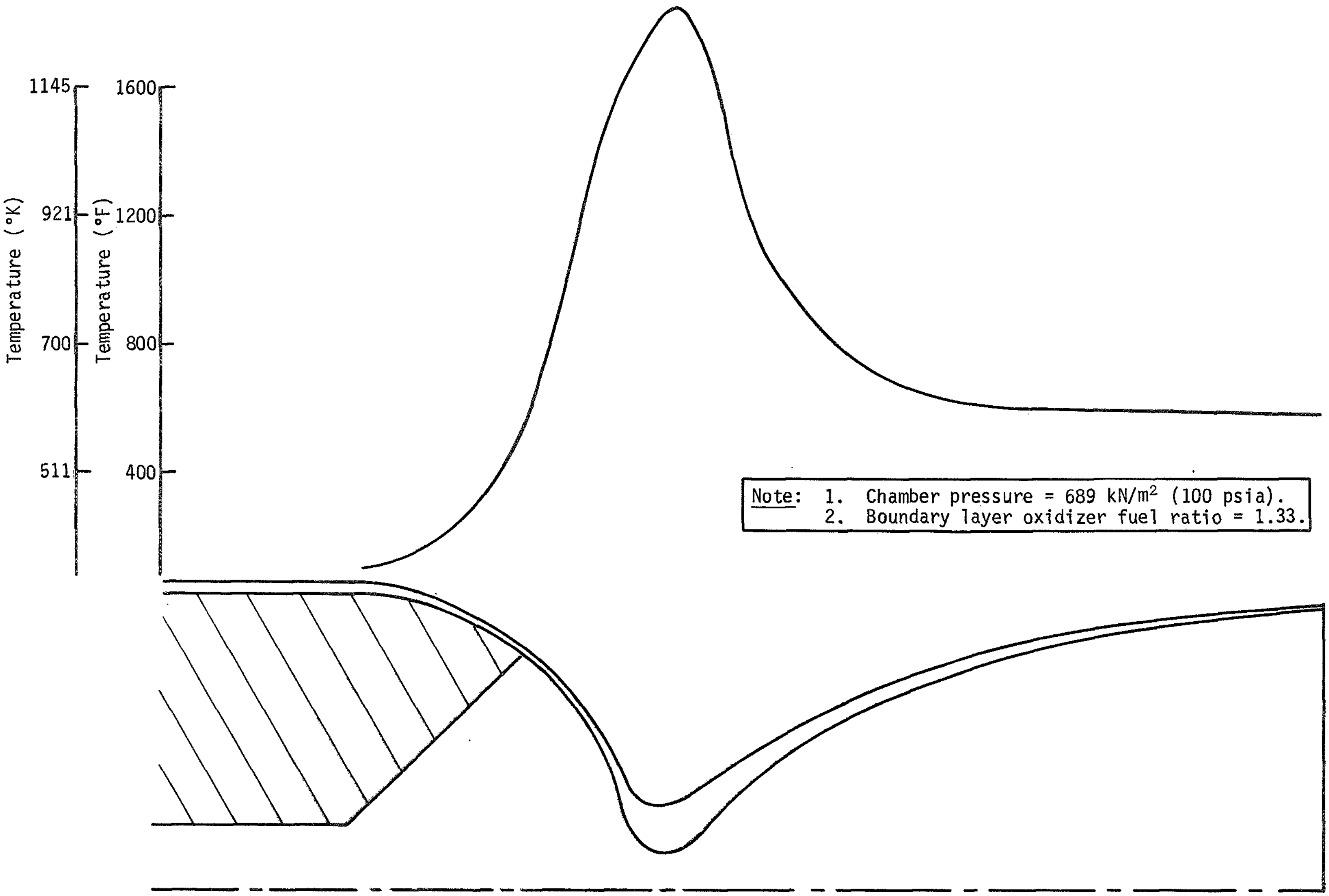
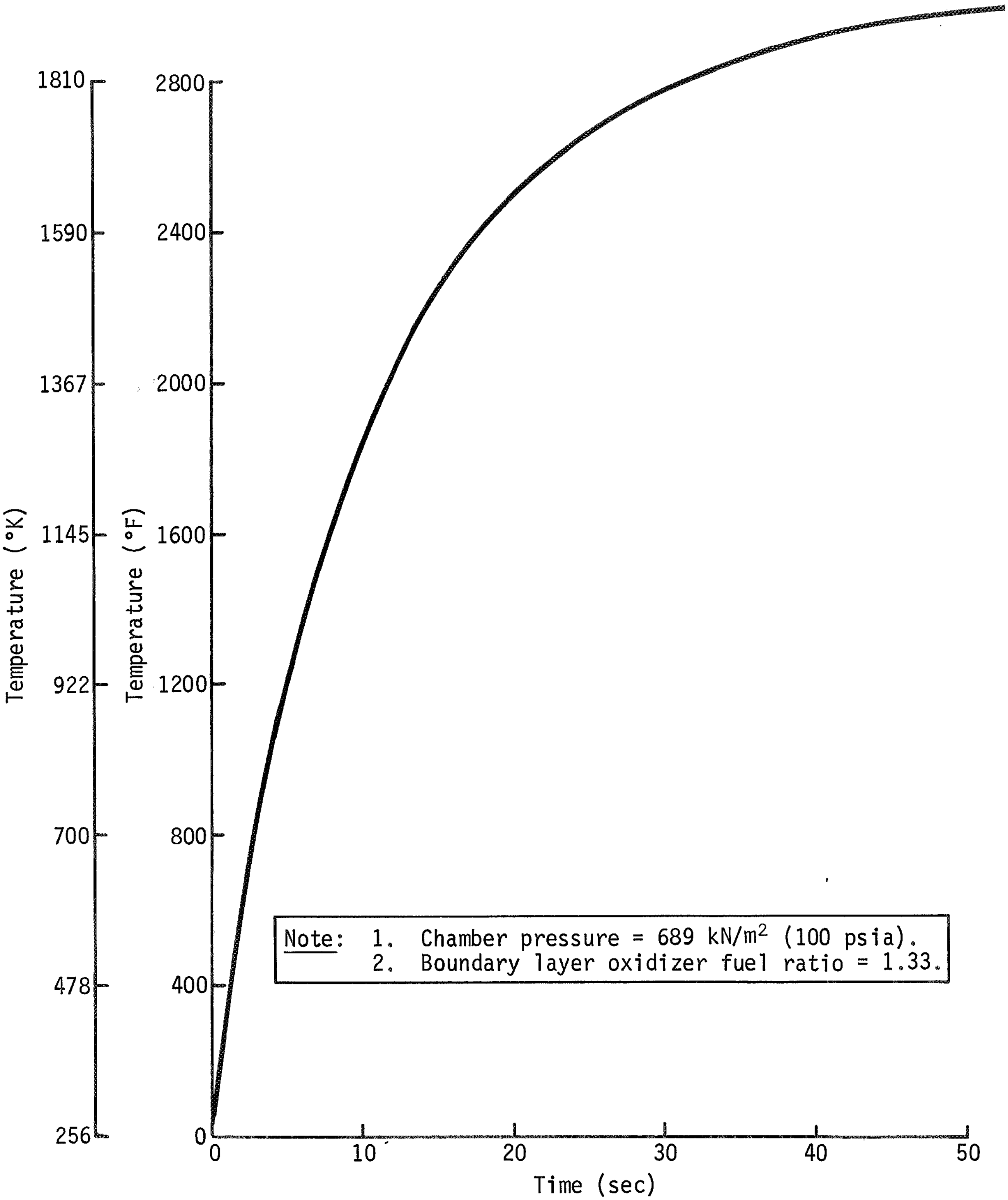


Fig. III-23 Radiation View Factor vs Location on Nozzle



Note: 1. Chamber pressure = 689 kN/m^2 (100 psia).
2. Boundary layer oxidizer fuel ratio = 1.33.

Fig. III-24 Nozzle Wall Temperature after 10-sec Firing vs Location on Nozzle



Note: 1. Chamber pressure = 689 kN/m^2 (100 psia).
2. Boundary layer oxidizer fuel ratio = 1.33.

Fig. III-25 Throat Temperature vs Time

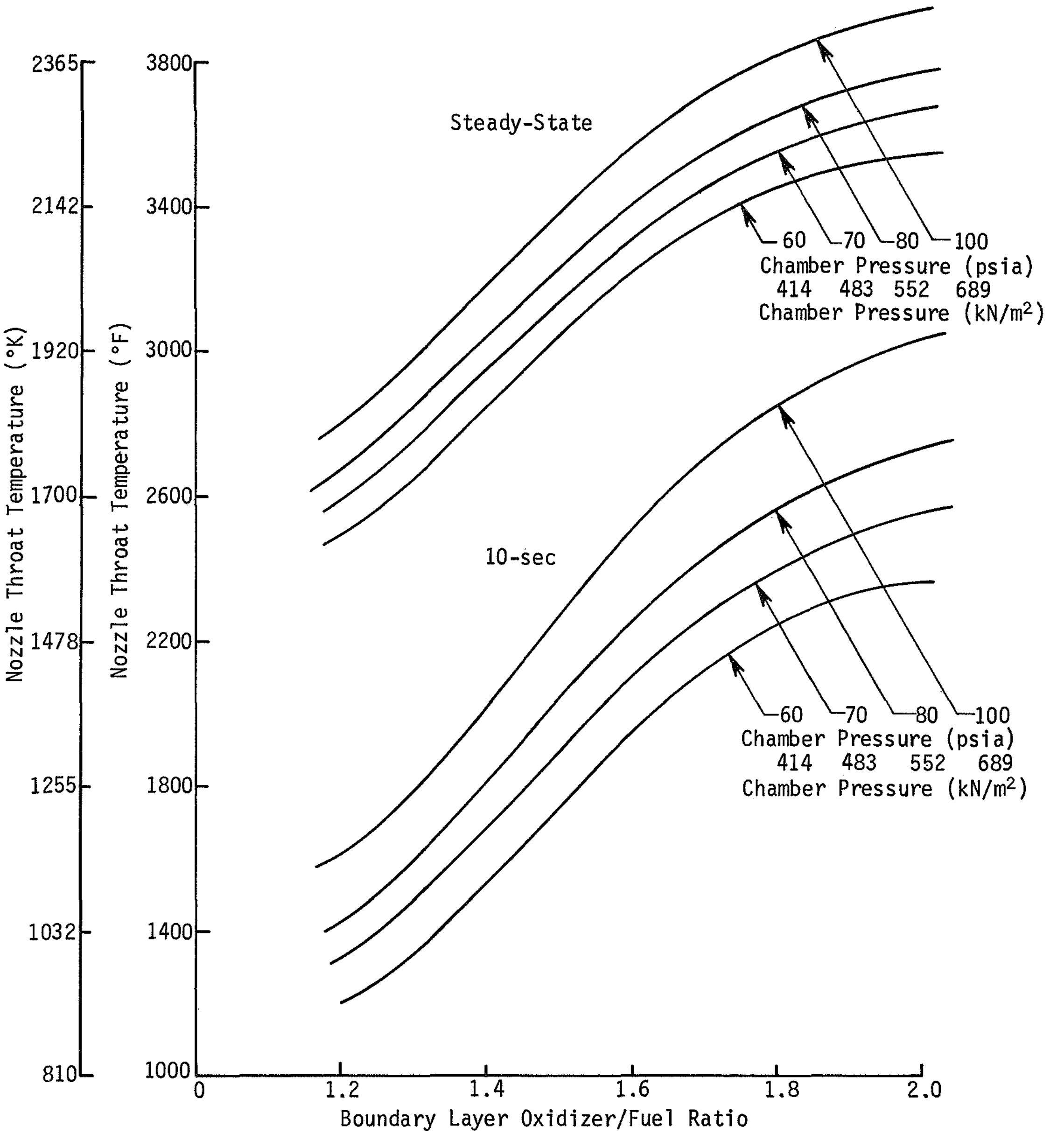


Fig. III-26 Nozzle Throat Temperature vs Oxidizer/Fuel Ratio

D. CANDIDATE MOTOR COMPONENT DESIGNS

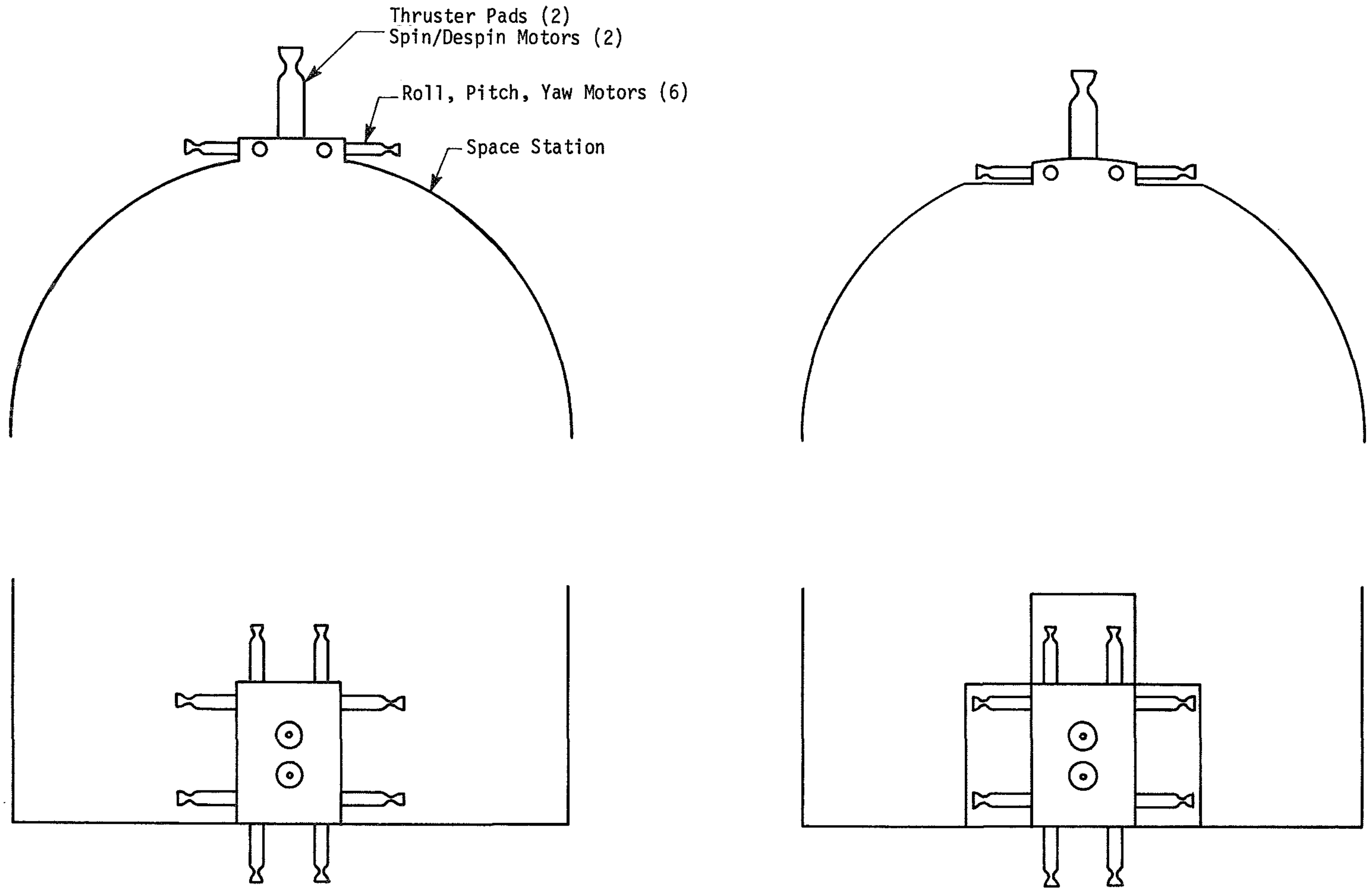
A number of alternative motor component designs have been developed, in addition to the design approaches shown in the design model TCA. These alternative components have an important effect on TCA maintenance, repair, and resupply requirements, but have a minor effect on motor performance. Therefore, most alternative components can be developed independently of the parametric analysis presented in Section III-C. Candidate nozzle designs, however, were presented in Section III-C because they relate to motor operating conditions (chamber pressure and O/F ratio), and hence affect performance.

1. Attitude Control Motor Thruster Pad Design

The current design requirements specify two ACS thruster pads at the aft end of the Space Station. Each pad will contain eight 222-N $\left(50\text{-lb}_f\right)$ attitude control thrusters and two spin/despin thrusters. The spin/despin thrusters will be perpendicular to the wall of the Space Station, but the ACS thrusters will be parallel to the wall when in the firing position. Thruster pad designs that allow the motors to be withdrawn for fuel grain replacement or repair are discussed in the next subsection.

Two thruster pad designs that allow axial motor refurbishment are shown in Fig. III-27. The extended-pad approach would use a streamlined raised thruster pad extending 102 to 152 mm (4 to 6 in.) beyond the wall of the Space Station. The indented pad approach would maintain the original Space Station outer diameter, but would provide depressed platforms or slots to extend the roll-yaw thrusters. This design could be adapted for eight ACS motors by using a canted forward slot. Contamination of the Space Station from the exhaust gases could be a problem with this indented-pad approach.

The nozzles can be canted, in either approach, to minimize contamination.



(a) Extended Pad Approach

(b) Indented Pad Approach

Fig. III-27 Modified Hybrid Thruster Pads for Axial Motor Refurbishment

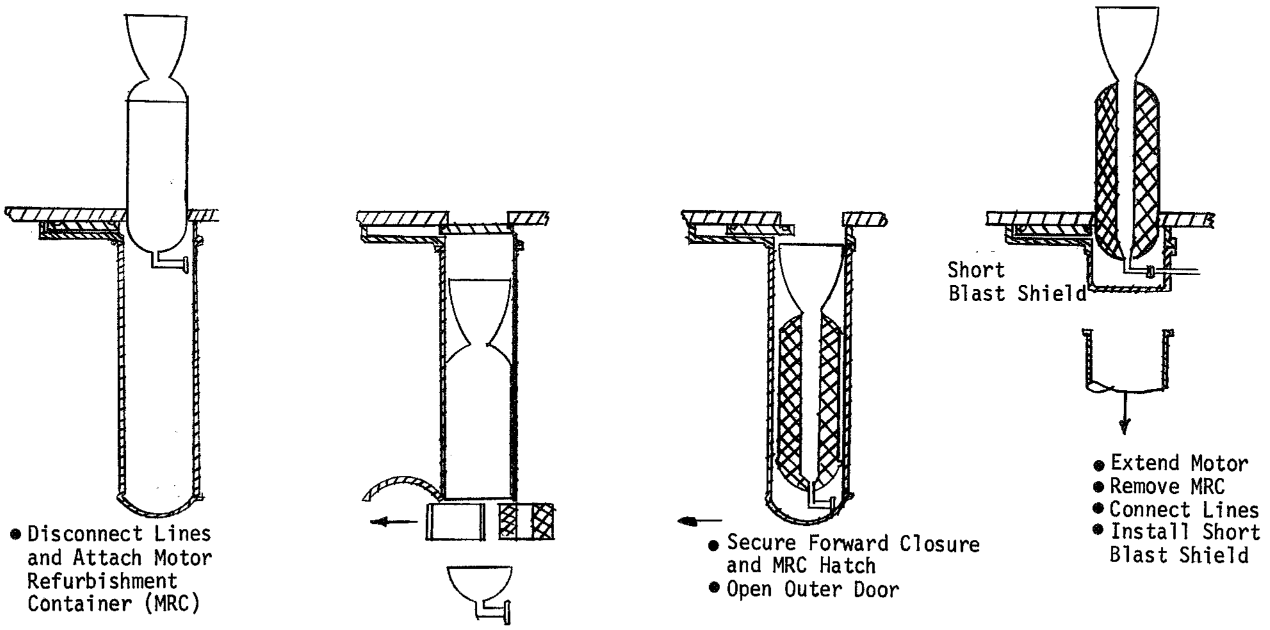
2. Motor Refurbishment and Fuel Grain Replacement Concepts

Fuel grain replacement is the primary scheduled maintenance task for a hybrid ACS. Therefore, an attractive design must feature a simple means to replace fuel grains and refurbish or replace the motor assembly as needed. The following ground rules were used in developing motor refurbishment concepts:

1) Any design that requires EVA as part of either scheduled maintenance or emergency repairs is undesirable;
2) Designs that require a pressurized compartment and intravehicular activity (IVA) for emergency repairs (i.e., replacement of seals) must be evaluated in terms of the increased maintenance requirements they present;
3) Ideally, all components should be accessible to personnel working in a shirt-sleeve environment;
4) During launch, the TCAs should be located inside the Space Station or in streamlined protective fairings on the outside.

a. Movable Tube Concept - The movable tube concept shown in Fig. III-28 allows the complete TCA to be extended and retracted perpendicular to the wall of the Space Station. The TCA in this candidate design consists of three major parts: a motor case and nozzle assembly, a cartridge-loaded fuel grain, and a forward closure assembly, which includes the injector, ignition system, oxidizer shutoff valve, and electrical controls. The motor case extends through the wall of the Space Station and is held in place with a flange sealed by an O-ring. Although the cabin pressure [101.35 kN/m^2 (14.7 psia)] acting on the forward closure results in a force that exceeds the motor thrust, camlock safety latches are provided to hold the motor securely in place. When the fuel grain requires replacement, the oxidizer and electrical control lines are disconnected from the forward closure and the safety latches are released.

A thin-walled motor refurbishment container (MRC), designed for a 101.35-kN/m^2 (14.7-psia) external pressure, is snapped into place over the motor with a bayonet fitting sealed by an O-ring. The pressure inside the MRC is vented to space, and the TCA is retracted into the MRC using a mechanical method, such as having a travelling nut on a ball screw or using a clothes line

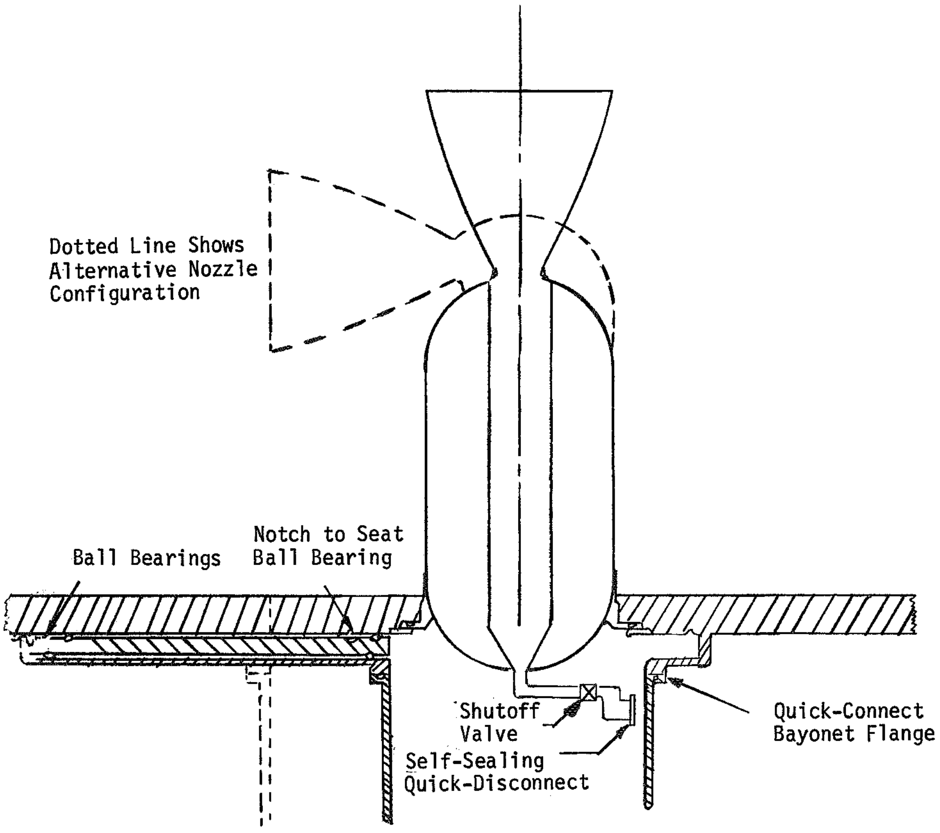


- Disconnect Lines and Attach Motor Refurbishment Container (MRC)

Retract Motor and Replace Fuel Grain

- Secure Forward Closure and MRC Hatch
- Open Outer Door

- Extend Motor
- Remove MRC
- Connect Lines
- Install Short Blast Shield



Detail A-A

Fig. III-28 Movable Tube Concept

design operated by a hand crank. Once the TCA has been withdrawn, an outer door is rolled into place and the MRC is repressurized. The MRC has a hinged door that can be opened to expose the motor. At this point, the forward closure can be removed to replace the fuel grain, or the entire TCA can be removed for inspection or replacement. Motor extension follows the same process in reverse. One or two MRCs would be sufficient for the entire hybrid system.

The movable concept maintains a shirt-sleeve environment for all TCA maintenance and repair operations.

There are five primary seals, all easily replaceable. None are exposed to vacuum conditions, low (or high) temperatures, or solar radiation. The two seals on the MRC may be replaced at any time. The motor seals can be replaced by retracting the motor. The outer door can be inspected and the seal can be replaced by removing a bolt-on cover.

The movable tube concept can be adapted to a canted nozzle by using an elliptical MRC. This would allow the 16 ACS motors to be extended in the same manner as the spin/despin motors. The moment generated by the 222-N $\left(50\text{-lb}_f\right)$ baseline thrust should not present a problem.

b. Parallel Transfer Concept - The transfer concept shown in Fig. III-29 allows the motor to be moved parallel to the wall of the Space Station and keeps the motor completely outside the Space Station during operation. The motor rests on a movable platform supported by four jacks. The motor is retracted by lowering the platform about 152 mm (6 in.), rotating it 180 deg, and returning it to its original position. Once inside, the compartment can be pressurized and the motor can be reached through an access hatch. A window could be provided at the opposite end of the chamber to permit visual inspection of the case and nozzle without removing the motor.

This parallel transfer concept could easily be adapted to a pair of motors -- one on line and the other one checked out and ready for firing.

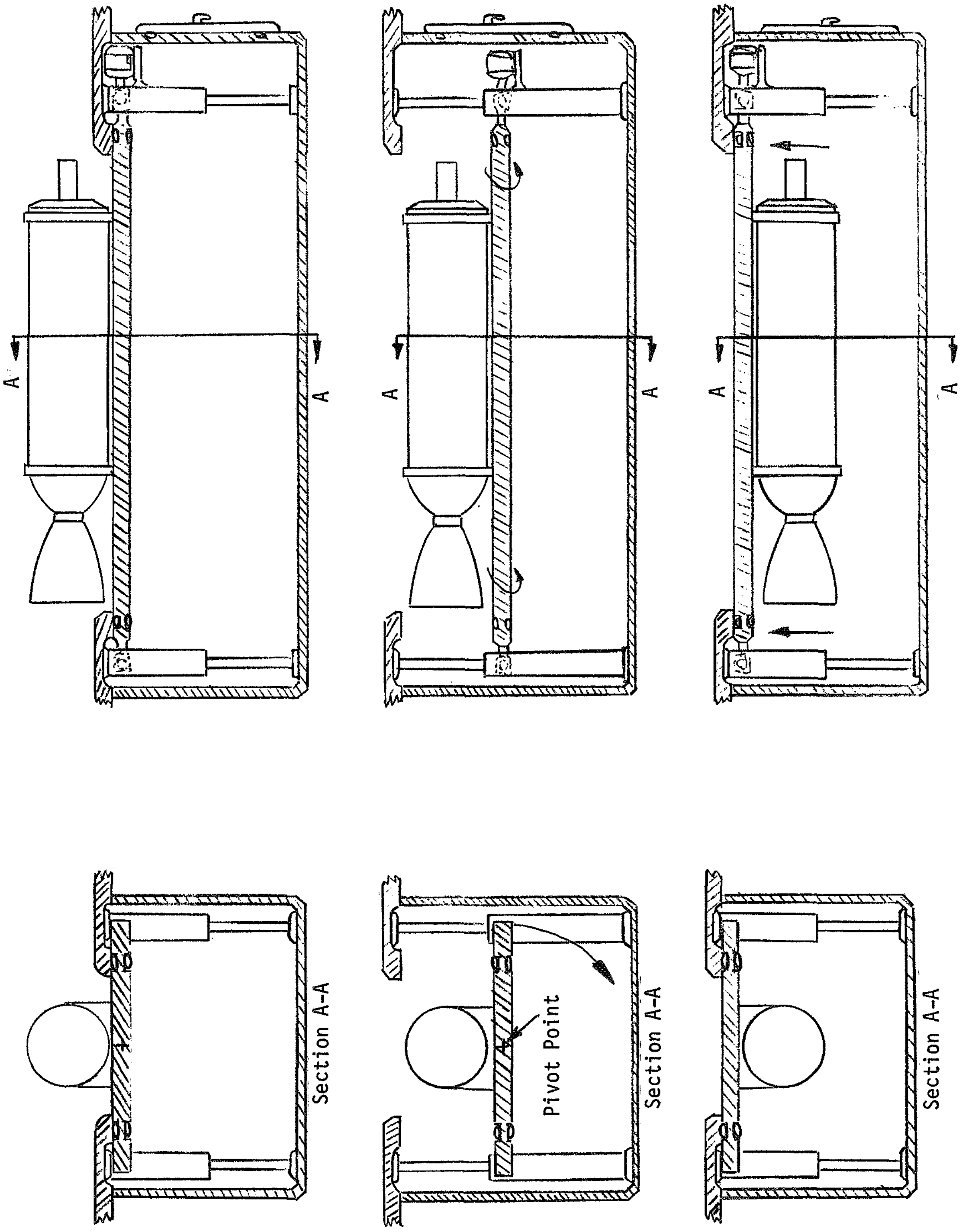


Fig. III-29 Parallel Transfer Concept

c. Nozzle Cap Approach - The nozzle cap approach, shown in Fig. III-30, provides an extremely simple method for fuel grain replacement or motor repair. Before replacing a fuel grain, the nozzle cap is extended, rotated, and retracted over the nozzle. This prevents cabin atmosphere from leaking to space while the forward closure is removed to replace a fuel grain. A single nozzle cap could be used to service a pair of ACS motors. If the motor cap seals require replacement, the TCA pallet [which is less than 30.5 cm (1 ft) square] can be removed and replaced by depressurizing the compartment where the ACS thruster pad is located.

d. External Cover Concept - The external cover concept shown in Fig. III-31 allows the entire motor assembly to be withdrawn without the use of support equipment. The motor assembly rests on a pallet that can be easily retracted inside the Space Station for replacing grains, repairing the motor, or inspection. Before retracting the motor, an external cover is rotated into position and clamped down, and the volume inside the cover is pressurized. If any of the external seals require replacement during the life of the Space Station, the cover assembly can be retracted inside the Space Station by depressurizing that compartment.

e. External Clamshell Approach - The external clamshell approach, shown in Fig. III-32, allows the motor assembly to be retracted without using internal support equipment and is similar to the nozzle cap approach. However, the external clamshell approach allows the entire motor case to extend outside the Space Station. Motor retraction is accomplished by rotating shut two external clamshell doors around the motor. A lock rod is then extended between the doors to hold them shut when the clamshell is externally pressurized with cabin air. The forward closure can then be removed for grain replacement, or the entire TCA can be retracted inside the Space Station.

3. ACS Motor Forward Closure Retention Concepts

Since fuel grain replacement is the most frequent hybrid maintenance task, the motor forward closure should be easily removable, yet provide a safe, reliable seal. In addition, the forward closure should be designed to be quickly and simply removed by one man without special power tooling. During motor operation, the forward closure must be securely held in place so there is no possibility of having it become detached.

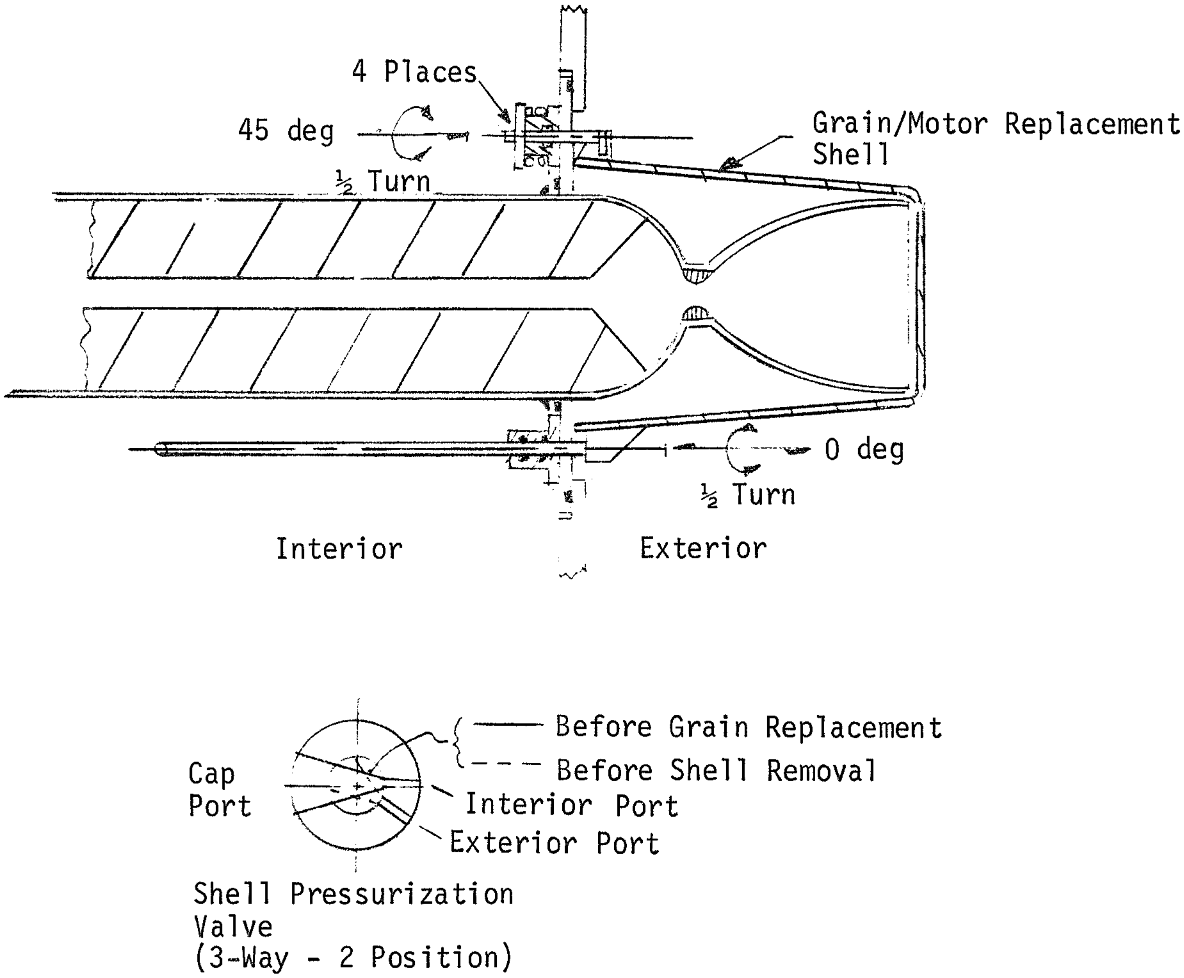


Fig. III-30 Nozzle Cap Approach

<u>Note</u>: Shell pressurization same as in Fig. III-30.

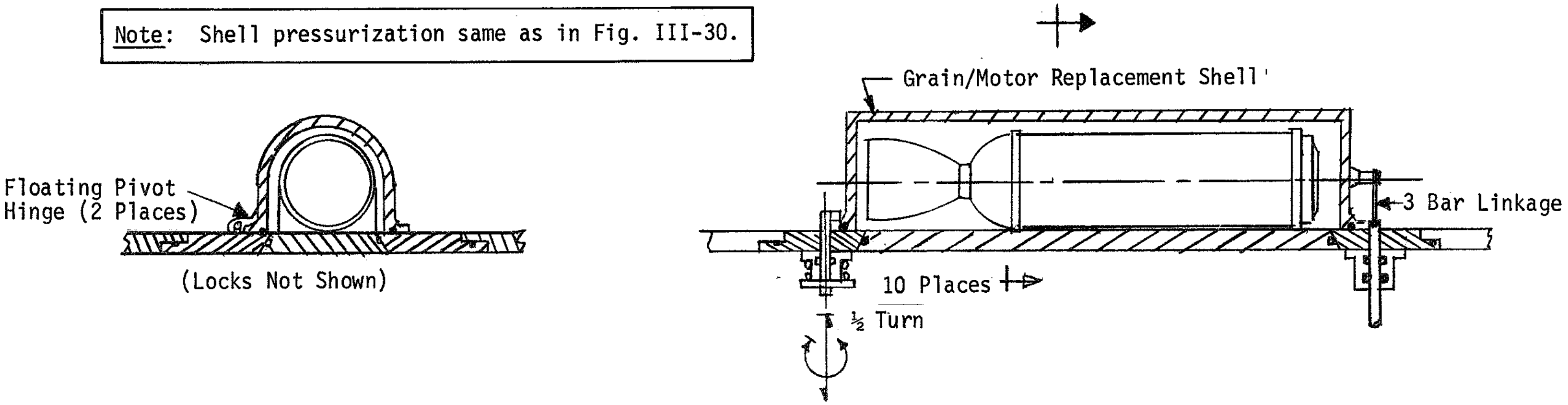
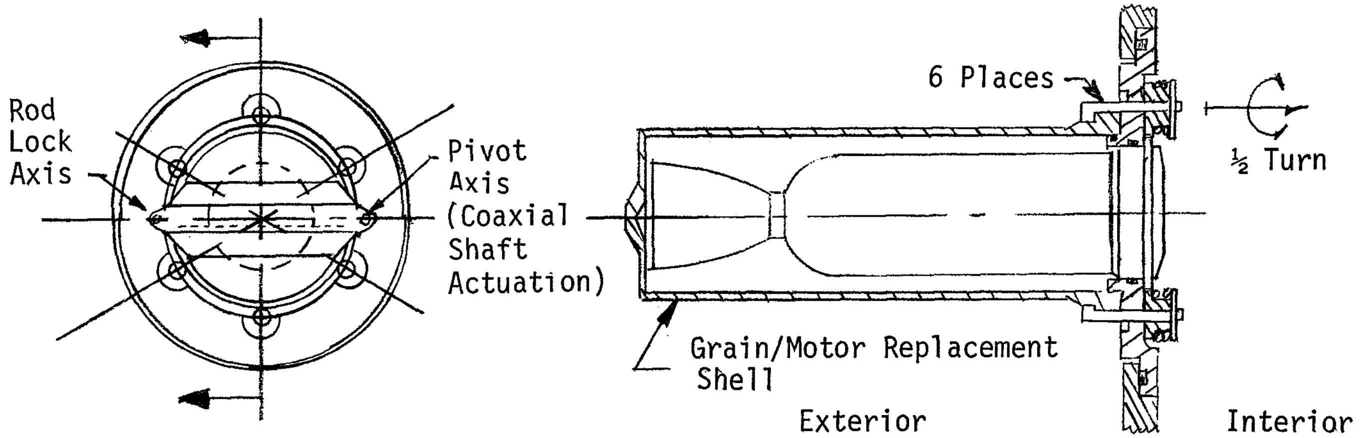


Fig. III-31 External Cover Concept



Note: Shell pressurization same as in Fig. III-30.

Fig. III-32 External Clamshell Approach

a. Snap Ring Connection - A snap ring connection (Fig. III-33) is one of the simplest and most reliable forward closure attachment concepts. The forward closure has four snap ring restraints to hold the snap ring to the removed forward closure. This increases crew safety during attachment or removal of the forward closure. The snap ring design requires a simple tool. Since no external torques are required, this design should be easy to use in a weightless environment.

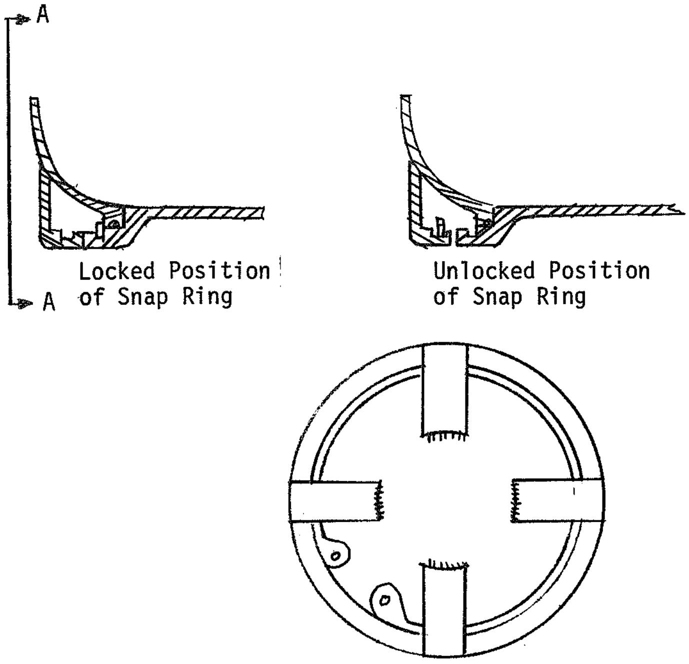
b. Double Bayonet Flange Connection - The double bayonet flange connection (Fig. III-34) uses a simple tool to translate linear motion to rotary motion. The rotary motion engages a bayonet fitting that holds the forward closure to the motor case. The tool is held to the motor case by another bayonet fitting, and will not release unless the forward closure is correctly installed.

c. Bayonet Screw Connection - The bayonet screw connection (Fig. III-35) features a double lock mechanism that provides maximum safety, along with ease of operation. The counterclockwise bayonet flange holds the forward closure in place while the closure is screwed clockwise against the motor case flange using the bayonet flange to generate the necessary torque. This design provides a double seal and lock because both the screw fitting and the bayonet connection must be released to unseal and remove the forward closure assembly.

d. Pin Connection - The forward closure is attached and held to the motor case by four radial pins (Fig. III-36). A strap, wire, or tape-retention design holds the pins in place. This design offers a simple method of attaching the forward closure with the least amount of physical effort. Because no external torques are required, this design would be easy to use in a weightless environment.

e. Bolted Flange - The forward closure is held to the motor case by four bolts (Fig. III-37). Simple hand tools, such as a ratchet socket wrench, are used to assemble the closure to the case.

f. Additional Attachment Concepts - A variety of additional attachment concepts are shown in Fig. III-38. These include a standard snap ring, a rotating camlock with an extending shaft that locks the cam in a closed or open position, a screw-tightened hand knob, a snap ring held in place with a CO_2 expanding tube, a suitcase-type latch, and an Ortman key. Several of these concepts, although shown with a screwed-on closure, could also be used with a hinged forward closure.



Locked Position of Snap Ring

Unlocked Position of Snap Ring

Section A-A

Fig. III-33 Snap Ring Connection

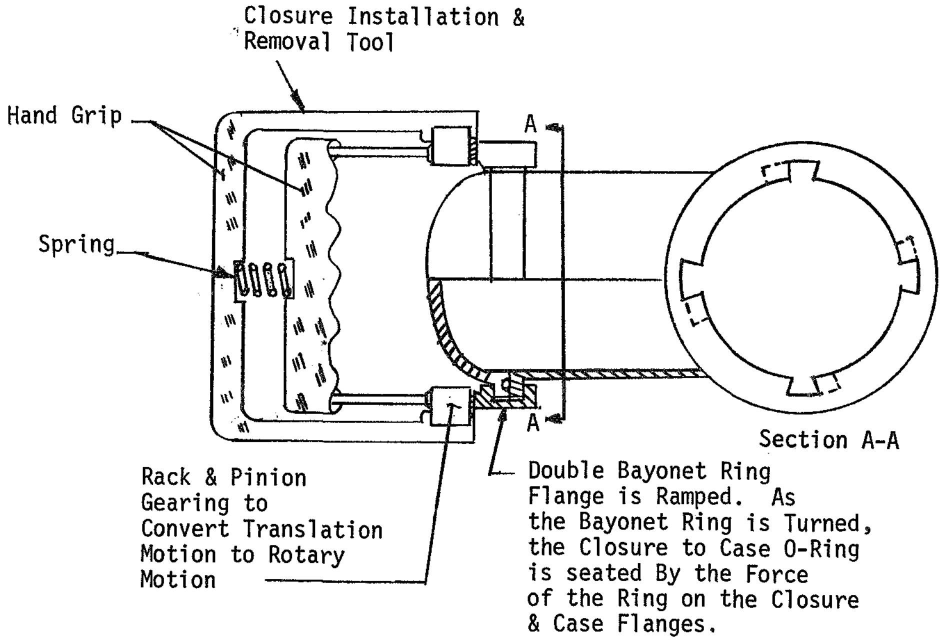
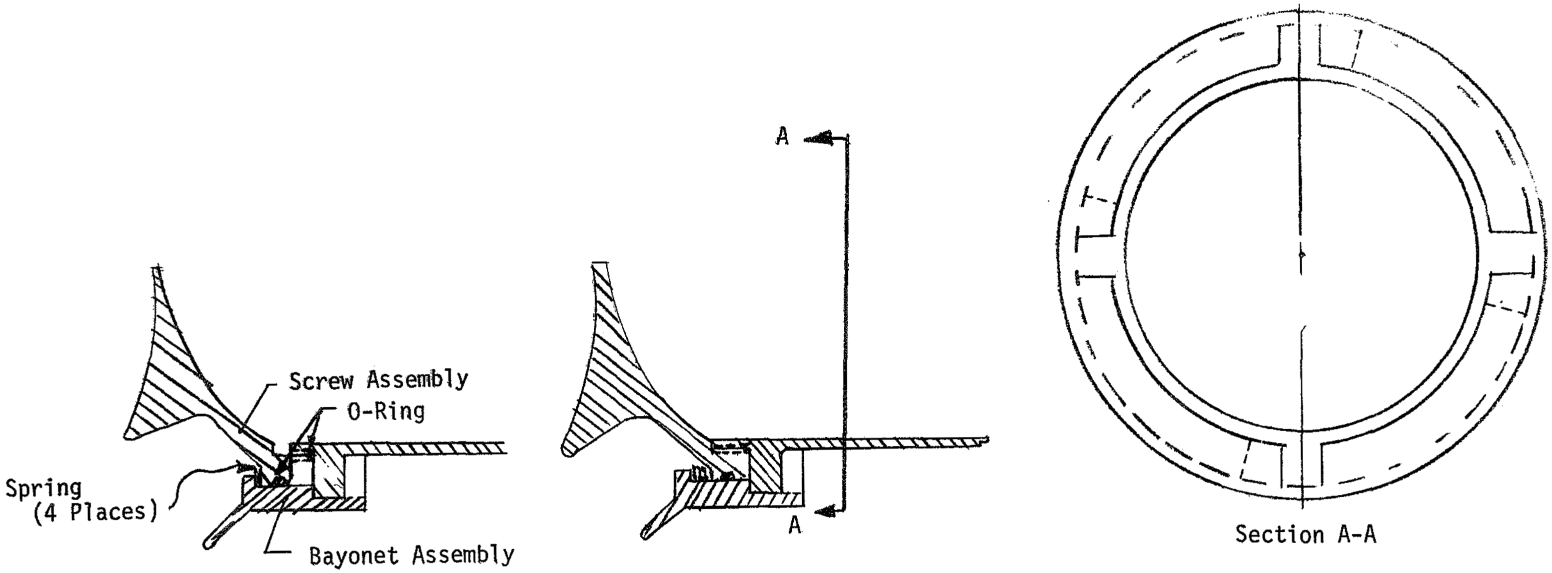


Fig. III-34 Double Bayonet Flange Connection



Open Position

Locked Position

Section A-A

Fig. III-35 Bayonet/Screw Connection

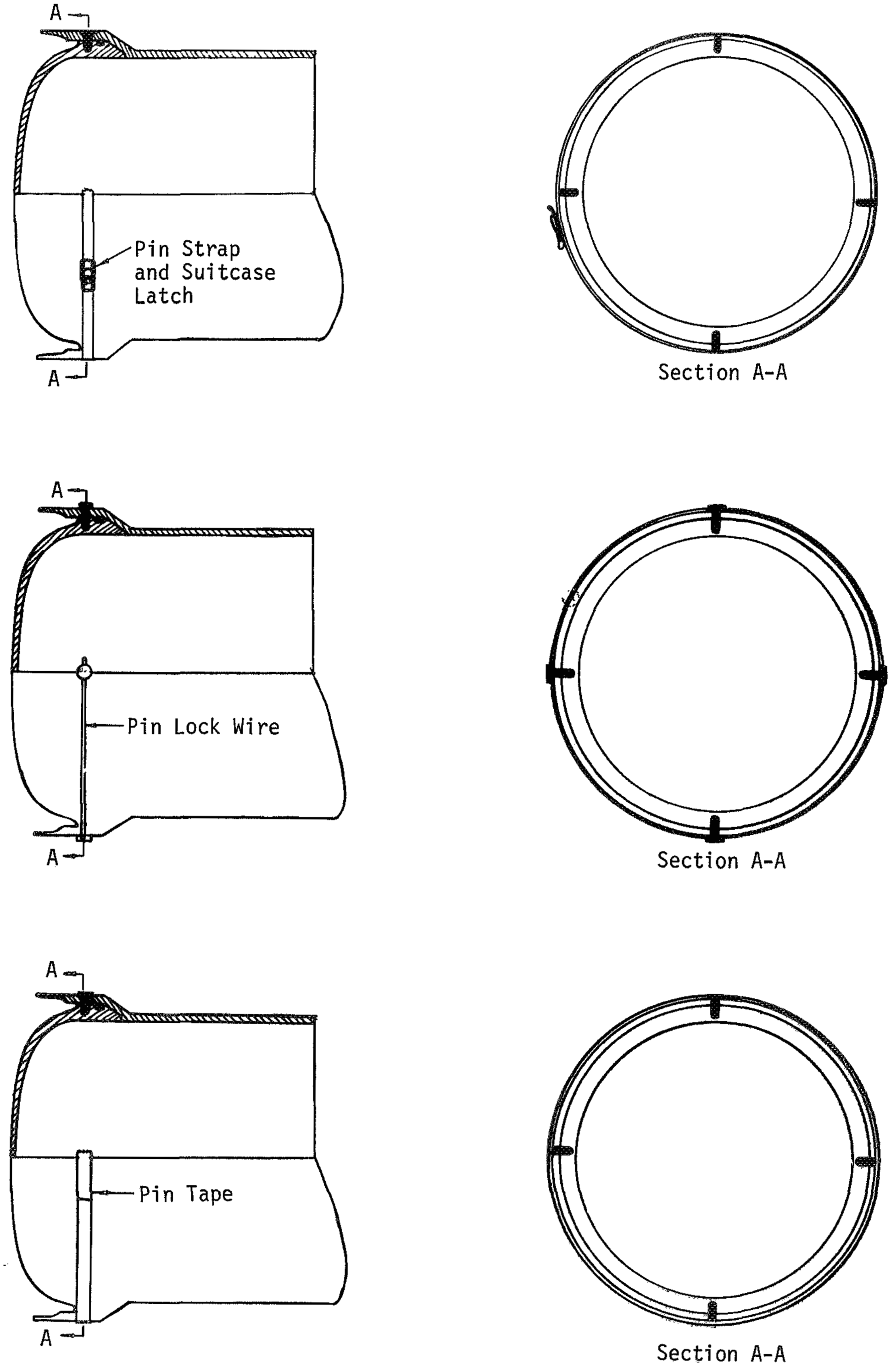


Fig. III-36 Forward Closure/Case Pin Attachment Concepts

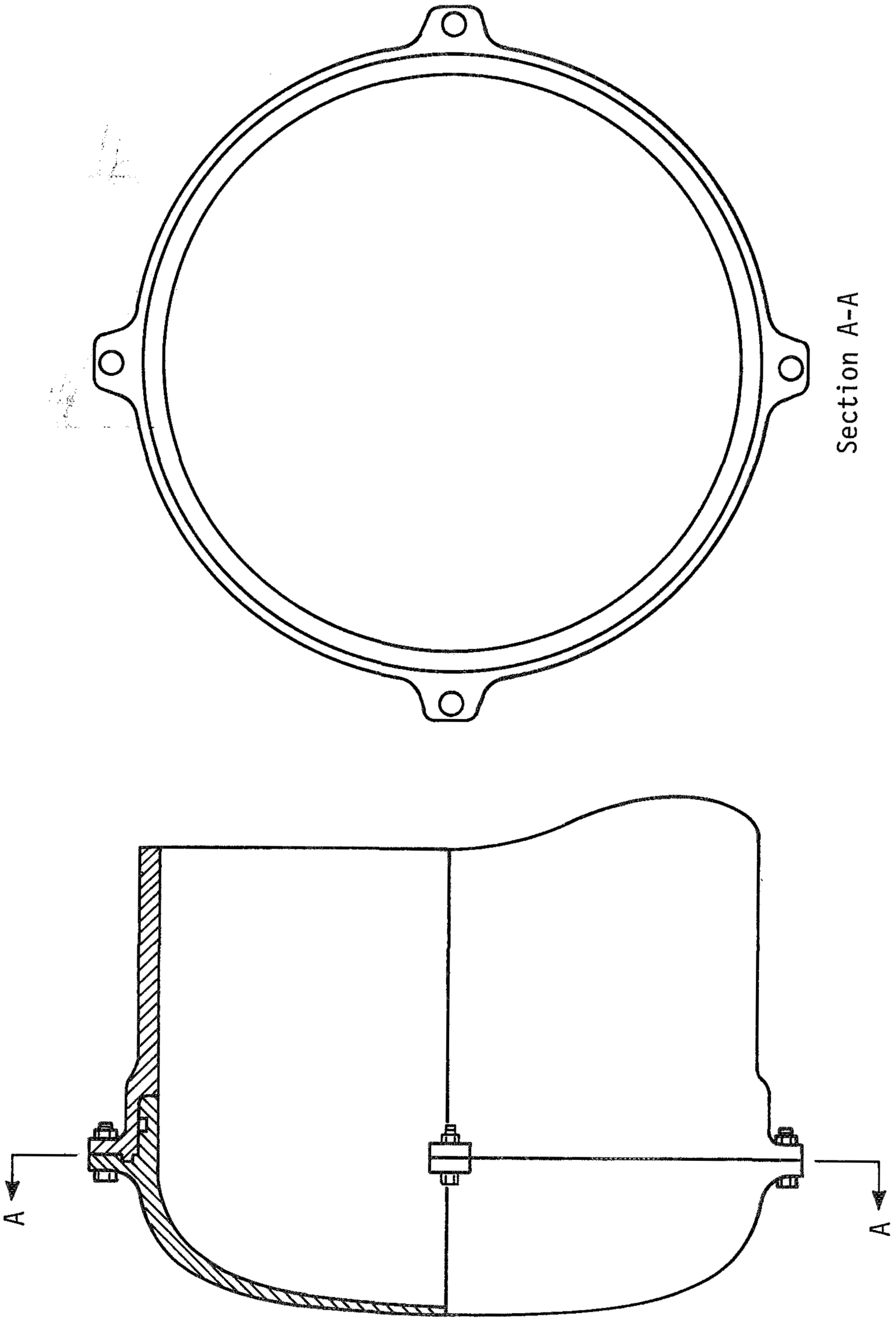


Fig. III-37 Forward Closure/Case Bolted Flange Concept

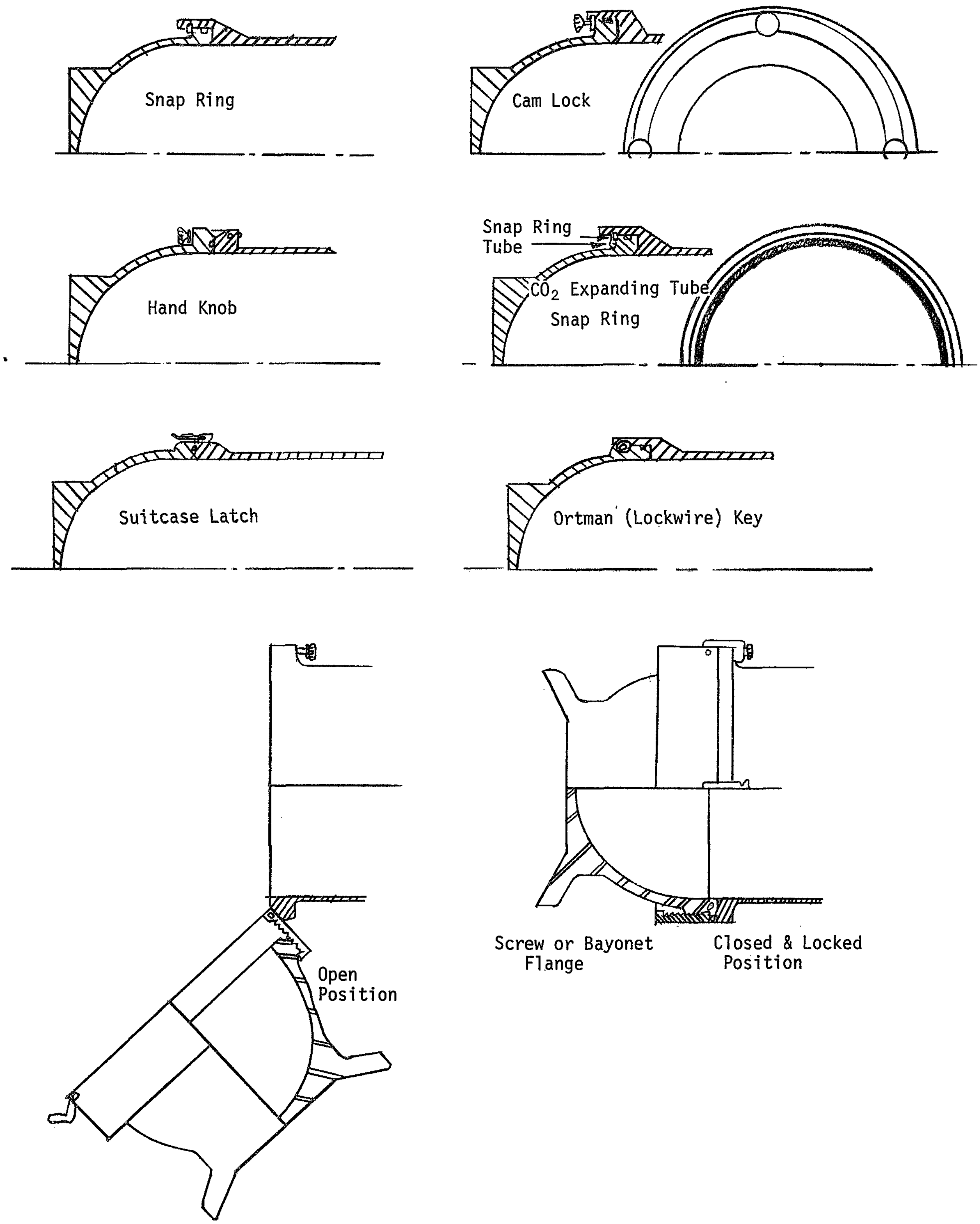


Fig. III-38 Additional Attachment Concepts

4. Candidate Ignition Concepts

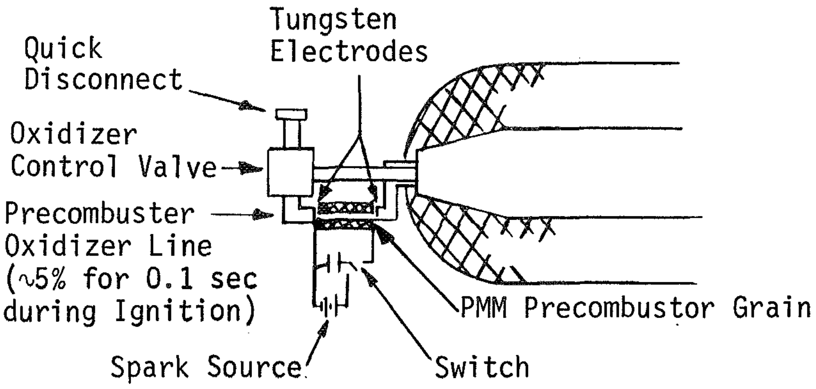
The initiation of hybrid combustion can be achieved by a number of means. The igniter must be safe, reliable, and as maintenance-free as possible. Although the primary oxidizers -- GOX and H_2O_2 -- are not hypergolic with the fuels considered, they are, nevertheless, relatively easy to ignite. Several ignition concepts are shown in Fig. III-39.

a. Spark-Initiated Precombustor - During ignition, a small portion (∿5%) of the oxidizer flow is passed through a miniature fuel grain precombustor with electrodes at each end. A spark is initiated between these electrodes to ignite the precombustor. For 0.100 to 0.200 sec, the hot, fuel-rich precombustor gases are injected around the main oxidizer stream into the motor chamber to initiate hybrid combustion. The secondary oxidizer flow is then shut off and the precombustor is extinguished.

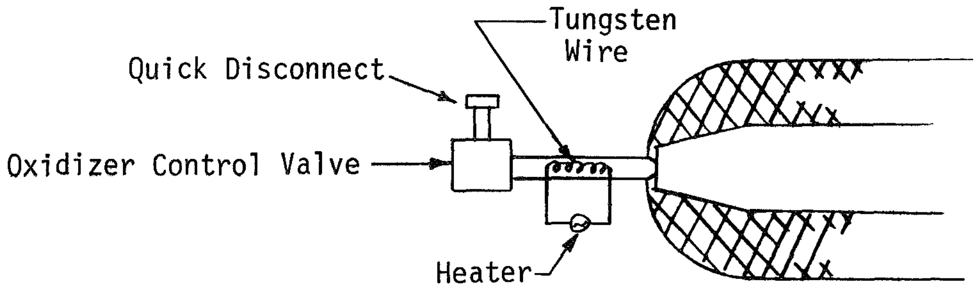
b. Electrically Heated Oxidizer - Hypergolic ignition can be achieved by electrically heating the oxidizer. This requires a relatively high power level, but a short duration (e.g., 0.1 sec), so total energy requirements are relatively low (∿5 Btu). The temperature rise at the oxidizer reduces the injector mass flow and facilitates a smooth ignition transient.

c. Pyrogen Hot Gas Igniter - For missions that require one or only a few motor ignitions per fuel grain, a simple, single-shot, pyrogen-type igniter could be an attractive solution. The igniter would supply hot, fuel-rich gases to burn with the oxidizer, and would not attempt to heat the fuel grain. The pyrogen could be injected directly into the motor chamber, as shown, or into a precombustor upstream of the igniter.

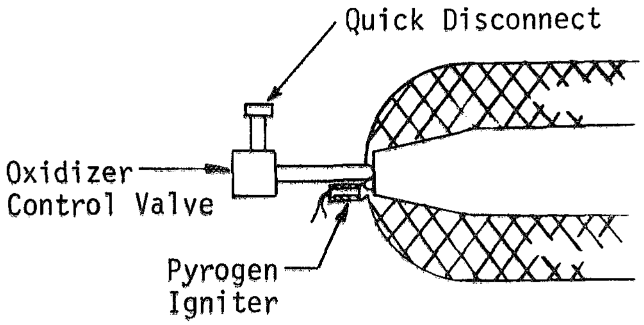
d. Butane Spark-Initiated Precombustor - Sparked butane igniters have been used on several small hybrid motors with complete success. A trip switch is used to inject a measured amount of butane (e.g., 20% of the oxidizer flow for 0.050 sec) into a precombustor. The mixture is then sparked and the hot gases are injected into the combustion chamber, where they initiate hybrid combustion with the fuel grain. This design has proven to be completely safe and extremely reliable. The only maintenance is periodic replenishment of the butane supply. This ignition concept was used on the baseline design with one slight modification. Because each thruster pad holds six ACS motors, the baseline design used a centralized butane supply and trip switch assembly, rather than individual units on each motor.



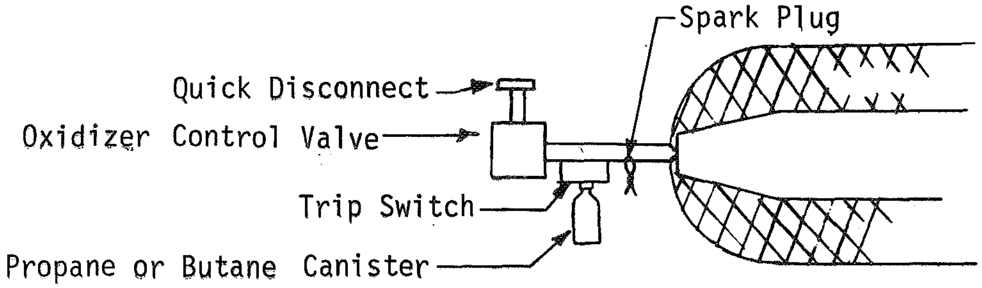
(a) Spark-Initiated Precombustor



(b) Electrically Heated Precombustor



(c) Pyrogen Hot Gas Igniter (Single Shot)



(d) Butane or Propane Spark-Initiated Precombuster

Fig. III-39 Candidate Ignition Concepts

5. Fuel Grain Depletion Indicators

Proper hybrid motor performance depends on maintaining the correct propellant flowrate and the correct O/F ratio. When the hybrid fuel grain regresses to the chamber wall, a part of the motor wall becomes exposed to the chamber gases; the resulting heat flux must either be conducted away or allowed to radiate to space. The chamber gas becomes increasingly oxidizer-rich. This reduces the delivered specific impulse, while causing a significant increase in the corrosivity of the combustion products in the aft closure and nozzle, often at a slightly higher temperature. Prolonged operation in this mode could lead to grain breakup and ejection of unburned pieces of fuel. Therefore, to maintain repeatable motor performance and achieve extended motor life, the fuel grain must be replaced at or just prior to fuel depletion. Several methods can be used to determine when fuel is depleted.

a. Trip Wire - A fine mesh of wire can be imbedded in the fuel grain approximately 1.27 mm (0.050 in.) from the outside. When the fuel has regressed to this point, the wires will melt and reliably provide a loss in continuity that can be used to signal motor shutdown. Several layers of wires could be used to provide a measure of available total impulse (e.g., 50%, 90%, and 100%).

b. Thermocouples - Since fuel burnout will occur over a period of several seconds, due to slightly nonuniform regression, an array of thermocouples on the motor case could be used to signal fuel depletion. These thermocouples could potentially serve additional functions, such as measuring when the case had cooled sufficiently to retract, or monitoring temperatures in the aft closure or nozzle to detect hot spots that might lead to a burnthrough.

c. Elapsed Time Meter - An elapsed time meter would provide the simplest measure of available total impulse, and would probably be accurate to within 5% at burnout. There will probably be critical maneuvers, and it would be necessary to know whether there is sufficient total impulse to complete the maneuver with one motor or whether the alternative motor will be needed to complete the maneuver.

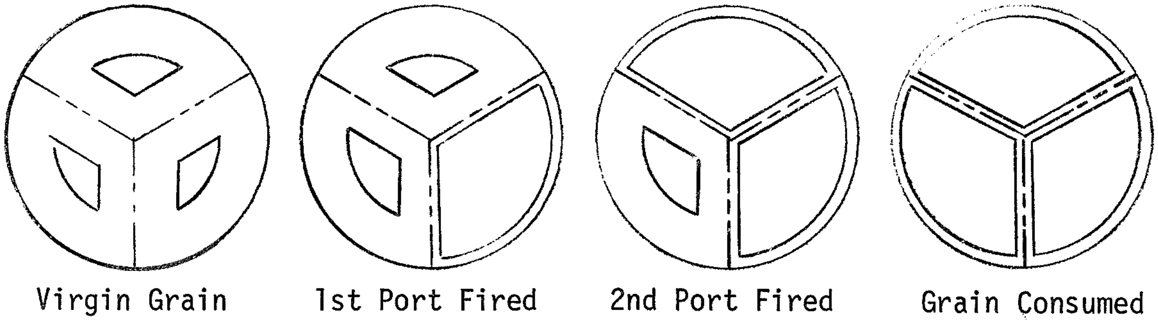
d. Performance Measurement Instruments - Performance indicators such as chamber pressure, oxidizer injection pressure, and thrust can be used to signal fuel depletion. A reduction in chamber pressure and thrust at a constant oxidizer supply pressure would indicate off-mixture ratio operation caused by fuel depletion. This instrumentation could also be used to signal nozzle or aft closure burnthrough or throat erosion.

6. Candidate Grain Design Concepts

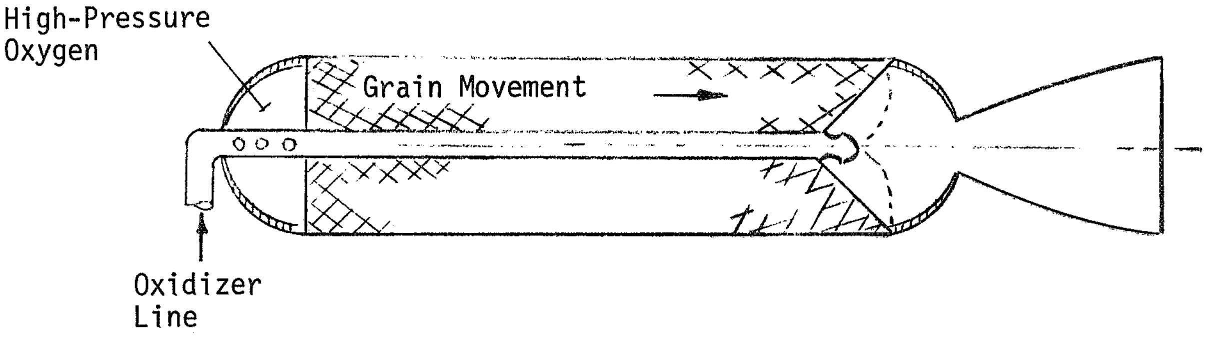
Although the design model TCA uses a conventional hybrid grain, several alternatives may offer advantages in terms of maintenance, repair, and resupply.

a. Multiple Grain Motor - The minimum regression rate, which is equivalent to the minimum oxidizer flux, is the primary factor that determines the maximum total impulse at a given thrust level. Figure III-40(a) shows a grain design that nearly triples the maximum total impulse over a conventional design. Oxidizer is injected consecutively into each port until burnout (as shown) or into alternate ports after each burn. Trip wires or some other grain-depletion indicator could be used to signal fuel depletion in each port and prevent its reuse. When the fuel in all ports had been consumed, the grain would be replaced. Because the maximum area in each port is no greater than the port area in a conventional design, the regression rate will always be above the minimum. However, when one port is being fired there will be some recirculation of hot gases in the other two ports. This will be most pronounced at one or two effective port diameters from the aft end, and some charring or melting of the fuel can be expected in this region. Although tests would probably be required to establish the severity of this problem, there are several possible design modifications that would permit using a multiple grain approach if the resulting savings in maintenance made this approach worthwhile.

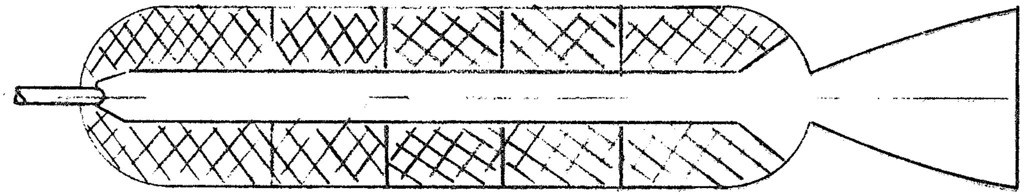
b. Moving Fuel Grain - A moving fuel grain TCA, similar to the one shown in Fig. III-40(b) has been developed and successfully tested at UTC. This design maintains constant chamber geometry, constant G_o, and has a total impulse limited only by the length of the grain. The oxidizer line extends through the grain to an injector at the aft end. Both shallow and steep conical fuel surfaces have been used. Gaseous oxidizer pressurizes the forward end of the motor to between 69 and 103 kN/m^2 (10 to 15 psia) above chamber pressure, then flows down the injection line and is injected at the aft end. As the fuel regresses, the grain moves aft. As the grain moves, the edges often soften and curl into the flow stream. This can lead to small pieces of unburned fuel or solid carbon in the exhaust. This problem can be overcome by introducing a secondary mixing chamber to increase gas residence time.



(a) Multiple Grain - Single Motor



(b) Moving Fuel Grain



Note: The hybrid grain can be segmented without end burning. The size and weight of the hybrid segments can be controlled for easy handling and storage.

(c) Segmented Grains

Fig. III-40 Candidate Grain Designs

c. Segmented Fuel Grains - Because hybrid fuel regression is a turbulent boundary-layer, convective heat-transfer phenomenon, small cracks or imperfections in the grain have no effect on motor ballistics. Therefore, hybrid grains can be laterally or even longitudinally segmented to facilitate handling, storage, and resupply. This is shown in Fig. III-40(c).

d. Waste Fuel Grains - The handling and disposal of wastes will present formidable design problems for a manned Space Station. Using wastes for fuel would provide a safe, useful means of disposal and substantially reduce the propellant resupply problem, even though it introduces a number of interfaces with other Space Station activities. Briefly, waste material would be collected and separated to remove metal and any biologically active ingredients. Then the raw waste fuel would be processed by shredding and mixing to create a uniform consistency. The waste fuel would then be cast or pressed into hybrid grains, inspected, and stored for future use.

Several waste models have been presented for a manned Space Station. The waste model shown in Table III-4 represents a minimum (lower bound) level of waste generation and was selected for this study. Semiannual waste generation for a 12-man Space Station would be at least 711 kg $\left(1568\ \mathrm{lb}_m\right)$. About 1/3 of the waste -- 231 kg $\left(510\ \mathrm{lb}_m\right)$ -- will consist of food containers, food scraps, waste paper, worn out clothing, and waste from the environmental control system. The remaining 480 kg $\left(1058\ \mathrm{lb}_m\right)$ is human waste (feces and urine solids). To avoid a serious sanitation and crew acceptance problem, human wastes have not been considered for waste fuel grains. A chemical model using cellulose and water was used to predict theoretical performance for a waste fuel/oxygen propellant system. Figure III-41 shows the theoretical vacuum specific impulse of GOX/cellulose and GOX/(50% cellulose-50% H_2O) vs the O/F ratio. Although the addition of water seems to have little effect on the fuel-rich part of the performance curve, it substantially reduces the optimum O/F ratio and significantly lowers the peak performance. Without special drying facilities, the 50% cellulose-50% water fuel system seemed most feasible, based on the selected waste model. Although efficient combustion may be difficult to achieve with this formulation, an oxygen/waste system could deliver an I_{sp} of 247 sec at O/F = 0.6, $\varepsilon = 60.0$, and $P_c = 689\ \mathrm{kN/m^2}$ (100 psia), assuming a 90% I_{sp}.

Table III-4 Waste Model for Manned Space Station

ITEM	WEIGHT FOR 6 MEN FOR 90 DAYS		WEIGHT FOR 12 MEN FOR 180 DAYS	
	lb	kg	lb	kg
Biological Wastes				
Feces (solid)	183.5	83	734.0	333
Urine (solid)	81.0	37	324.0	147
Environmental Control & Water Recovery Wastes				
Wicks	14.6	7.5	58.4	26
Charcoal	8.9	4	35.6	16
Complexing Agents	11.3	5	45.2	21
Wash Water Charcoal	8.6	4	34.4	16
Ion Exchange Resin	2.2	1	8.8	4
Millipore Filters	1.0	0.5	4.0	2
Other (Food Containers, Waste Paper, Food Scraps, & Worn Out Clothing)	81.0	37	324.0	147
Total Nonbiological	127.6	59	510.4	232
TOTAL	392.1	179	1568.4	712

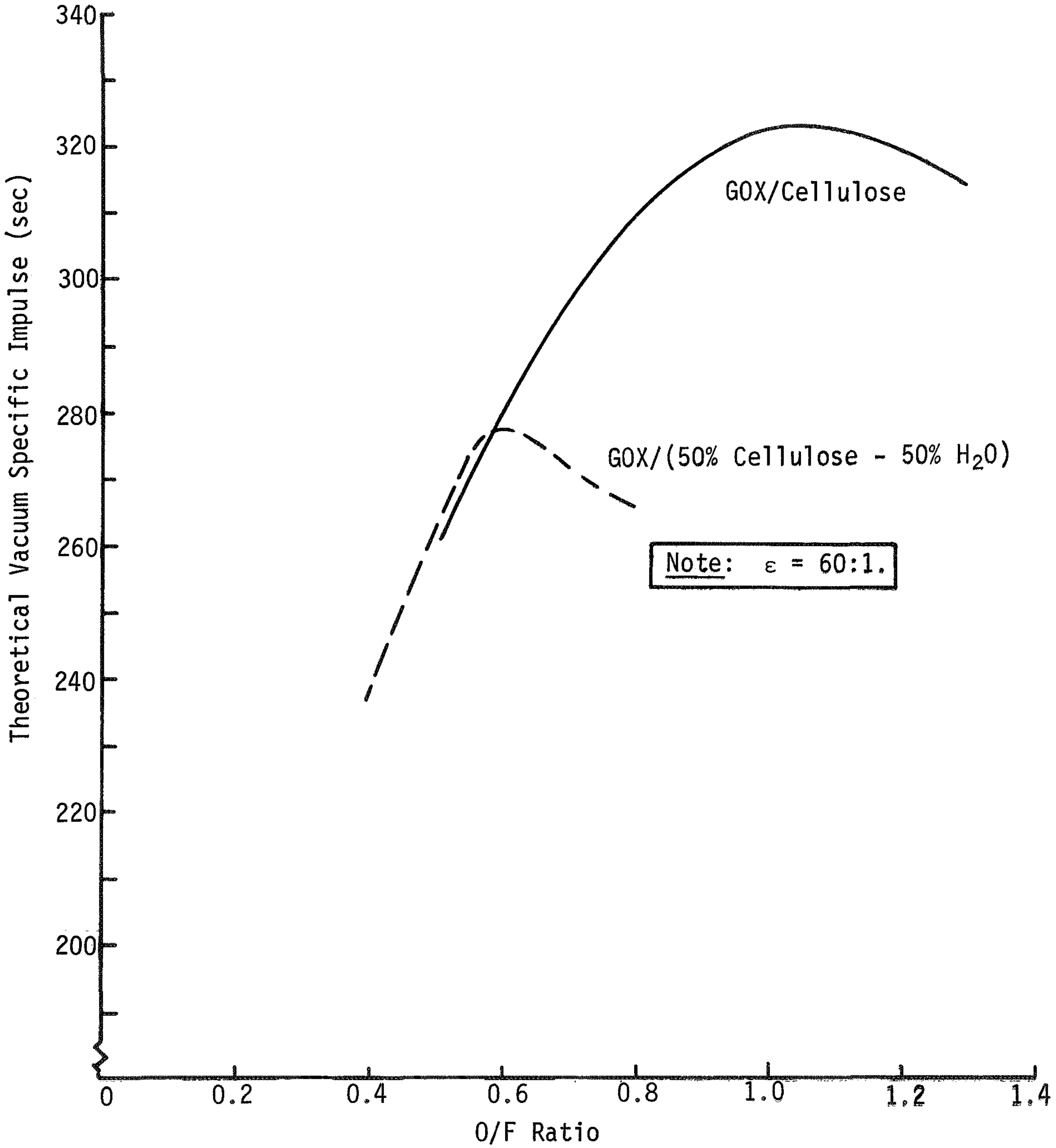


Fig. III-41 Performance of Waste Material as Hybrid Fuel - Theoretical Vacuum Specific Impulse vs Oxidizer/Fuel Ratio

Development work will be required to demonstrate desirable ballistic characteristics with waste fuel grains. Waste grains should have reasonably uniform regression characteristics to ensure reproducibility and minimize fuel grain reprocessing. Reasonable combustion efficiency will be required to achieve desired performance and clean exhaust characteristics. Finally, low minimum regression rates would be desirable to increase total impulse between grain changes. Although extensive testing will be required to demonstrate these desired ballistic characteristics, there are no known technical reasons why these properties could not be attained.

Hybrid combustion of waste can potentially satisfy Space Station auxiliary propulsion requirements and dramatically reduce resupply requirements. However, considerable development work will be required on the processing of waste fuel grains and the operation of waste fuel motors. In addition, a detailed analysis should be performed to identify and evaluate the human and facility interfaces between waste management and auxiliary propulsion. That task is beyond the scope of this study.

E. SPIN/DESPIN REQUIREMENTS

After evaluating the spin/despin requirements, it was concluded that the propulsion requirements for spin/despin are fundamentally different from those for normal attitude control, and an attempt to perform both functions with one motor would result in a decidedly nonoptimum design.

The proposed auxiliary propulsion requirements were shown in Table II-1. The APS impulse required for the 10-year mission is 6.90×10^6 N-sec $\left(1.5295 \times 10^6 \text{ lb}_f\text{-sec}\right)$. The proposed two thruster pads each carry eight 222-N $\left(50\text{-lb}_f\right)$ motors. Using GOX/(PMM/PBD) at 483 to 689 kN/m^2 (70 to 100 psia) these 16 motors could deliver 1,423,430 N-sec $\left(320{,}000 \text{ lb}_f\text{-sec}\right)$ (or 16 to 24% of the 10-year APS requirements) before replacement. If the CMGs are inoperative for the first 90 days, the impulse requirements average 17,215 N-sec $\left(3870 \text{ lb}_f\text{-sec}\right)$ per day, and fuel grains would have to be replaced every 5 days during this period. However, during the remaining 9-3/4 years, the impulse requirements only average 42,890 N-sec $\left(9642 \text{ lb}_f\text{-sec}\right)/$month, which would require replacing a fuel grain every 2 months. This is an acceptable replacement interval, so it appears that the total impulse capability of a 222-N $\left(50\text{-lb}_f\right)$ hybrid is suited for the proposed attitude control functions.

Spin/despin motor operation is significantly different from ACS operation. A spinup-to-despin maneuver will be conducted over a period of a few hours. Therefore, the spinup motor will operate either in several long pulses that are relatively close together or in a single burn. These motors are only required for the first 18 months. After that time, they only take up valuable space and should be removed.

The spins/despins are important maneuvers and may require considerable attention by the crew. Therefore, excessive APS maintenance requirements are undesirable. The 222-N $\left(50\text{-lb}_f\right)$ ACS motor, whose impulse capability is ideally suited to the attitude control mission, is nonoptimum for the spin/despin maneuvers. A spinup or despin requires 3,105,080 N-sec $\left(698{,}050 \text{ lb}_f\text{-sec}\right)$ of total impulse, which is equivalent to about thirty-five 222-N $\left(50\text{-lb}_f\right)$ motor grains. Firing and replacing 35 grains in 4 hr is an unacceptable maintenance requirement.

A pair of motors designed for spin/despin could perform this task as efficiently as the ACS motors perform theirs. A minimum-maintenance design would use two 1423-N $\left(320\text{-lb}_f\right)$ thrust motors with 1,556,877 N-sec $\left(350{,}000\ \text{lb}_f\text{-sec}\right)$ of total impulse. These motors could be loaded and checked out days or weeks before a spin/despin maneuver. Together, they would provide the required 31.1×10^5 N-sec $\left(7 \times 10^5\ \text{lb}_f\text{-sec}\right)$ and would eliminate replacing fuel grains during the maneuver. The fuel grains for these motors would be 889 mm (35 in.) long, 462 mm (18.2) in diameter, and weigh 141 kg $\left(310\ \text{lb}_m\right)$ if they were segmented into eight 18-kg $\left(39\text{-lb}_m\right)$ segments.

An alternative design would use two 1070-N $\left(240\text{-lb}_f\right)$ motors, each delivering 1,036,435 N-sec $\left(233{,}000\ \text{lb}_f\text{-sec}\right)$, with the fuel grains divided into five 18-kg $\left(40\text{-lb}_m\right)$ segments. In this design, after the first motor was fired, its grain would be replaced while the second motor was fired. The first motor would then be refired to complete the spin/despin maneuver.

Either design could be refurbished by the portable tube approach or the nozzle cap approach. After 18 months, all the spin/despin motors and spares could be returned to earth.

F. OXIDIZER AND PRESSURANT CONSIDERATIONS

1. Oxidizer Consideration

The study of theoretical propellant performance considered GOX, H_2O_2, NTO, CPF, and PF as the oxidizers. In most propulsion studies, performance is of major importance in selecting candidate propellants. In this study, the most important factors in selecting the oxidizer were:

1) Corrosiveness;
2) Toxicity;
3) Safety.

Because the mission of interest is manned and the oxidizer may be handled many times, the oxidizer must be noncorrosive, nontoxic, and safe during handling and storage. This latter requirement implies that the oxidizer must be nonflammable and insensitive to mechanical shock. An evaluation of these oxidizers is presented in Table III-5.

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Table III-5 Oxidizer Characteristics*

OXIDIZER	COLOR	ODOR	FREEZING POINT		BOILING POINT		TEMPERATURE USED FOR DENSITY MEASUREMENT		DENSITY		TOXICITY	CORROSIVE PROPERTIES	AVAILABILITY	FLAMMABLE-EXPLOSIVE	STORAGE & HANDLING	SENSI T MECHA SH
			°K	°F	°K	°F	°K	°F	kg/m^3	lb/ft^3						
Liquid Oxygen (O_2)	Light Blue	None	54.5	-361.57	90.5	-296.77	90.5	-296.77	1073	67.0	Nontoxic	Low	Abundant	Nonflammable or Explosive	Special Equipment Required	Sensi Only Conta Is Br
Nitrogen Tetroxide (N_2O_4)	Yellow to Red-Brown Liquid	Acid-like Odor	262	11.93	294	69.53	266	19.13	1418	88.5	Highly Toxic	Active	Limited	Nonflammable	No Leakage, Use Dry Steel Containers	Insens
Hydrogen Peroxide (H_2O_2)	Clear & Colorless	Odorless	272.5	30.83	423.5	302.63	293	67.73	1362	85.0	Nontoxic	Active	Available	Nonflammable	Easy to Store & Handle	Insens
Chlorine Pentafluoride ($C\ell F_5$)	Water White as a Liquid	Sweet & Pungent	170.5	-152.77	259.5	7.43	222	-60.07	1894	118.2	High Toxicity	Highly Reactive	Somewhat Limited	Nonflammable in Air	Store in Isolated, Well-Ventilated Structures	Insens
Perchloryl Fluoride ($C\ell O_3F$)	Colorless Gas	Mild Sweetish	127	-231.07	226.5	-51.97	172	-150.07	1795	112.0	Moderately Toxic	Low	Available	Nonflammable	No Problem	Not Sho Sensiti

*Boris Kit and Douglas S. Evered: *Rocket Propellant Handbook*. The MacMillan Company, New York, 1960.

Arthur Rose: *The Condensed Chemical Dictionary*. Reinhold Book Corporation, New York, 1968.

George L. Clark: *The Encyclopedia of Chemistry*. Reinhold Publishing Corporation, New York, 1966.

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Table III-5 Oxidizer Characteristics*

ICITY	CORROSIVE PROPERTIES	AVAILABILITY	FLAMMABLE-EXPLOSIVE	STORAGE & HANDLING	SENSITIVITY TO MECHANICAL SHOCK	THERMAL STABILITY	CAUSTIC	COMPLEXITY OF FEED SYSTEM	HEAT CAPACITY AT 294°K (68°F)		THERMAL CONDUCTIVITY AT 294°K (68°F)		REMARKS
									J/gm/°K	Btu/lb/°F	J/m^2/sec	Btu/ft^2/sec	
oxic	Low	Abundant	Nonflammable or Explosive	Special Equipment Required	Sensitive Only If Container Is Broken	Stable	Severe Burns	Contamination-Free Equipment Required	9.4	2.25	51.0	98,430	When mixed with a hydrocarbon fuel, forms an extremely shock-sensitive gel.
ly :	Active	Limited	Nonflammable	No Leakage, Use Dry Steel Containers	Insensitive	Stable	---	Material Problem	8.54	2.04	45.7	88,201	Inhalation may cause fatal lung injury.
xic	Active	Available	Nonflammable	Easy to Store & Handle	Insensitive	Heat Accelerates Decomposition	Severe Burns	Possible Problem with Aluminum Material	14.63	3.50	---	---	Stable when pure, but decomposes when contaminated.
ity	Highly Reactive	Somewhat Limited	Nonflammable in Air	Store in Isolated, Well-Ventilated Structures	Insensitive	Excellent at Ambient Temperature	Damaging to the Skin	Possible Material Problem	---	---	---	---	Reactions with organic compounds and with water take place with explosive violence.
tely	Low	Available	Nonflammable	No Problem	Not Shock-Sensitive	Stable Up to 85°F	---	Possible Material Problem	6.05	1.45	---	---	Dangerous with benzene and other materials whose resulting products can explode.

2

3

The oxidizers that best satisfy the requirement for low corrosiveness are LOX, NTO, and PF. Those satisfying the requirement for nontoxicity or mild toxicity are LOX and H_2O_2. The oxidizers that meet the criteria for safety in handling and storage are LOX, NTO, H_2O_2, and CPF.

Table III-6 ranks the oxidizers that fulfill the majority of listed requirements.

Table III-6 Summary of Oxidizer Evaluation

OXIDIZER	NO. OF CHARACTERISTICS SATISFIED
Liquid Oxygen	3
Hydrogen Peroxide	2
Nitrogen Tetroxide	2
Perchloryl Fluoride	1
Chlorine Pentafluoride	1

The following considerations are pertinent for the leading four oxidizers. The equipment for LOX is available and it may be possible to combine it with the environmental life support system; however, storage can be a problem if liquid oxygen is used "only" for the APS. The main problem with H_2O_2 is that few materials can be used with it without corroding during long-term missions. Nitrogen tetroxide can have toxicity problems. Thus, LOX and H_2O_2 appear most attractive as the candidates for the oxidizer.

Most metals are not chemically affected by LOX.[*] One exception is titanium, which can enter into explosive reactions with liquid oxygen under conditions of sufficient impact. Certain nonmetals react violently in the presence of GOX and should be avoided. Nylon is one of these materials. Table III-7 presents the material compatibility of various components with LOX.

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[*] Theodore Baumeister: *Standard Handbook for Mechanical Engineers*. McGraw-Hill Book Co, Inc, New York, New York, 1967.

Glen W. Howell and Terry M. Weathers: *Aerospace Fluid Component Designers Handbook*. Clearing House, Redondo Beach, California, 1967.

Heinz H. Koelle: *Handbook of Astronautical Engineering*. McGraw-Hill Book Co, Inc, New York, New York, 1961.

Table III-7 Material Compatibility with Liquid Oxygen

COMPONENT	COMPATIBLE MATERIALS
Valve Bodies	Stainless Steels 304, 310, 316, 321, & 347; K-Monel; Hastalloy B; Aluminum Alloys 2014-T6, 6061-T6, 5456H-24, 5154, 5052, 5086, 356-T6, & 6061; Alloy Steel N-155
Springs	Stainless Steels 321 & 347; Alloy Steel A-286; K-Monel; Inconel; Inconel-X
Stems	Stainless Steels 321 & 347; Alloy Steel A-286; Haynes No. 25; Inconel-X
Bellows	Stainless Steels 304, 321, & 347; K-Monel; Inconel-X
Bearings	Stainless Steels 440C & 52100
Valving Units (Seats & Poppets)	Stainless Steels 321 & 347; Teflon; Kel-F; Aluminum 1100
Packing	Teflon, Kel-F
Lubricants	Teflon Coatings & Molybdenum Disulfide; Halogenated Oils May Be Used for Installation Only
Bolts, Nuts, & Screws	Stainless Steels 321 & 347; Alloy Steel A-286; Inconel-X
Thread Sealants & Antisieze Compounds	LOX-Safe
Coatings	Chromium, Nickel Anodize (aluminum)
Diaphragms	Stainless Steels 321 & 347; Teflon; Beryllium Copper, Mylar

Tantalum, zirconium, and aluminum and some of its alloys are the metals considered compatible for long-term contact with H_2O_2. Stainless steels and nickel are also satisfactory for many component applications where long-term continuous exposure is not a requirement. Fluorinated polymers, including Teflon, Kel-F, and Viton, are compatible nonmetals. Table III-8 shows the material compatibility of various components with H_2O_2.

2. Pressurant Consideration

Pressurants were also evaluated in the event a pressurized feed system was going to be used. Primary factors important in selecting the pressurant were:

1) Compatibility with the oxidizer;
2) Toxicity;
3) Condensibles;
4) Availability.

The candidate pressurants that were considered and their characteristics are shown in Table III-9. For resupply and repair purposes, the pressurant should be compatible with the oxidizer and nontoxic; as shown in Table III-9, the pressurants satisfying these requirements are helium, neon, nitrogen, air, argon, krypton and xenon. Economics dictate that the pressurant be available and low-cost: pressurants satisfying this requirement are helium, nitrogen, and air. In addition, the pressurant should not have any condensibles, which eliminates air.

Helium is the only low-molecule-weight gas suitable for all propellants under all conditions. Nitrogen is compatible with all propellants, but it is soluble in low-temperature propellants such as liquid fluorine and LOX. Table III-10 presents a ranking of the pressurants.

Table III-8 Material Compatibility With Hydrogen Peroxide

COMPONENT	COMPATIBLE MATERIALS
Valve Bodies	Stainless Steels 304, 304 ELC, 316, 321, & 347; Aluminum Alloys 1060, 1260, 5052, 5652, 6061, & B-356; Titanium
Springs	Stainless Steels 302, 304, & 17-7 pH
Stems	Stainless Steel 17-7 pH
Bellows	Stainless Steels 304, 321, & 347
Bearings	6061 A1
Valving Units (Seats & Poppets)	Stainless Steels 321 & 347
Seals	Viton A, Teflon, Kel-F, Polyethylene
Packing	Teflon, Kel-F
Lubricants	Fluorolubes
Threaded Sealants & Antisieze Compounds	Teflon Tape
Coatings	Nickel Plating
Diaphragms	Stainless Steels 304, 321, & 347; Teflon

Table III-9 Pressurant Characteristics

PRESSURANT	Solubility in Propellant	Cost	Availability	Condensables	Storage and Handling	Toxicity	Compatibility with Propellant	Molecular Weight	Density in Stored Form (Liquid)		Boiling Point at 1033 gm/cm^2 (14.7 psi)	
									kg/m^3	lb/ft^3	°K	°F
Hydrogen	Low	Low	Common	None	Dangerous	Nontoxic	Dangerous	2	66	4.12	20	-423.67
Helium	Low	Low	Common	None	No Problem	Nontoxic	O.K.	4	118	7.36	4	-452.47
Methane	Low	Low	Common	Several	Flammable	Nontoxic	Bad	16	400	24.96	111	-259.87
Ammonia	High	Low	Common	Some	O.K.	Toxic	O.K.	17	644	40.19	240	-27.67
Neon	Low	Expensive	Rare	None	O.K.	Nontoxic	O.K.	20.2	1130	70.51	27	-411.07
Nitrogen	High	Low-Medium	Common	None	O.K.	Nontoxic	O.K.	28	757	47.24	77	-321.07
Air	High	Low	Common	Some	O.K.	Nontoxic	O.K.	29	810	50.54	78	-319.27
Argon	Low	High	Rare	None	O.K.	Nontoxic	O.K.	39.9	1310	81.74	87	-303.07
Carbon Dioxide	High	Low	Common	Some	O.K.	Toxic	O.K.	44	--	--	195	-108.67
Krypton	Low	High	Rare	None	O.K.	Nontoxic	O.K.	83.7	2260	141.02	116	-250.87
Xenon	Low	High	Rare	None	O.K.	Nontoxic	O.K.	131.3	2935	183.14	165	-162.67

Table III-10 Summary of Pressurant Evaluation Studies

PRESSURANT	NO. OF CHARACTERISTICS SATISFIED
Helium	4
Nitrogen	3
Air	3
Neon	2
Krypton	2
Argon	2

G. CANDIDATE OXIDIZER FEED SYSTEMS

Eighteen oxidizer feed systems were considered for the APS. These systems were devised to satisfy the following requirements:

1) 10-year lifetime;
2) Ease of maintenance and repair;
3) Ease of resupply;
4) Minimum crew commitment for maintenance and repair;
5) Minimum resupply;
6) High reliability.

It is recognized that these requirements have complex interactions.

1. Design Philosophy

The 10-year life requirement dictates that the oxidizer feed system be reparable and contain a degree of redundancy. This means that each propulsion module should have two interconnected systems that are virtually independent. Furthermore, in each system there should be sufficient redundancy to eliminate single-point-failures. Thus, each candidate system contains an assembly of quad check valves. This arrangement eliminates a potential failure on one side of the quad valve by permitting flow through the redundant side. It also permits the failed side of the quad valve to be replaced without hindering the operation of the propulsion system.

Another approach was the use of two-stage pressure and flow regulation assembly to obtain coarse regulation, followed by fine regulation.

The candidate oxidizer systems also had common interconnections (crossover valves) between the two systems that made up a propulsion module. These interconnections were located downstream of the pressurant tank (if one was present), downstream of the oxidizer tank, and just upstream of the TCA units. This approach provided interaction between the two systems of the propulsion module if required.

Each system also contained relief valves and burst discs at locations where pressure buildups, if not relieved, could result in catastrophic failure.

Consideration was also given to reparability. The components were designed for quick removal with a minimum of physical effort. Because a group of components (one side of the quad valve assembly, for example) or a section of the oxidizer feed system might become defective, modularization was used, when possible, to provide a modular replacement capability.

Finally, it was recognized that the system fluids should be isolated from components that are being repaired or replaced. This requirement was satisfied by venting all fluid storage containers and transfer lines to vacuum, using cold traps to reclaim the fluid. This not only permitted storing the fluid, it also permitted isolating the system fluid if it became contaminated.

2. Descriptions of Candidate Systems

Previously described analyses indicated the desirability of using LOX and helium as the oxidizer and pressurant, respectively, for the hybrid APS. The candidate feed systems used these commodities where applicable. The candidate systems are listed in Table III-11. Note that, in many cases, the candidate systems are essentially identical, and differ only in that a bladder, diaphragm, or bellows is substituted for a capillary screen.

a. Blowdown Stored-Gas Feed System - System 1 (Fig. III-42) - In the blowdown system, stored helium gas is used to pressurize the LOX, which is in a positive expulsion bellows tank. The pressurant is recompressed while the oxidizer is being resupplied, thereby eliminating the need to resupply pressurant. As the LOX is expelled, it is passed through a heat exchanger to provide GOX.

b. Regulated Stored-Gas Feed System - System 2 (Fig. III-43) - In this system the stored helium gas is regulated for flow and pressure before it enters the LOX bellows tank. As the control valve is opened, the regulated LOX enters the heat exchanger.

Table III-11 Candidate Oxidizer Feed Systems

SYSTEM	TYPE
1	Blowdown Stored-Gas Feed System
2	Regulated Stored-Gas Feed System
3	Heater Self-Pressurization Feed System
4	Heat Sink Material Self-Pressurization Feed System
5	Hydrazine Main Tank Injection Feed System
6	Electromechanical Bellows Feed System
7	Mechanical Bellows Feed System
8	Solid Gas Generator Feed System
9	Jet Pump Feed System
10	Turbopump Feed System
11	Solid Gas Generator Feed System with Capillary Screen
12	Gaseous Oxidizer Feed System
13	Blowdown Stored-Gas Feed System with Capillary Screen
14	Regulated Stored-Gas Feed System with Capillary Screen
15	Regulated Stored-Gas Feed System with Bladder
16	Blowdown Stored-Gas Feed System with Diaphragm
17	Regulated Stored-Gas Feed System with Diaphragm
18	Blowdown Stored-Gas Feed System with Bladder

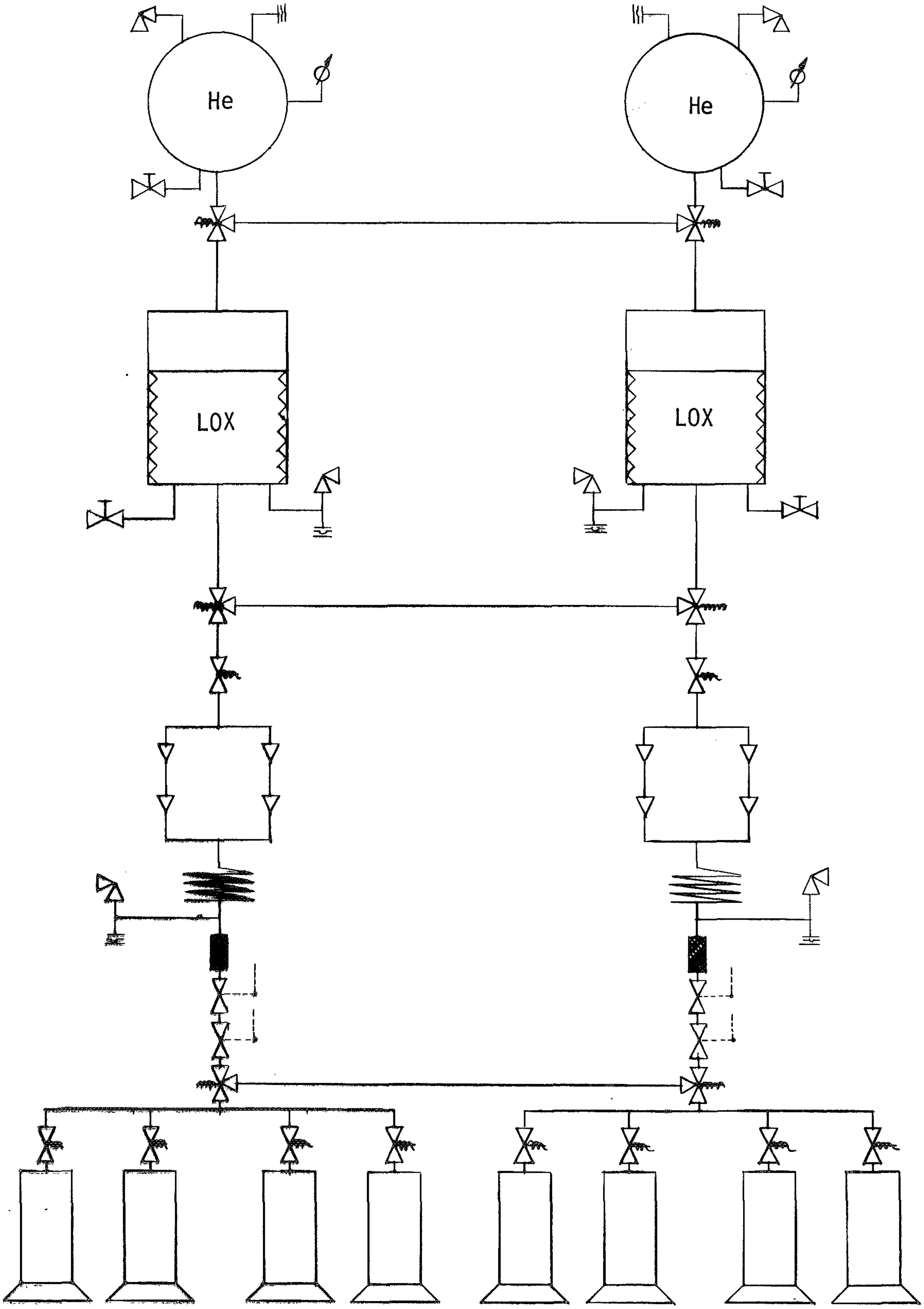

Fig. III-42 Blowdown Stored-Gas Feed System

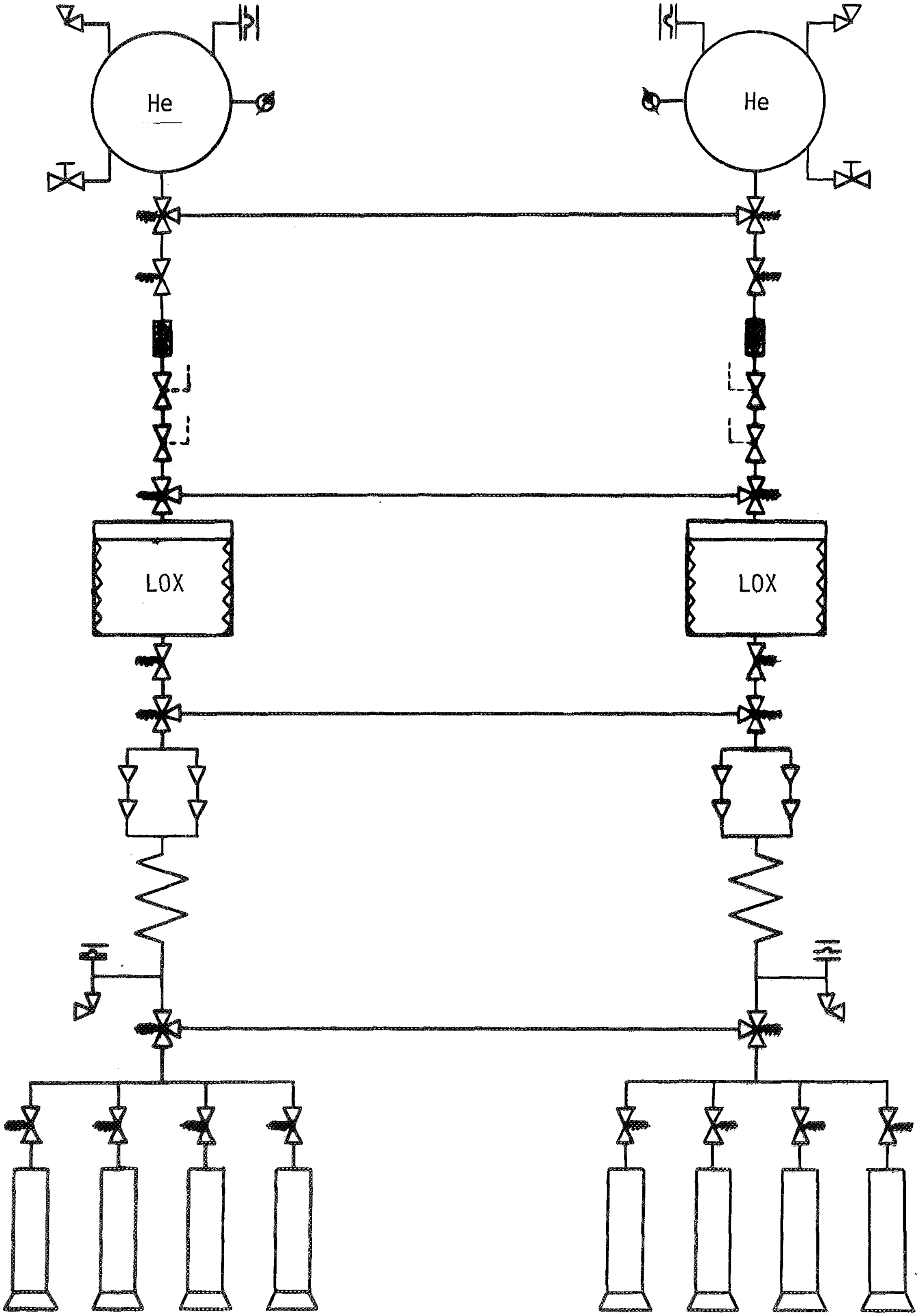

Fig. III-43 Regulated Stored-Gas Feed System

Upstream of the heat exchanger is a quad check valve assembly that prevents backflow of gaseous oxygen. Gaseous oxygen leaves the heat exchanger and enters the engines through isolation valves. A pressure gage is attached to the nitrogen sphere to determine when resupply is complete. A filter upstream of the regulators prevents particle contamination of these components. All valves except the fill valve are solenoid-operated, but could also have a manual override.

c. Heater Self-Pressurization Feed System - System 3 (Fig. III-44) - The self-pressurization system relies on vapor pressure from the volatile liquid,* in this case, LOX, to pressurize the system. Consequently, a heat source is required to vaporize the LOX. In this system, it is an electric heater that is controlled by a pressure sensor to maintain the ullage at a constant pressure. LOX is fed through the nozzle heat exchanger when the solenoid control valve is opened. The resulting gas is then regulated to the proper pressure and flow, and fed into the rocket engines. Because of the heater, this system will require electrical power, but no other interfaces are needed.

d. Heat Sink Material Self-Pressurization Feed System - System 4 (Fig. III-45) - This system is similar to System 3, except that the electric heater is replaced by a heat storage material.* The storage material is such that it remains frozen at the temperature and pressure at which the LOX boils off and pressurizes itself. As LOX is withdrawn, the increase in ullage volume decreases the ullage pressure. This pressure change is eliminated as the LOX absorbs heat-of-fusion from the heat storage material. This process keeps the LOX under pressure at all times. When the control valve is opened the LOX is fed into the

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*S. F. Griffoni: *All-Metal, Volatile-Liquid Positive Expulsion System.* ER-5980, Contract NAS9-1004. TRW Inc, Power Systems Division, Redondo Beach, California, June 1964.

R. G. Eatough: "Expulsion of Storable Propellants Utilizing a Volatile Liquid as the Pressurizing Medium." *SAE Transactions*, Vol 76, November 1968, p 1983-1992.

C. N. Tripp: *Volatile Liquid Pressurization.* The Marquardt Corporation, Van Nuys, California, 1967.

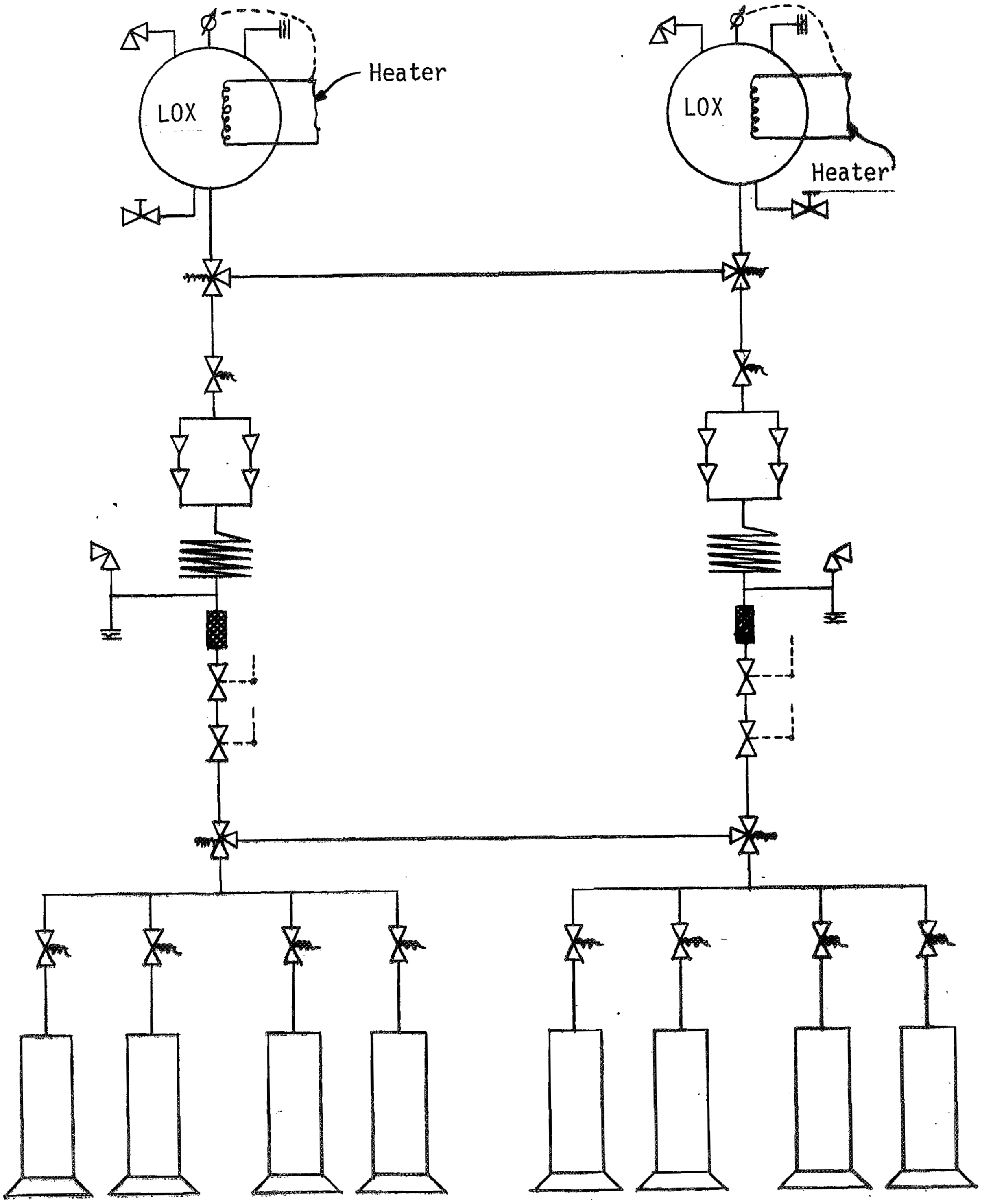


Fig. III-44 Self-Pressurization Heater Feed System

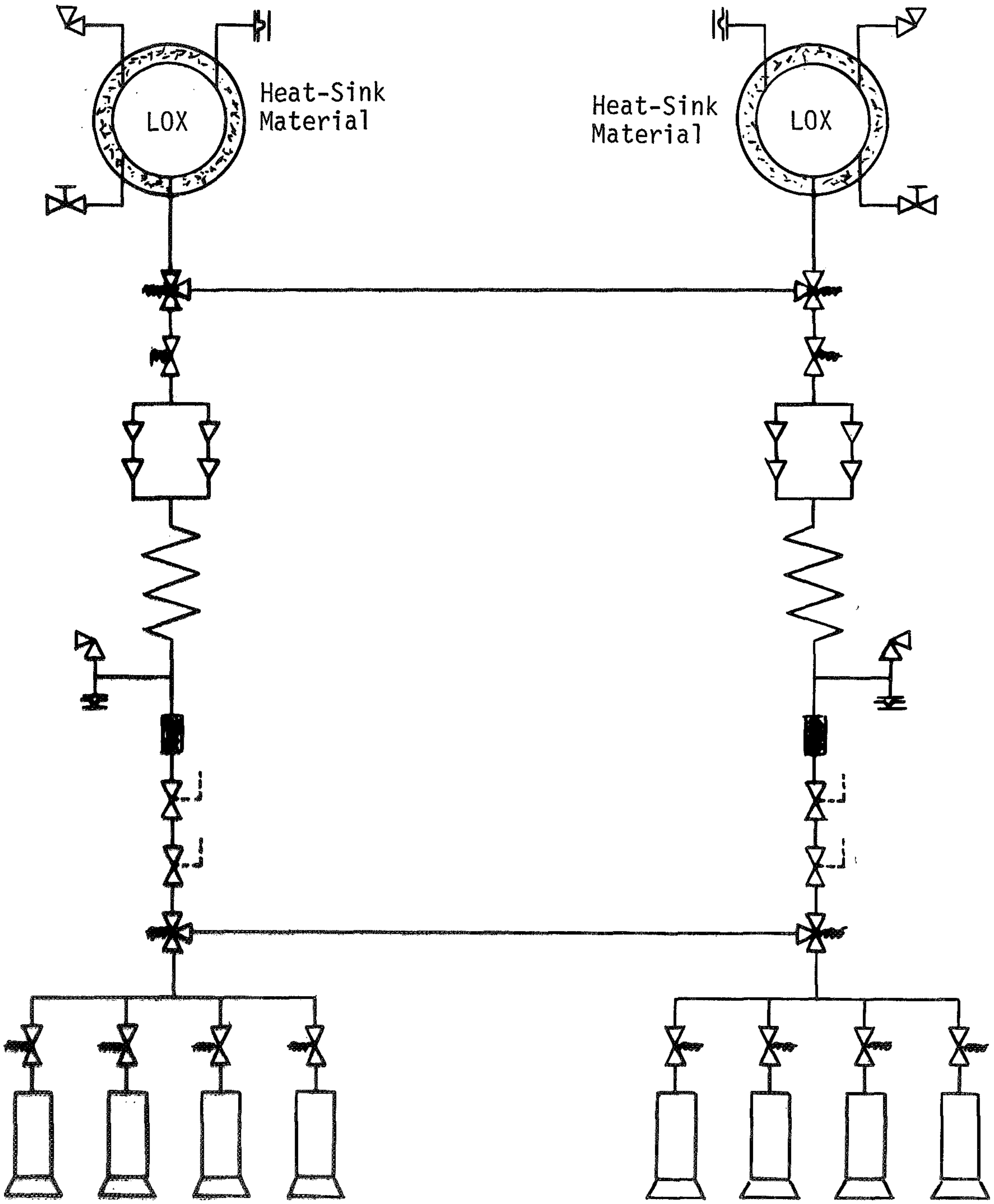


Fig. III-45 Heat-Sink Material Self-Pressurization Feed System heat exchanger and converted to GOX. As the GOX leaves the heat exchanger, it is passed through regulators that control its flow and pressure. From here, the regulated gas enters the engine assemblies. Development of the heat storage material will be required for this system.

e. Hydrazine Main Tank Injection Feed System - System 5 (Fig. III-46) - In this system, hydrazine or some other hypergolic fuel is used with LOX and helium. The stored helium gas pressurizes the hydrazine tank, which, in turn, feeds into the LOX tank. As the hydrazine comes into contact with the LOX, combustion occurs, which pressurizes the LOX tank. The LOX is then fed through a series of check valves to the heat exchanger, where it is converted to GOX. The GOX then enters the engine assemblies. The check valves will shut off any individual engine if it is found to be faulty. This system will require resupplying both LOX and hydrazine; the helium can be recompressed while the hydrazine is being resupplied.

f. Electromechanical Bellows Feed System - System 6 (Fig. III-47) - The use of a gas pressurant to expel the liquid oxygen is eliminated in this system, thereby eliminating all lines and components for a pressurant system. The LOX expulsion tank is modified to accept an electric motor with a threaded screw drive that compresses the bellows and expels the LOX at a given rate. The LOX is then fed through a series of check valves into the heat exchanger. Gas leaves the exchanger and is channeled into a series of regulators, where its flow and pressure are determined. From here, the regulated GOX enters the engine assemblies. Redundancy is provided by using crossover valves located after the LOX tank and before the engine assemblies. Burst discs and relief valves are installed as a safety measure. This system will require electrical power to operate the drive motor.

g. Mechanical Bellows Feed System - System 7 (Fig. III-48) - This system is similar to System 6, except that the LOX bellows tank uses the force of the bellows and an additional spring in place of the electric motor assembly. The LOX is external to the bellows and the spring, and therefore compresses this assembly during resupply. The system has no electrical interface and eliminates all components related to a pressurant system. When the control valve is opened, the LOX is expelled and passes through the quad check valves into the heat exchanger. Gas emerges, passes through a filter and regulators that control gas flow and pressure, and enters the rocket engines.

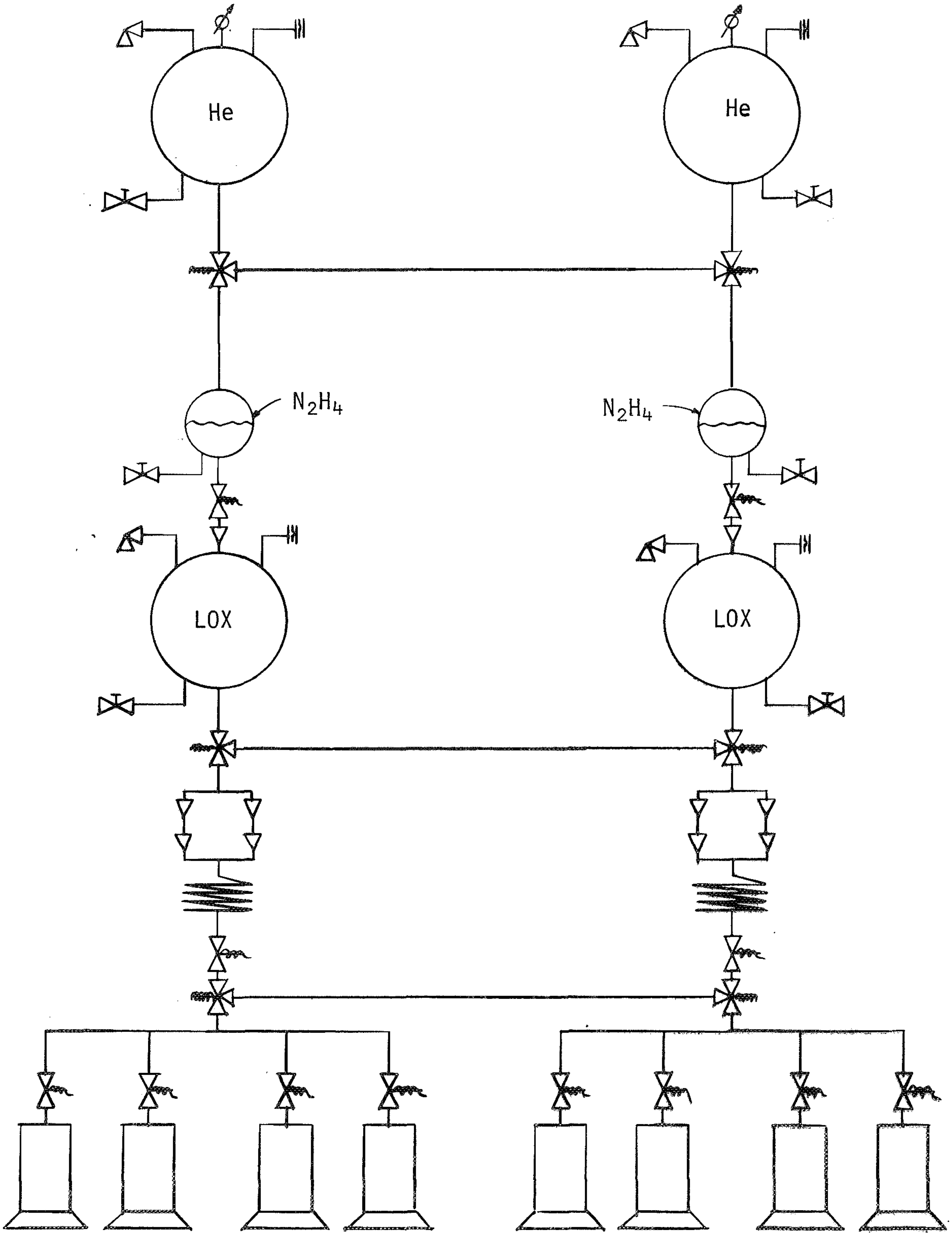


Fig. III-46 Hydrazine Main Tank Injection Feed System

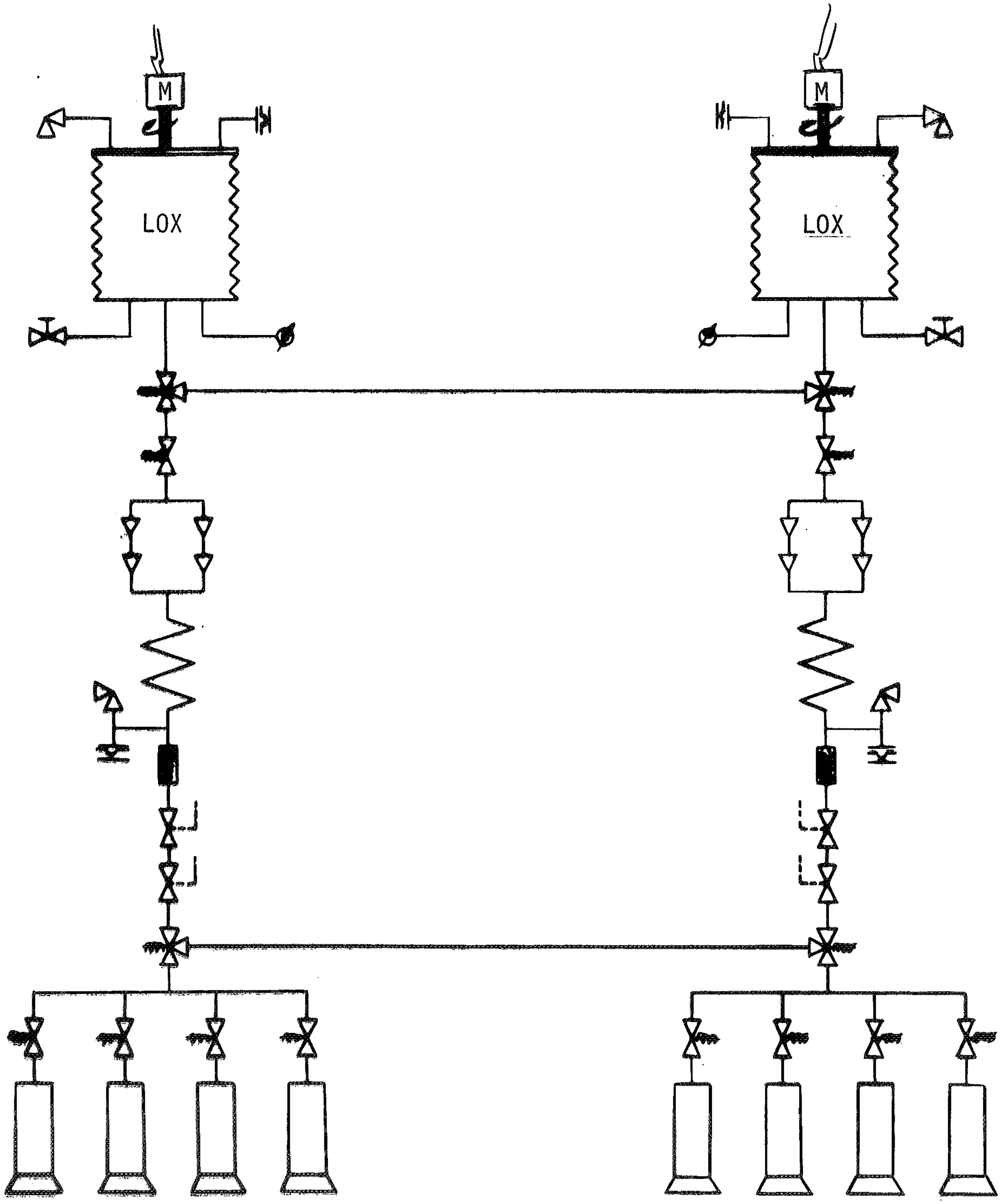


Fig. III-47 Electromechanical Bellows Feed System

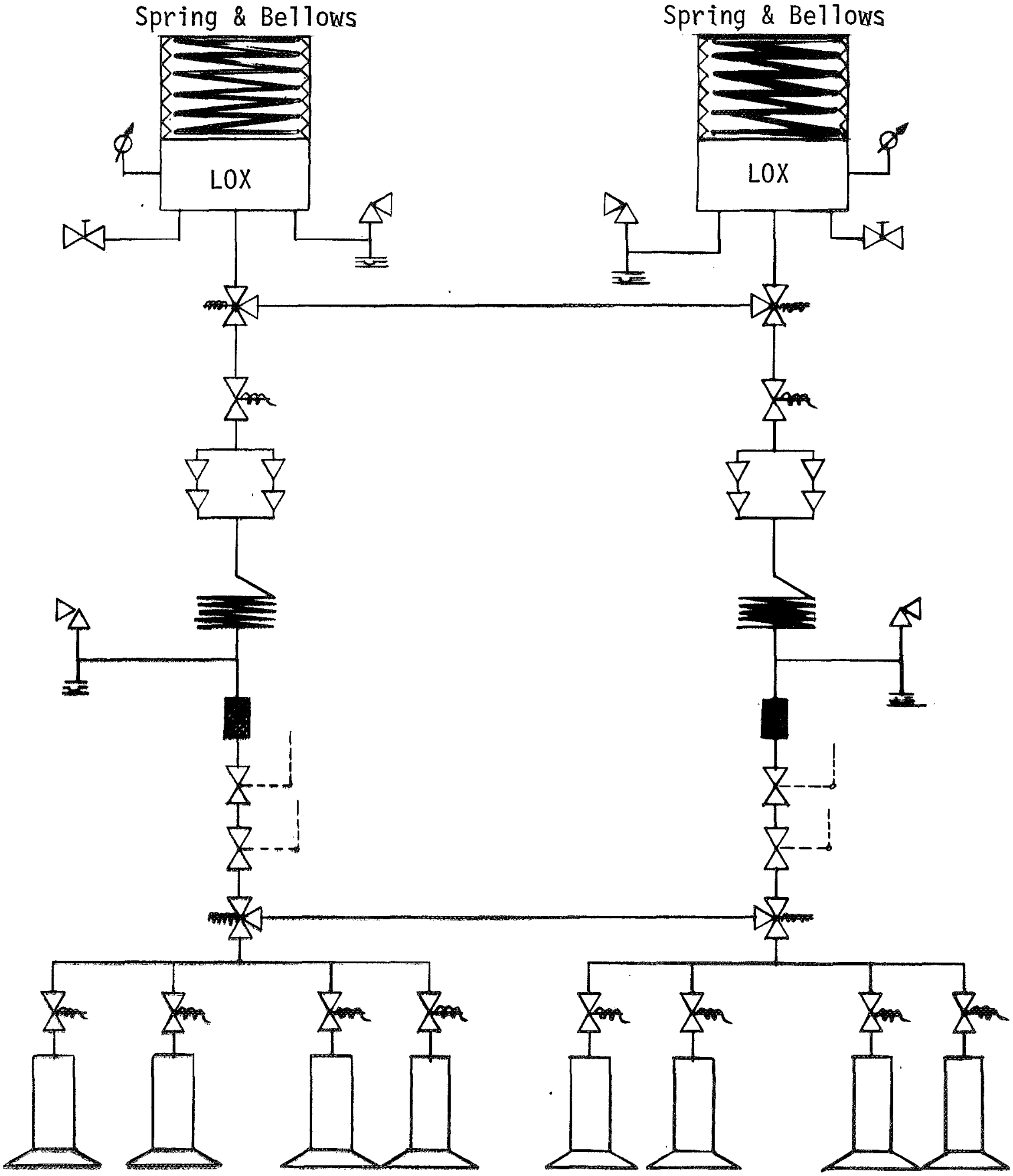


Fig. III-48 Mechanical Bellows Feed System

h. Solid Gas Generator Feed System - System 8 (Fig. III-49) - A solid gas generator is used to provide pressurant to the LOX tank in this system. As the gas is produced, it passes through a filter and regulator. The controlled flow and pressure of nitrogen gas expels the LOX through a quad check valve assembly and heat exchanger. The resulting gas is fed to the engine assemblies.

i. Jet Pump Feed System - System 9 (Fig. III-50) - A jet pump is used to feed the oxidizer to the engine assemblies in this system. A helium tank, under low pressure, is required to bring the LOX to the jet pump. The jet pump is started by a separate pressurized start tank that releases high pressure through the jet pump and draws the LOX through and to the engines. After the engines are started, the pressure in the nozzle replaces the pressure from the start tank. One of the interesting aspects of this system is the absence of moving parts. The LOX tank is the positive expulsion bellows type.

j. Turbopump Feed System - System 10 (Fig. III-51) - The turbopump system uses helium gas as a pressurant and LOX as the oxidizer. The helium exerts a positive pressure head on the LOX to provide combustion with the PMM housed in the thruster chamber assembly. The LOX is contained in a metal bellows with a relief valve and a burst disc in line to prevent a high internal bellows pressure. Once the solenoid valve downstream of the LOX bellows is activated, a turbine driven by a gas generator starts pumping the LOX through a heat exchanger. This heat exchanger converts the LOX to GOX, which is passed directly over the PMM to start combustion. Downstream of the heat exchanger, the GOX is filtered and regulated to the proper flow and pressure by a two-stage regulator system. After the engine solenoid valves are activated, the GOX enters the engines. Upon depletion of the LOX from the bellows container, the bellows is refilled, thereby repressurizing the helium pressurant to its original operating pressure in the pressurant sphere. Eliminating the resupply of pressurant simplifies the system and reduces weight.

k. Solid Gas Generator Feed System with Capillary Screen - System 11 (Fig. III-52) - In this feed system, a solid gas generator produces the pressurant required to expel the LOX fuel. The LOX is initially contained by a hydrophilic screen, but passes through the screen upon application of the pressurant. The pressurant gas will not pass through the hydrophilic screen. After leaving the screen, the LOX passes through a heat exchanger, which converts it to GOX. This is then fed to the engines for

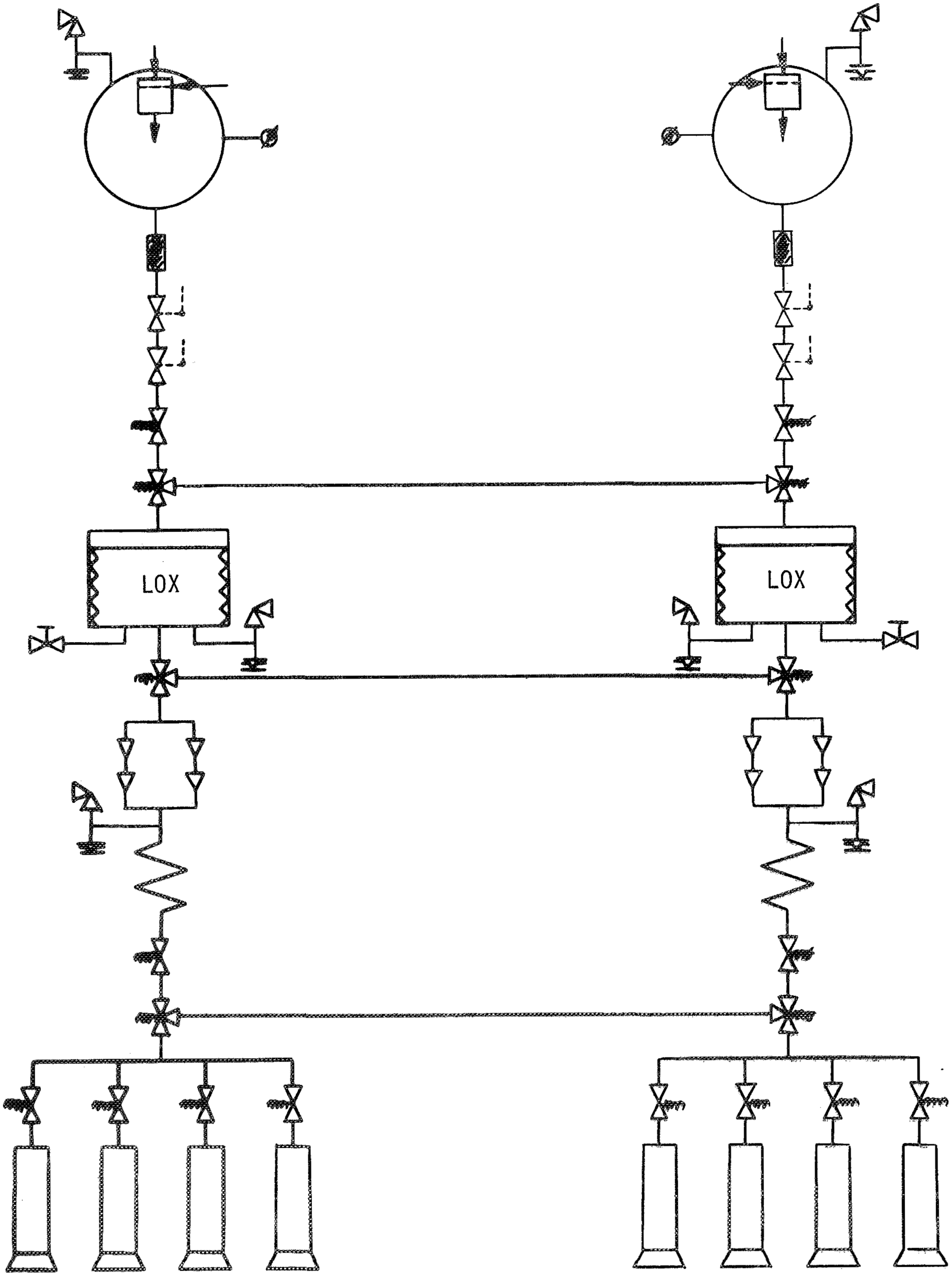


Fig. III-49 Solid Gas Generator Feed System

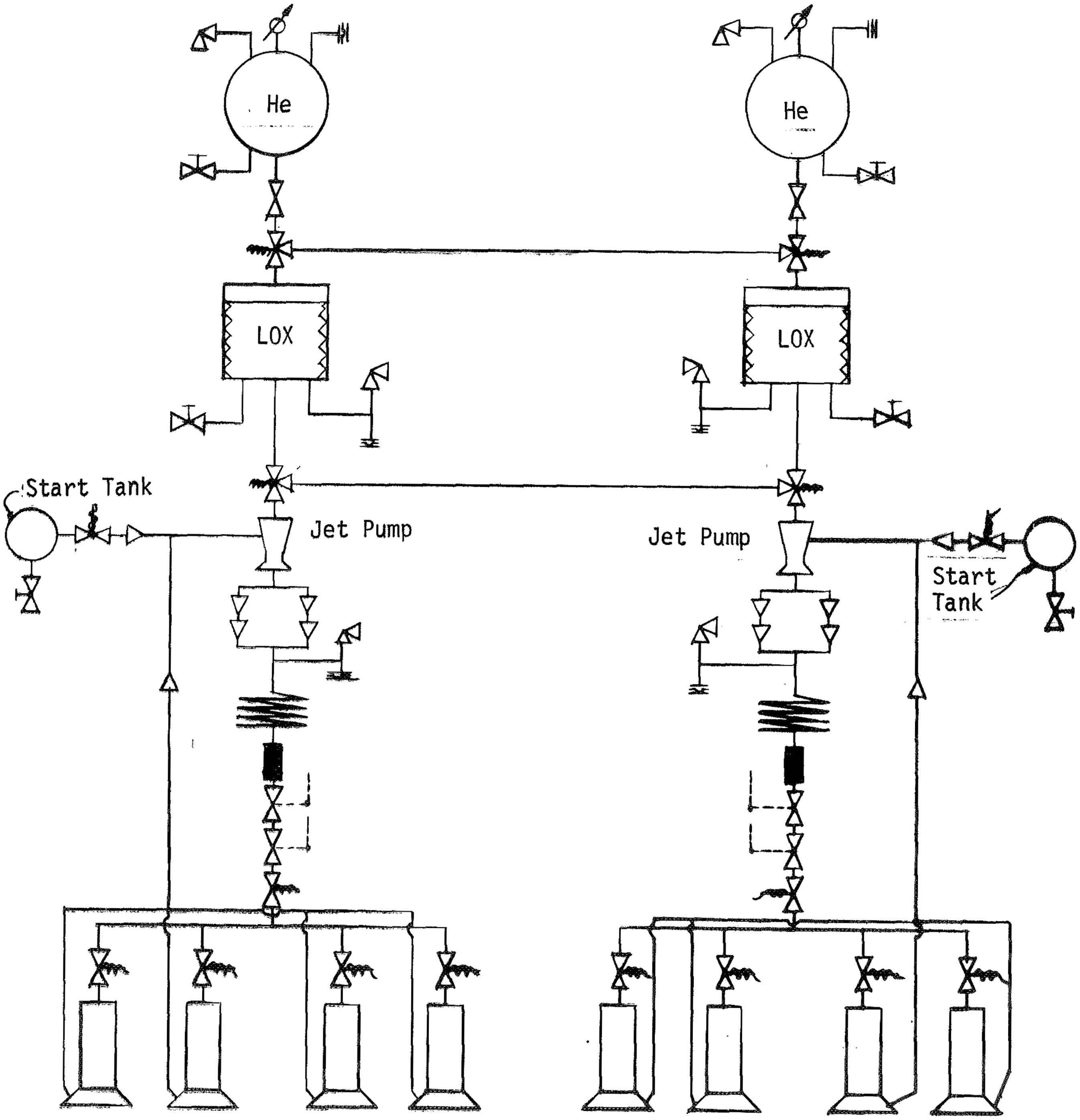


Fig. III-50 Jet Pump Feed System

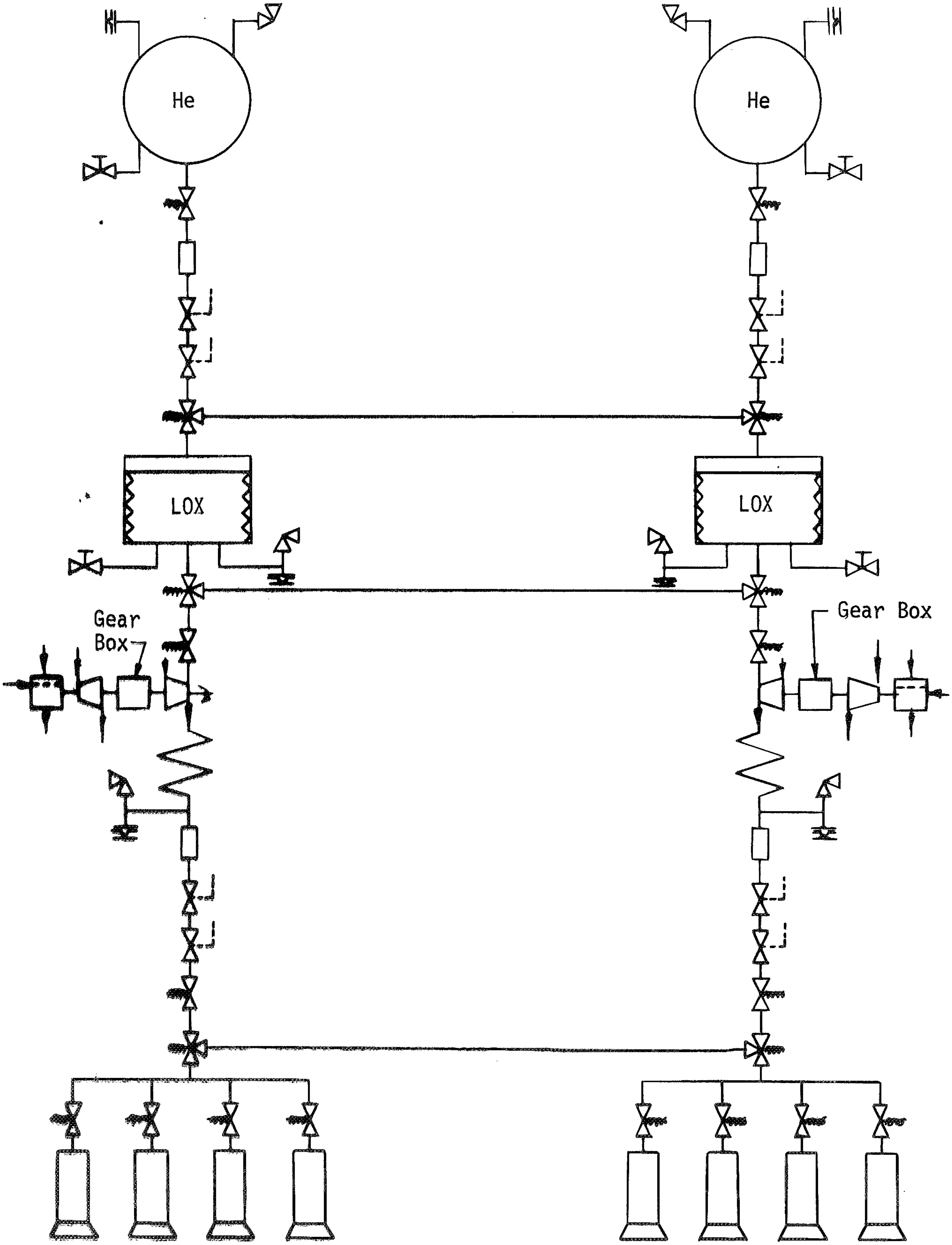


Fig. III-51 Turbopump Feed System

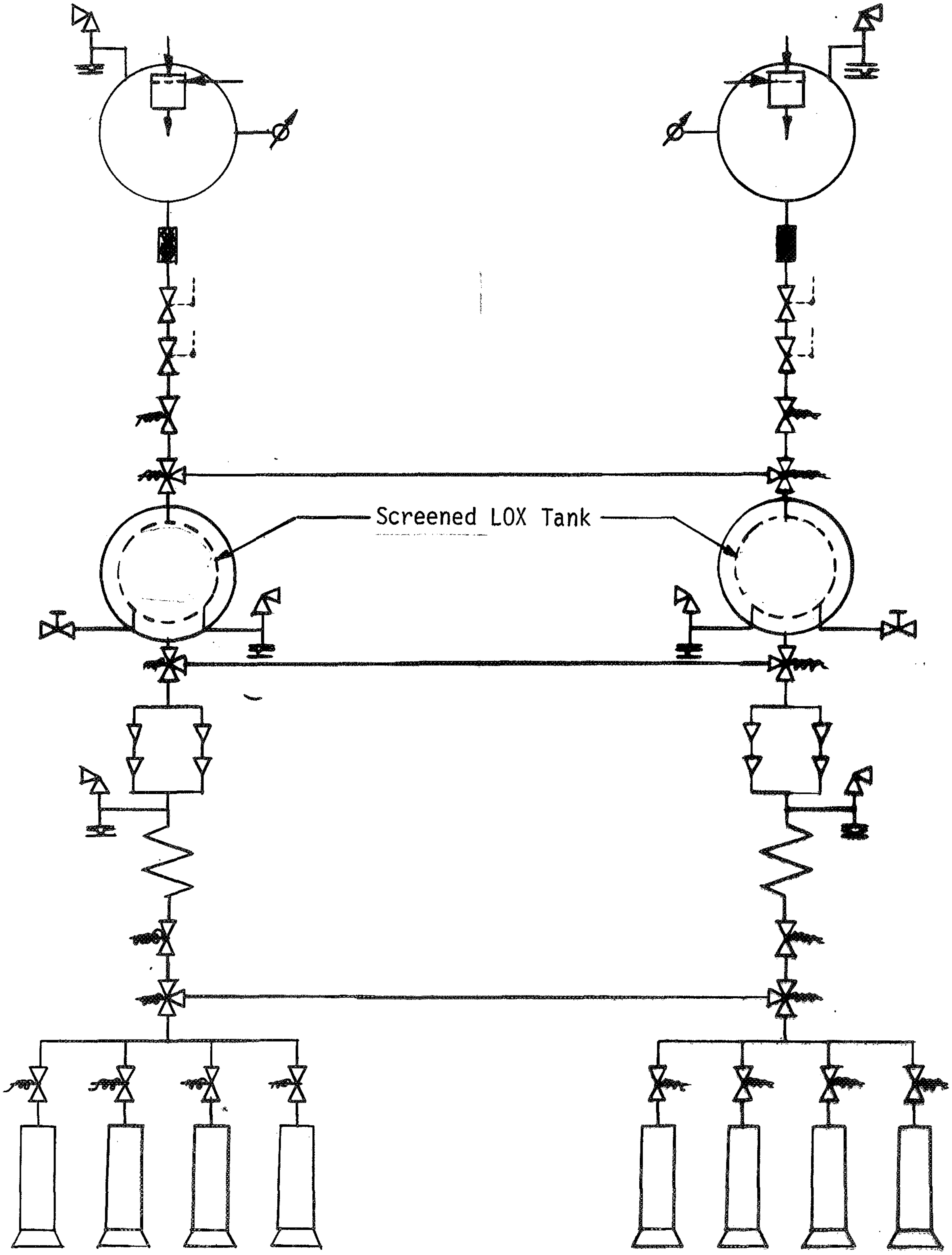


Fig. III-52 Solid Gas Generator Feed System with Capillary Screen combustion. This system will require external power for the solid generator igniter.

ℓ. Gaseous Oxygen Feed System - System 12 (Fig. III-53) - This system uses compressed oxygen gas as the stored oxidizer. When oxidizer is required, the control valve is opened and the gas passes through a filter and a series of regulators to the TCAs. This system eliminates many of the components found in other systems. The oxidizer-pressurant interface is eliminated and there is no need for items like metal bellows, bladders, diaphragms, and other similar items. In addition, no nozzle heat exchanger or vaporizer is needed because the oxygen gas is in the form required for thrust chamber injection. However, this system requires a larger, heavier oxidizer tank than other systems.

m. Blowdown Stored-Gas Feed System with Capillary Screen - System 13 (Fig. III-54) - Stored helium gas is used to pressurize the LOX fuel in this system. The LOX is contained by a hydrophilic screen that will allow the passage of LOX, but not the helium pressurant. After expulsion from the capillary screen, the LOX passes through a heat exchanger, where it is converted to the gaseous state. It is then filtered, regulated, and fed into the rocket engines for combustion.

n. Regulated Stored-Gas Feed System with Capillary Screen - System 14 (Fig. III-55) - This system is similar to System 2, except the bellows is replaced with a spherical capillary screen that contains the stored LOX. The screen will pass liquid, but not gas. When the screen tank is pressurized from the inside, the LOX is forced through the screen and pressurizes the system. When the pressurant valve is opened, nitrogen will pass through a filter and regulators and into the capillary screen. LOX is expelled and passed through the nozzle heat exchanger into the TCAs.

o. Regulated Stored-Gas Feed System with Bladder - System 15 (Fig. III-56) - Similar to Systems 2 and 14, this system replaces the bellows and capillary screen with a flexible-elastic bladder that is enclosed in the LOX tank. The bladder expands as it is filled with gas, which causes the LOX to be expelled. The system is started by opening the nitrogen control valve. Gas flows through a filter and two-staged regulators into the bladder. LOX leaves the tank and passes through the heat exchanger, where it is converted into gas. The gas is then fed into the TCAs.

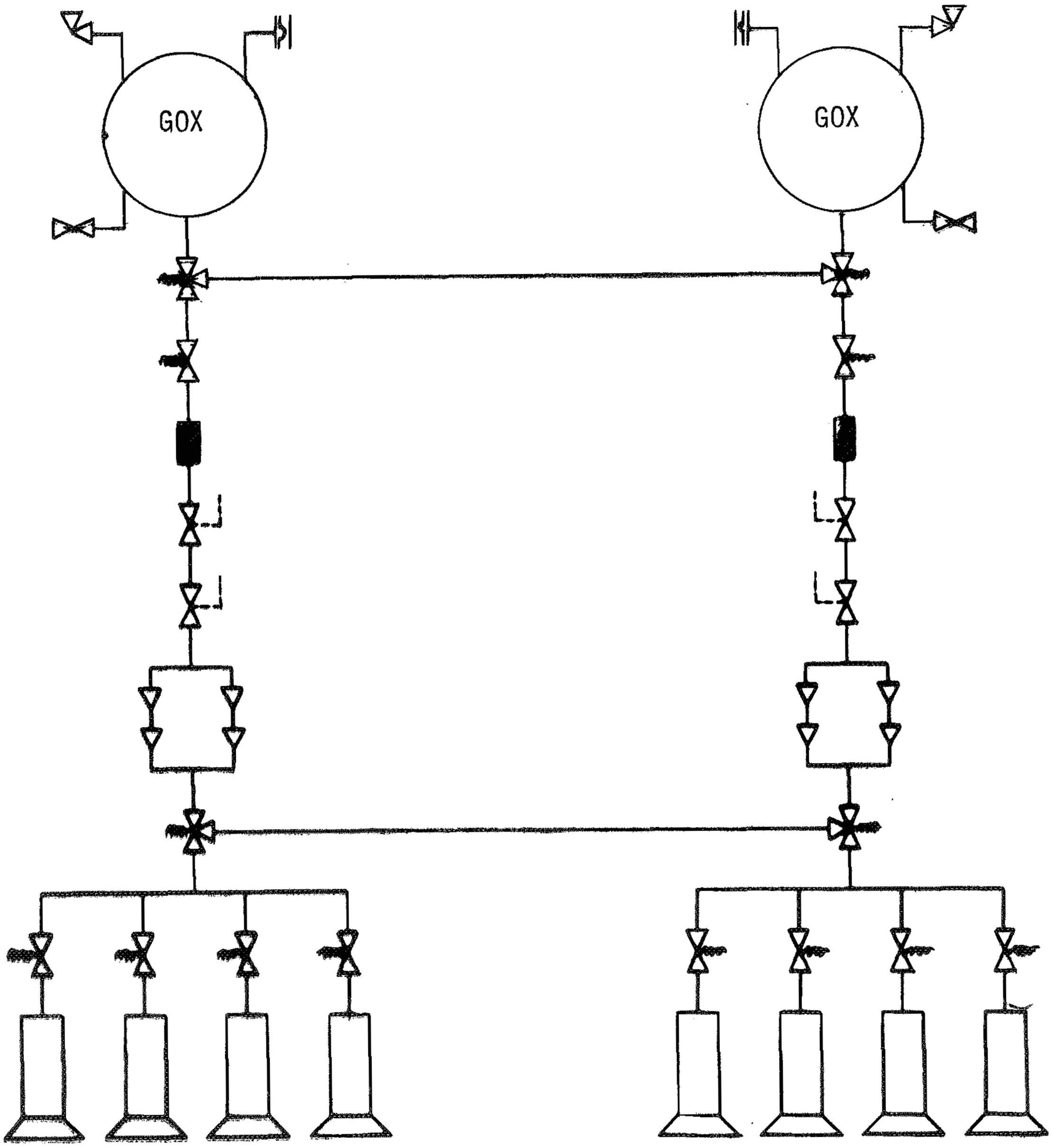


Fig. III-53 Gaseous Oxygen Feed System

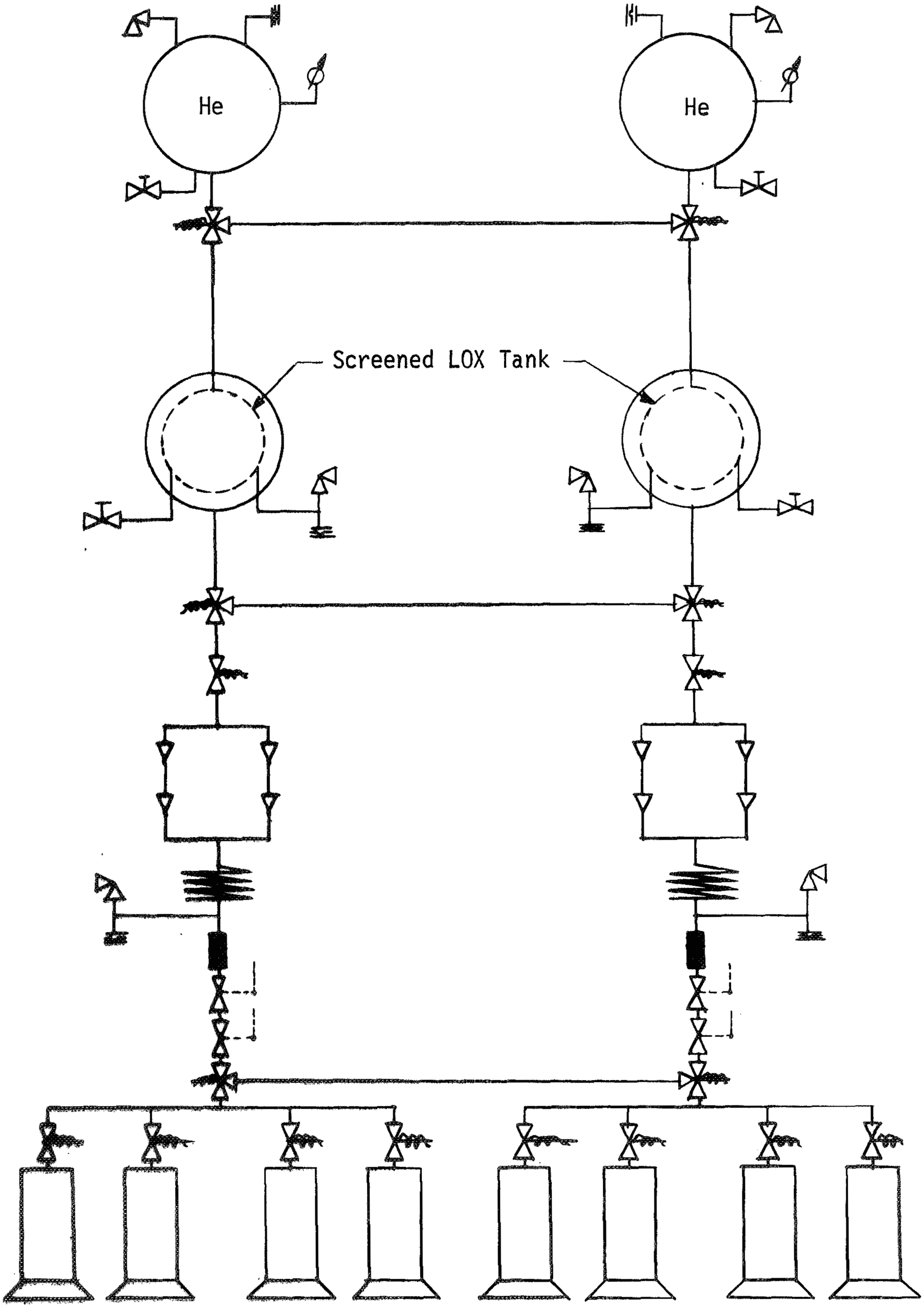


Fig. III-54 Blowdown Stored-Gas Feed System with Capillary Screen

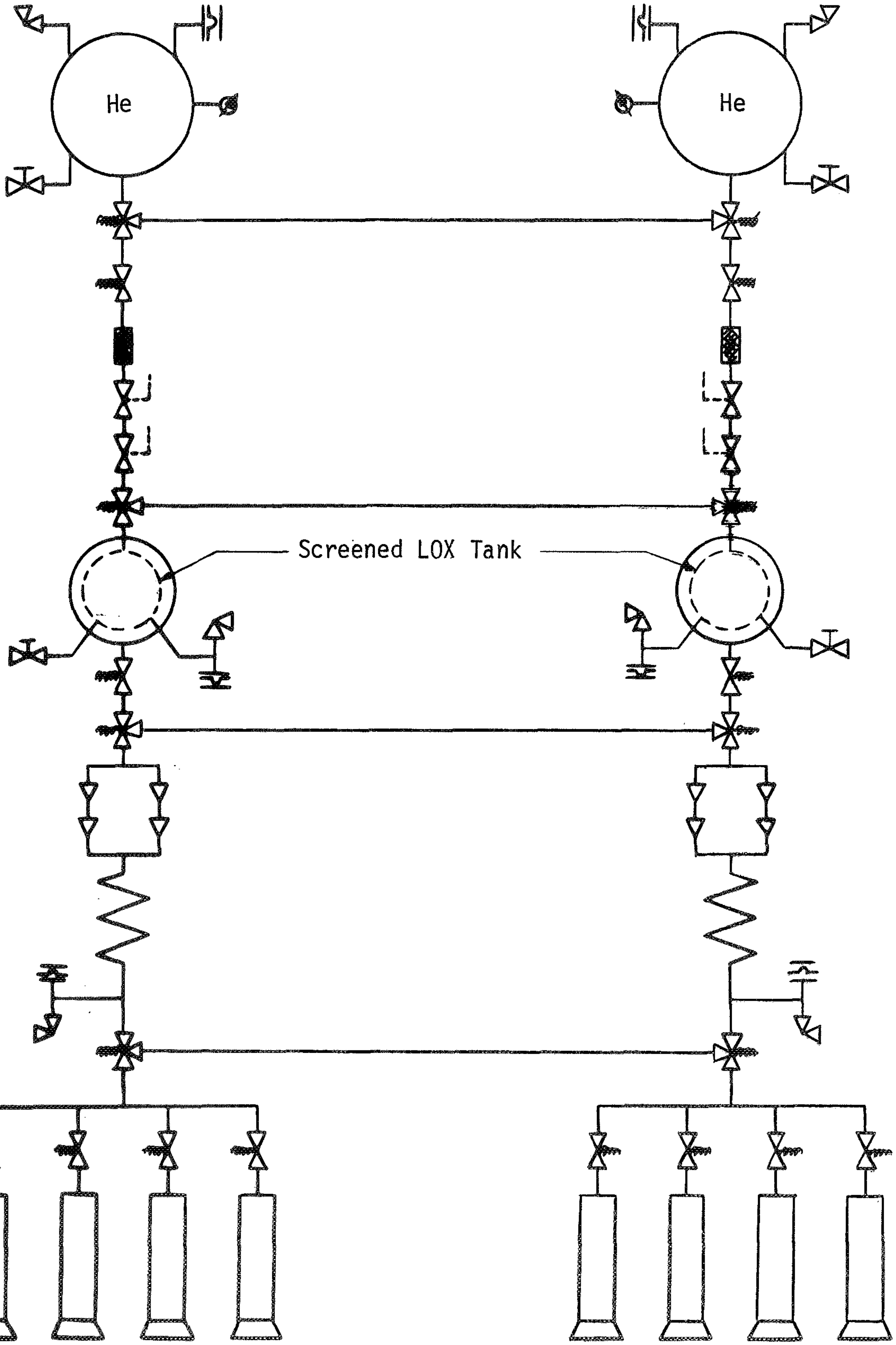


Fig. III-55 Regulated Stored-Gas Feed System with Capillary Screen

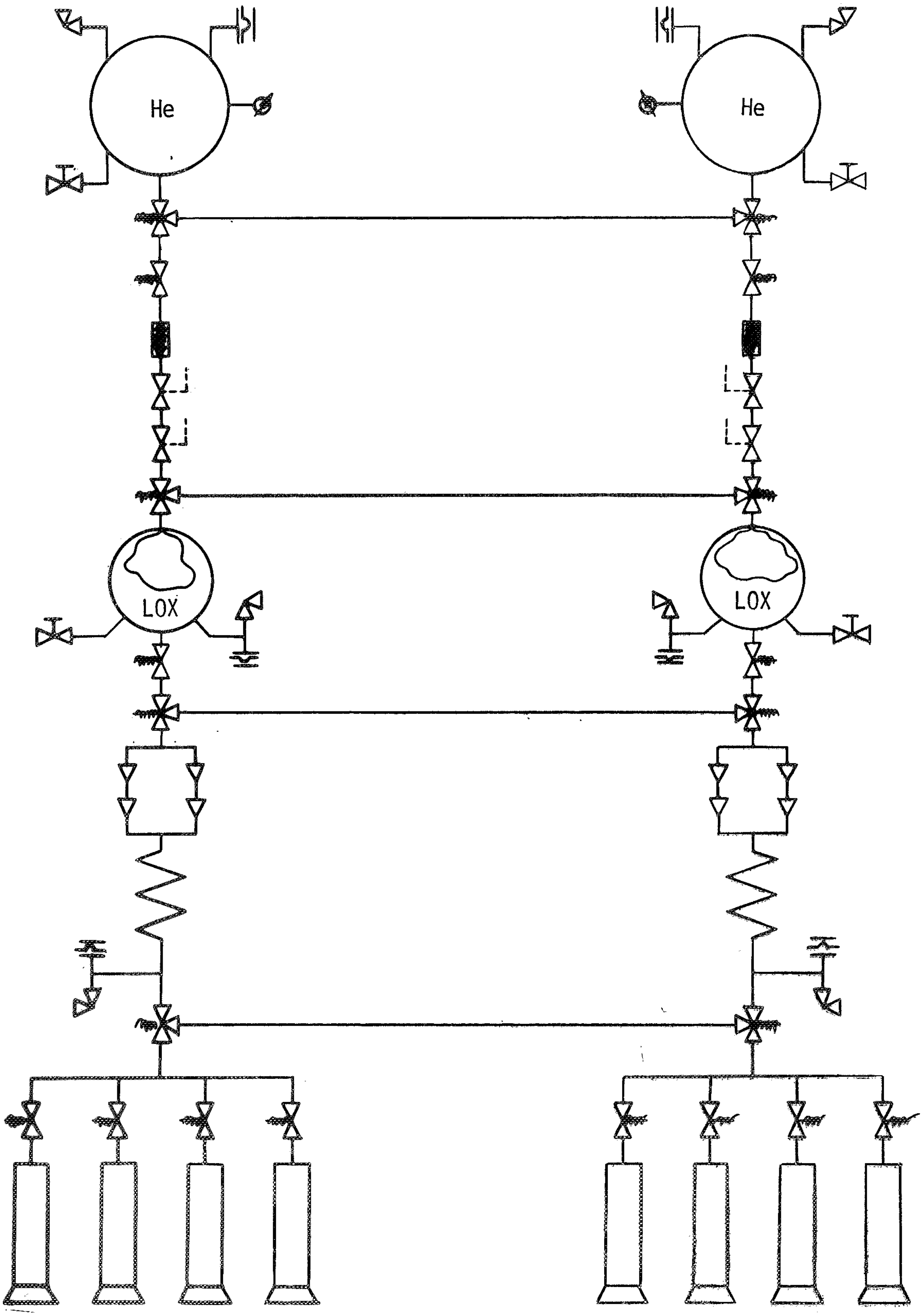


Fig. III-56 Regulated Stored-Gas Feed System with Bladder

p. Blowdown Stored-Gas Feed System with Diaphragm - System 16 (Fig. III-57) - In this system, helium gas is used to pressurize a diaphragm which expels the LOX. Once the LOX is expelled, the propellant tank will be refilled through the fill valve to repressurize the helium pressurant, thereby eliminating pressurant resupply. From the propellant tank, the LOX passes through a quad check valve assembly and into the heat exchanger. The heat exchanger will convert the LOX to GOX, which will be filtered, regulated, and fed into the engine assemblies.

q. Regulated Stored-Gas Feed System with Diaphragm - System 17 (Fig. III-58) - This system is similar to Systems 2, 14, and 15 except that the bellows, capillary screen, or bladder is replaced with a flexible diaphragm. The diaphragm seals off the LOX tank and provides the interface between pressurant and oxidizer. The system is started by opening the helium control valve. Gas flows through a filter and two-staged regulators onto the diaphragm. LOX is expelled from the tank and passes through the nozzle heat exchanger, where it is converted into gas. The gas is then fed into the TCAs.

r. Blowdown Stored-Gas Feed System with Bladder - System 18 (Fig. III-59) - Stored nitrogen pressurizes a bladder within a propellant LOX tank in this system. After the bladder expands and forces the LOX through a quad check valve assembly, the pressurant tank can be refilled by resupplying the LOX tank. This procedure eliminates the need for pressurant resupply. From the quad check valve assembly, the LOX flows through the heat exchanger, is filtered and regulated, and fed into the rocket engine assemblies for combustion.

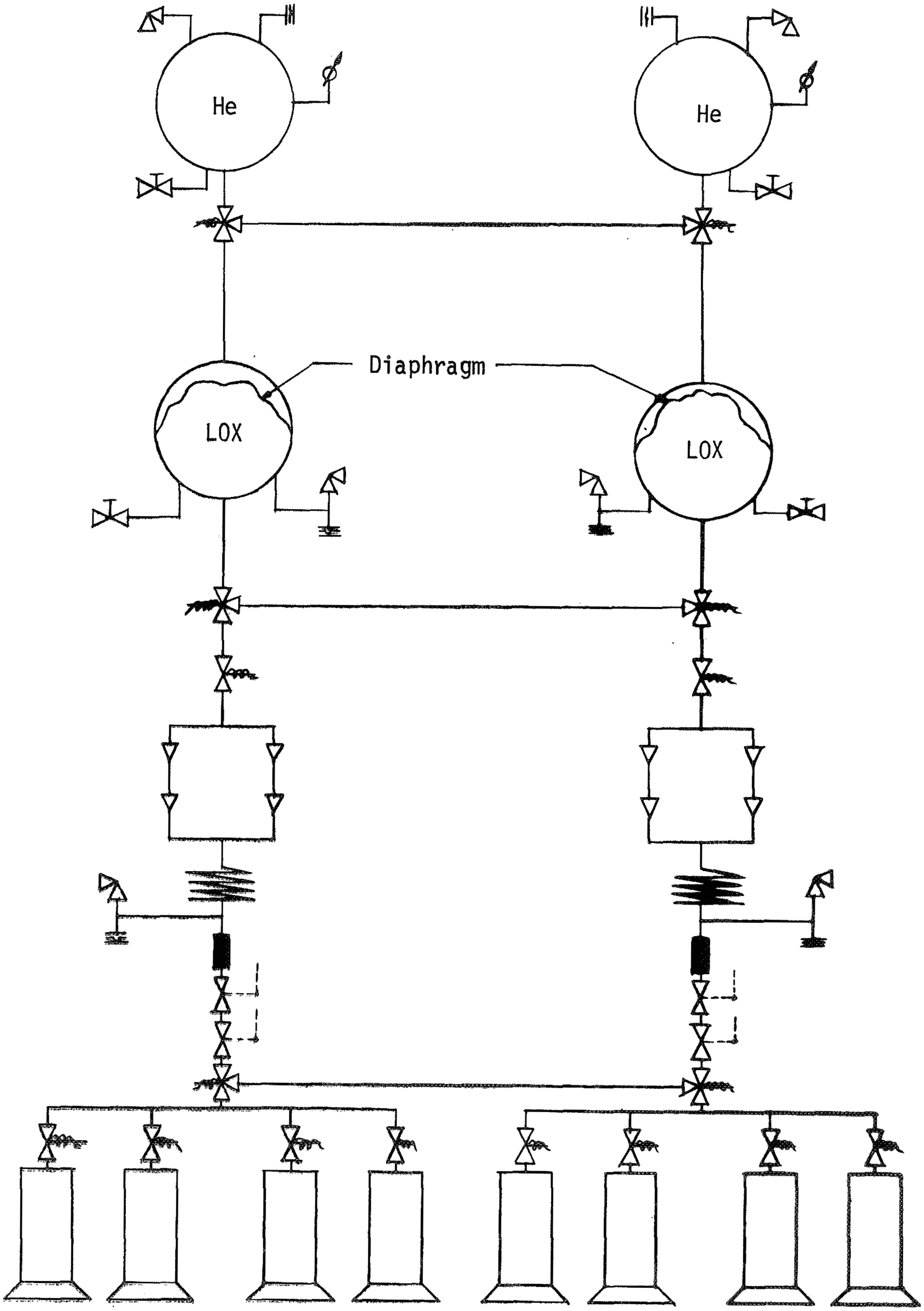


Fig. III-57 Blowdown Stored-Gas Feed System with Diaphragm

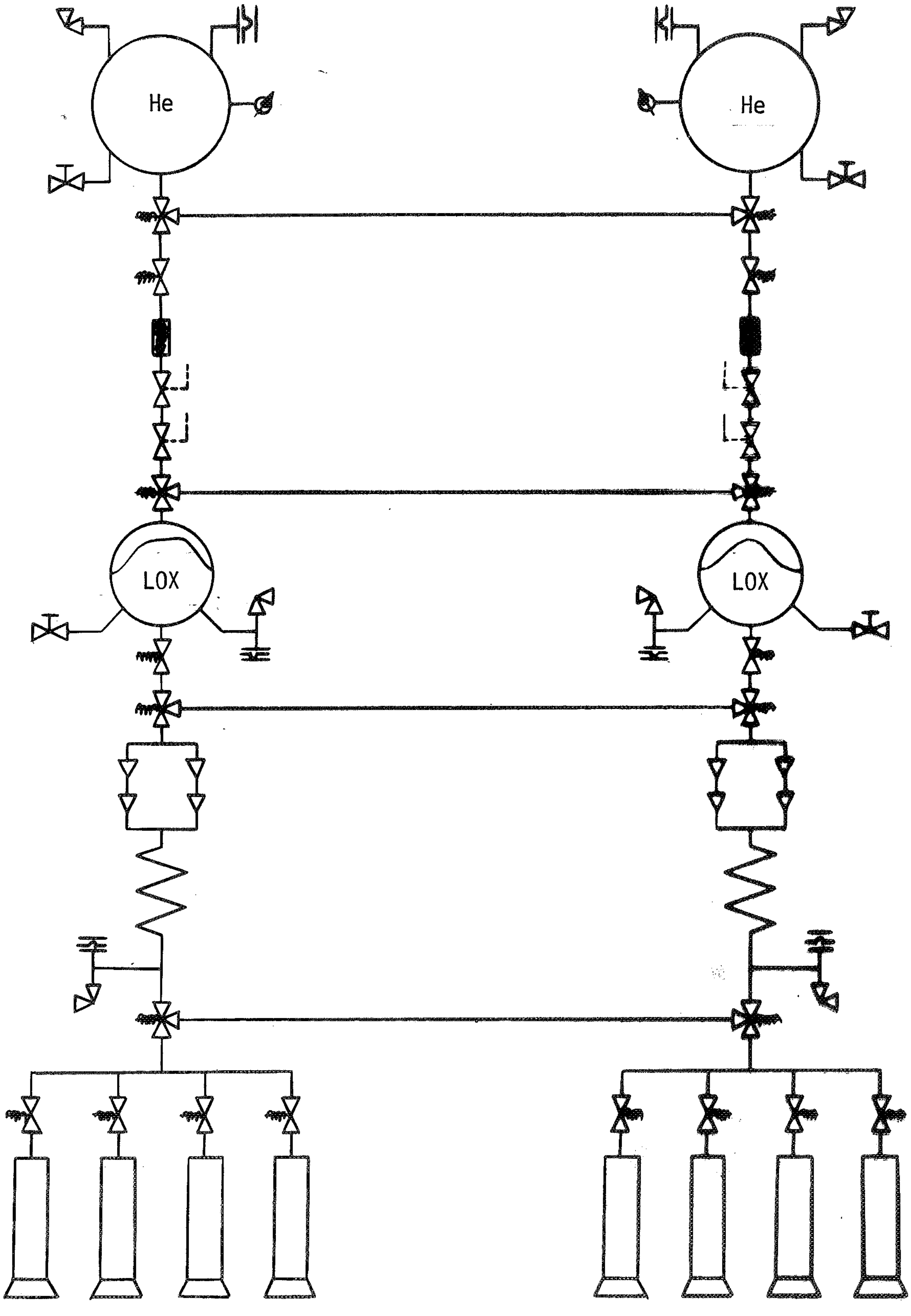


Fig. III-58 Regulated Stored-Gas Feed System with Diaphragm

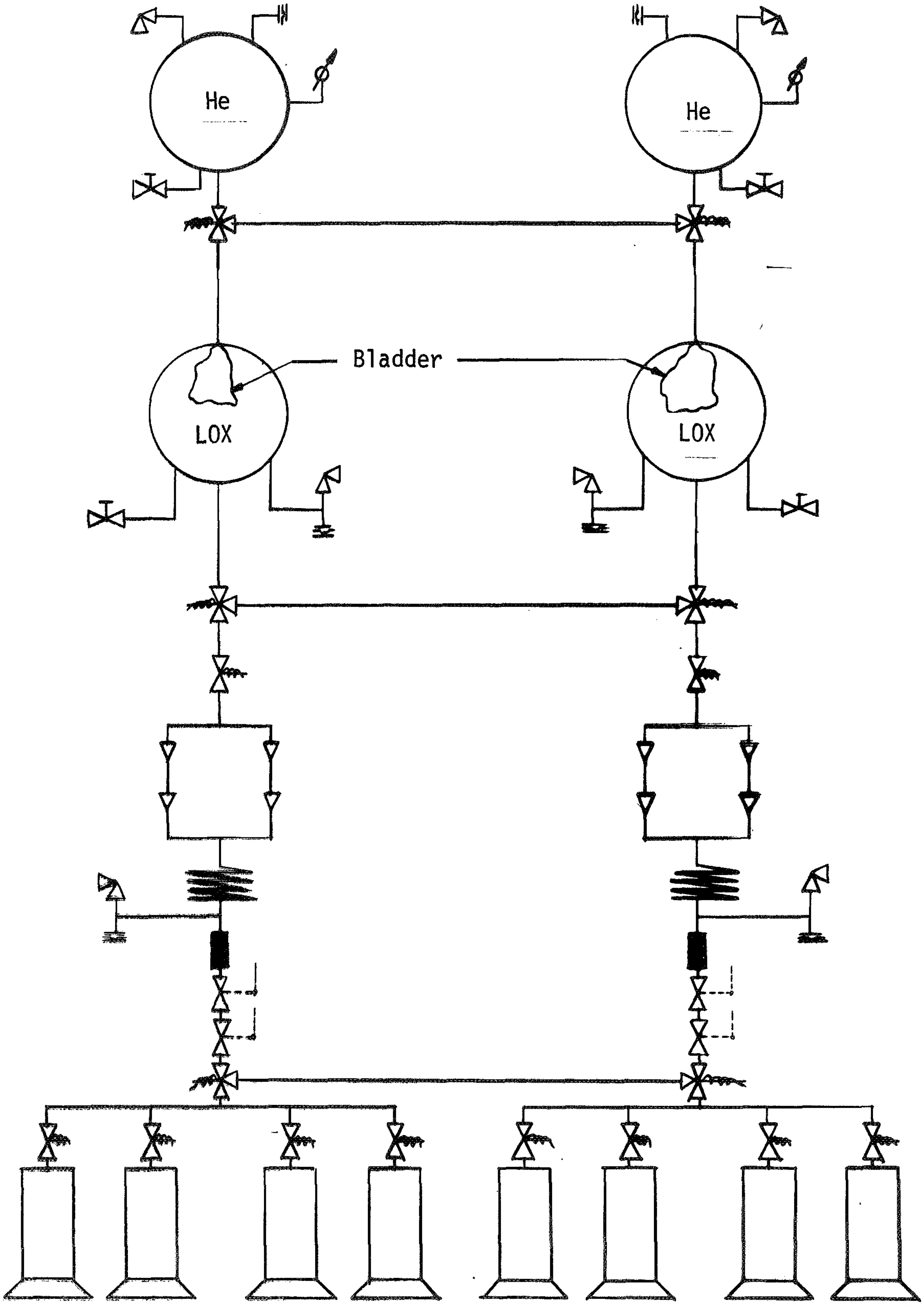


Fig. III-59 Blowdown Stored-Gas Feed System with Bladder

The 10-year mission duration of the Space Station program necessitates resupply, maintenance, and repair to sustain the operation of the hybrid APS. This study and prior studies have confirmed the fact that today's systems do not have the reliability necessary for the 10-year manned space mission. This means that for future, long-duration manned space missions, significant improvements in the capabilities of the various subsystems will be required to attain satisfactory probabilities of mission accomplishment. The projected increase in the reliability of components of the propulsion subsystem will not be sufficient in itself to achieve the overall assurance that is required. In addition, it is impractical to carry sufficient consumable commodities for the entire mission duration. The solution to these problems lies in periodically resupplying, maintaining, and repairing the hybrid propulsion system during orbital operations in a way that has minimum impact on the workload of the crew, while maintaining the hybrid APS in its initial operating state.

Resupply, maintenance, and repair requirements applicable to the propulsion subsystem are typified by the following:

1) Resupply - Normal resupply operations and support will be provided by the Space Shuttle on a nonemergency frequency of every 180 days. The propulsion subsystem can be resupplied by docking and attachment operations employing a freeflying module or special logistics vehicle, or by internal access;

2) Maintenance - Preventive or scheduled maintenance will be performed on a periodic basis to preserve the reliability of the oxidizer feed assembly, ensure successful operations, and prevent inadvertent failures and malfunctions. Maintenance will normally be scheduled for times when crew operations permit, and without necessitating propulsion subsystem shutdown or interruption of mission operations;

3) Repair - This refers to unscheduled maintenance, caused by malfunctions or damage, that must be performed to restore the capability of the hybrid APS, reactivate successful operations, and correct conditions causing degraded performance.

The studies conducted in Task 2 were under the following subtasks:

Subtask No.	Description
1	Candidate System Selection Criteria
2	Failure Modes and Component Reliability
3	Malfunction Detection and Repair
4	Maintenance Requirements
5	Onboard Servicing and Repair
6	Resupply Methods and Procedures

A. CANDIDATE SYSTEM SELECTION CRITERIA

A number of hybrid attitude propulsion systems have been conceived, based on resupply/repair and performance considerations. Each candidate hybrid APS was evaluated against certain selection criteria to determine the optimum system and resupply/repair methods to meet the 10-year operating life of the Space Station.

The selection criteria presented in Table IV-1 were established after consultation with NASA. The requirements for safety and technical status by 1975 are absolute, and no compromise can be made. The remaining selection criteria are listed in their order of importance. The highest rating is given to resupply, which reflects its high cost and complexity.

1. Safety - The degree of safety for each of the propulsion subsystems was determined in relation to the Space Station, mission success, and the crew members. The safety of repairing, resupplying, and operating was also determined;

2. Status of Technology - The "state-of-the-art" for each individual propulsion subsystem was compared and the development risk for its integration into the Space Station was determined. For a subsystem to be considered, all development must be complete by 1975;

3. Resupply - The resupply requirements for each individual propulsion subsystem were analyzed and the resupply of

Table IV-1 Space Station APS Selection Criteria and Order of Importance

PRIORITY	ITEM	WEIGHTING FACTOR
1	Safety	Absolute
2	Technical Status in 1975	Absolute
3	Resupply Requirements	20
4	Maintainability & Repair	15
5	Crew Requirements	15
6	Commonality	10
7	Onboard Equipment Requirements	10
8	Reliability	10
9	Space Station Interface Potential	5
10	Performance	5
11	Weight	5
12	Growth Potential	3
13	Cost	2
		100

propellants and pressurants was evaluated. Necessary transporting equipment and additional tankage weight for fuel and pressurant resupply were considered. The additional weight due to spares carried onboard for resupply requirements was also included in the system weight. The individual components of each concept were evaluated, and it was determined which components will need to be resupplied and at what time intervals. From the component resupply requirements, a spares inventory was determined for those components needing resupply. Crew commitment for the resupply procedures for each concept was analyzed;

4. Maintainability and Repair - Maintenance and repair requirements for each concept were determined;

5. Crew Requirements - Each subsystem was screened and its crew commitments determined. Crew timelines were established for performing scheduled and unscheduled maintenance, resupply, and repair of the feed system, and for reading system monitoring devices;

6. Commonality - Each concept was analyzed to determine its commonality of standardization within the system or with other systems onboard the Space Station. All concepts were essentially the same from this standpoint;

7. Onboard Support Equipment and Tooling - The onboard support equipment and tooling required for each propulsion subsystem was determined. This equipment was essentially the same for all concepts;

8. Integration Potential with Space Station - Each subsystem was analyzed to determine its degree of integration potential with the Space Station. All concepts were rated the same;

9. Reliability - A reliability analysis was conducted for each concept;

10. Performance - The performance of each concept was evaluated;

11. Weight - A weight analysis was performed for each candidate. First, the individual components for each system were considered and their respective weights were determined. Then a total system weight for the concept was tabulated and used for the analysis;

12. Growth Potential - Each subsystem was analyzed to determine the areas where new technology expansion exists;

13. Cost - The projected costs of each candidate were considered.

B. FAILURE MODES AND COMPONENT RELIABILITY

Malfunction detection, maintenance, repair, and resupply requirements for candidate hybrid components depend on the number and type of failure modes for each component. Furthermore, a consistent set of reliability numbers is required for a comparative evaluation of candidate design approaches.

1. Failure Mode Analysis of Hybrid TCA Components

Predicted failure modes for the hybrid TCA are listed in Table IV-2 for each candidate design component. These failure modes are related to the time of occurrence (i.e., during operation, while on standby, or during refurbishment) because this time affects the selected malfunction detection, maintenance, and repair procedures.

2. Component Reliability Analysis for the TCA

The component reliability analysis provides a comparison between different component design approaches and indicates which subcomponents have high failure rates.

Component reliability numbers were generated for each design for 2.4-year and 10-year operation. Based on the estimated 10-year APS total impulse of 6,568,508 N-sec $\left(1,476,660\ \mathrm{lb_f\text{-}sec}\right)$, and using 16 GOX/(PMM/PBD) motors operating at O/F = 2.4, P_c = 689 kN/m^2 (100 psia) with grain replacement at 98,528 N-sec $\left(22,150\ \mathrm{lb_f\text{-}sec}\right)$ of total impulse, the average grain replacement interval would be 2.4 years and the maximum operating time without refurbishment would be 10 years. Table IV-3 lists the predicted reliability for each component for the 2.4-year and 10-year design lifetimes.

Table IV-2 Hybrid APS Component Failure Modes

DURING MOTOR OPERATION

Grain Failures

- Failures Common to all Grain Designs
    - (Grain Is Completely Consumed)
- Failures of Segmented Grain
- Failures of Moving Fuel Grain
    - Grain Binds
    - O-Ring Seal on Grain Fails

Ignition Failures

- Failures Common to all Ignition Designs
    - Electrical Cable & Interface Malfunction
    - Oxidizer Control Valve Jammed Closed
- Failures of Butane or Propane-Initiated Precombustor
    - Malfunctioning Spark Plug (Not Firing)
    - Trip Valve Jammed Open, Jammed Closed, or Leaking
    - Canister Completely Discharged
- Failures of Pyrogen Hot Gas Igniter
    - Pyrogen Igniter-to-Chamber Seal Failure
    - Faulty Initiator Squib
- Failures of Electrically Heated Oxidizer Line Precombustor
    - Capacitor Failure
    - Heater Tungsten Element Burned Out
    - Open in Electrical Control Circuit of Heater
- Failures of Spark-Initiated Precombuster
    - Flow Splitter Valve Closed
    - Precombuster Grain Completely Consumed
    - Faulty Spark Source

Motor Failures

- Failure of Forward Closure Seal
- Failure of Aft Closure (Burnthrough)
- Failure of Nozzle
    - Throat Erosion or Burnthrough
    - Exit Cone
- Oxidizer Injection Nozzle & Tube Broken or Eroded
- Oxidizer Valve Fails to Close or Closes prematurely

DURING STANDBY

- Leakage around or through Oxidizer Control Valve
- Leaking Quick Disconnect
- Breakdown of Outer Skin Environment Seal
- Leakage around or through the:
    - Propane or Butane Canister
    - Trip Valve
- Leakage of Forward Closure Seal
- Electrical or Instrumentation Failure

DURING MOTOR REFURBISHMENT

Forward Closures

- Failures Common to All Forward Closures
    - O-Ring Seal Failure
    - Closure Binds on Assembly & Disassembly
- Snap Ring Connection
    - (Broken Snap Ring Pliers)
- Double Bayonet Flange
    - Broken Bayonet Ring
    - Broken Installation & Removal Tool
- Bayonet Screw
    - Screw Thread Failure
    - Bayonet Flange Failure
- Pin
    - Pin Jammed
    - Pin Retainer Strap or Wire Damaged
- Bolted Flange
    - Screw Thread Failure
    - Elongated Bolt Holes

Refurbishment Concepts

- Movable Tube Concept
    - Failure of Sliding Door Seal
    - Failure of Refurbishment Tube Seal
    - Failure of Retraction & Extension Mechanism
    - Jammed Sliding Door
    - Buckling of Refurbishment Tube
    - Failure of Three-Way Valve Controlling Pressure Inside Refurbishment Tube
- Parallel Transfer Concept
    - Failure of Outer Door Seal
    - Failure (or Binding) of Turning Motor & Mechanism
    - Failure (or Binding) of Raising or Lowering Motor & Mechanism
    - Failure of Three-Way Valve Controlling Pressure Inside Refurbishment Chamber
- Nozzle Cap Concept
    - Failure of Cap Seal
    - Failure (or Binding) of Cap Holding Mechanism
    - Failure (or Binding) of Cap Extension or Retraction Mechanism
    - Failure of Cap Extension Seal
    - Failure of Motor Pad Seal
    - Failure of External Motor Seal

Table IV-3 Component Reliability Predictions

COMPONENT	RELIABILITY	
	2.4 yr	10 yr
Ignition System		
Spark-Initiated Precombustor	0.9311	0.7380
Electrically Heated Oxidizer Line	0.9409	0.7705
Pyrogen Hot Gas Igniter	0.9749	0.8940
Butane Precombustor	0.9506	0.8040
Fuel Grain Configuration		
Single Port Grain	0.996	0.987
Segmented Grain	0.992	0.983
Moving Fuel Grain	0.982	0.973
Multiport Grain	0.982	0.946
Forward Closure Concepts		
Snap Ring (Tru-Arc)	0.984	0.932
Double Bayonet Flange	0.826	0.439
Bayonet/Screw Connection	0.828	0.455
Pin	0.984	0.932
Bolted Flange	0.989	0.935
Motor Refurbishment Concepts		
Movable Tube	> 0.9999	> 0.9999
Parallel Transfer	> 0.9999	> 0.9999
Nozzle Cap	0.9994	0.9920
External Cover	0.996	0.977
External Clam Shell	0.983	0.886

The following recommendations are based on the reliability analysis:

1) Active redundant carbon seals should be used in the moving grain concept to reduce the failure rate to an effective 0.371×10^{-6}/hr, based on a 2.4-year life;

2) Redundant oxidizer pressure regulators should be used for each thruster pad;

3) Manual 3-way valves have a failure rate of 4.4×10^{-6}/hr. Therefore, these valves should be checked before each motor refurbishment to reduce failures;

4) Redundant seals should be used to achieve high reliability, as shown below:

Life	Reliability of Static Seals	Reliability of Dynamic Seals
2.4 years	0.99992	0.9995
10.0 years	0.999	0.993

Because of the short (18-month) life of the spin/despin motors, they would probably not require redundant seals.

3. Failure Mode Analysis of the Oxidizer Feed System

The major sections of the proposed oxidizer feed assembly (OFA) were studied to determine what failure modes were most likely to occur, describe the possible or most likely causes for each assumed failure, determine the effect on the assembly, describe redundant or alternative modes of operation that enable the system to continue the mission, and establish failure classifications. The failure classifications are defined as follows:

1) Catastrophic Failure (Class 1) - Single failures that are potentially fatal and that would probably result in the loss of the craft due to a complete loss of function;

2) Critical Failures (Class 2) - Hazardous conditions during any phase of flight that can be corrected or adjusted either by crew action or by an automatic repair process;

3) Noncritical Failures (Class 3) - Failures that either degrade performance or require a special operating technique;
4) Minor Failures (Class 4) - Failures that require corrective maintenance, but do not degrade performance.

The major sections of the OFA were also given one of the following criticality rankings:

1) Not Likely - The reaction time is unlimited or has no major impact either on mission success or on the safety of the crew;
2) Likely - The reaction time is limited or may be critical for mission success if not uncompensated for;
3) Highly Likely - The reaction time is critical or the uncompensated effect is catastrophic.

The results of the failure mode analysis for the OFA are presented in Table IV-4.

4. Component Reliability Analysis for the Oxidizer Feed Assembly

The reliability of the proposed OFA was determined for a 1-year period. First, the reliability of each component making up the OFA was then calculated, based on its operational and nonoperational times, using

$$R_{\text{component}} = R_{\text{operational mode}} \times R_{\text{nonoperational mode}},$$

where

$$\text{Reliability} = e^{-\lambda+kt}$$

and

λ = Failure rate;

t = Time;

k = Operational factor.

Table IV-4 Failure Modes for the Oxidizer Feed System

SYSTEM FUNCTION	FAILURE TYPE	FAILURE CAUSE	EFFECT ON SYSTEM	COMPENSATING PROVISIONS	FAILURE CLASSIFICATION	CRITICALITY
He Pressure Supply Function	Leakage	Material & Weld Imperfection, Vibration-Induced Fatigue, Loose from Vibration	Gradual Loss of He Gas, Hence Incomplete Expulsion of Oxidizer	Redundant Helium Pressure Supply	Critical	Failure Not Likely, Time Is Limited
	Rupture	Material or Weld Imperfection, Micrometeoroid Penetration, Inadvertent Overpressurization	Loss of Feed Pressure	Redundant Helium Pressure Supply, Open Valves to Feed Propellant to Engines from Good Leg	Critical	Failure Not Likely, Reaction Time Critical
He Pressure Control Function	Leakage	Material & Weld Imperfection, Vibration-Induced Fatigue, Loose from Vibration	Gradual Loss of He Gas, Hence Incomplete Expulsion of Oxidizer	Redundant Helium Pressure Supply	Critical	Failure Not Likely, Time Is Limited
	Shutoff Valve Fails Closed	Faulty Electric Circuit, Damaged Valve Coil	None (Redundant Valves)	Redundant Shutoff Valves	Critical	Failure Not Likely, Time Is Limited
	Pressure Regulator Fails Open	Faulty Spring or Particle Contamination	None (Redundant Regulator)	Redundant Regulator in Series Will Control Pressure	Critical	Failure Not Likely
	Check Valve Fails Open	Faulty Spring or Particle Contamination	None (Redundant Check Valves)	Redundant Check Valves	Critical	Failure Not Likely
Oxidizer Supply Function	Leakage in Supply Tank	Material or Weld Imperfection	Loss of Oxidizer	Replace	Critical	Failure Not Likely

The total impulse required during the 1-year period is 905,000 N-sec $\left(204{,}700\ \mathrm{lb_f\text{-}sec}\right)$. The operational time (for any particular pair of thrusters) is 905,000 N-sec/445 N, or 0.567 hr. For the operational mode, $k = 1$; for the nonoperational mode, $k = 0.1$. The failure rates were obtained from the *Handbook of Piece Part Failure Rates*. The lower extreme generic failure rates were used because they provide the best possible reliability. The generic failure rates of the individual oxidizer feed assembly components are tabulated in Table IV-5. Table IV-6 gives the individual reliabilities of the components for 1 year.

Once the reliability of the individual components was known, we determined the reliability of the entire oxidizer feed system using

$$R_{\text{system}} = \left(R_{\text{component 1}}\right)\left(R_{\text{component 2}}\right) \cdot \cdot \cdot \left(R_n\right).$$

The reliability of the selected OFA, without redundancy, is 0.8791. To include redundancy, the reliability equation becomes:

$$R_{\text{redundancy}} = e^{-\lambda t}\ (1 + \lambda_1 t_1),$$

where

$e^{-\lambda t}$ = Reliability of system without redundancy;

λ_1 = Overall system failure rate;

t_1 = Total time.

With redundancy included, the reliability of the OFA for 1 year was 0.9924.

C. MALFUNCTION DETECTION AND REPAIR

1. Reasons for a Malfunction Detection System

A malfunction detection and fault isolation system performs three basic functions for a Space Station APS. It assures crew safety, maximizes mission effectiveness, and significantly reduces the frequency and complexity of inflight maintenance.

Table IV-5 Generic Failure Rates of Oxidizer Feed Assembly Components

COMPONENT	LOWER EXTREME, GF_r*
Low-Pressure Helium Tank	0.039
Burst Disc	0.54
Relief Valve	3.27
3-Way & 4-Way Valves	1.87
Annular Screen	1.40
Low-Pressure Tank Shell	0.10
Pressure Transducer	23.20
Control Valve	1.68
Filter	0.045
Quad Check Valve	0.0122
Control Regulator	0.70
Transfer Valve	0.26
Quick Disconnect	0.09
Lines & Fittings	0.05

*Failures/10^6 hr.

Table IV-6 Component Reliability of Oxidizer Feed Assembly (1-yr Period)

COMPONENT	RELIABILITY		
	OPERATING	NONOPERATING	TOTAL
Low-Pressure Helium Tank	0.9999		0.9999
Relief Valve	0.974		0.974
Fill Valve	0.9999	0.9999	0.9998
Pressure Transducer	0.816		0.816
3-Way & 4-Way Valves	0.9837		0.9837
Annular Screen	0.9878		0.9878
Small Pressure Tank	0.9999		0.9999
Control Valve	0.9853		0.9853
Quad Check Valve	0.9999	0.9999	0.9998
Relief Valve	0.9999	0.9971	0.9970
Filter	0.9999	0.9999	0.9998
Regulator	0.9999	0.9999	0.9998
3-Way Valve	0.9999	0.9984	0.9983
Burst Disc	0.9956		0.9956
Burst Disc	0.9999	0.9999	0.9998
Quick Disconnect	0.9999	0.9999	0.9998
Lines & Fittings	0.9999		0.9999
System Structure	0.9999		0.9999

Safety is a primary consideration for a Space Station APS. Detection equipment must be provided for any failure modes that, if ignored, could result in injury to the crew. This requirement establishes the need for and the minimum extent of an MDS.

An MDS can also significantly improve the mission effectiveness of the Space Station. Prompt and accurate warning of failures that affect the performance of the APS will enable the crew to take effective action to maintain full capability. This will ensure that all auxiliary maneuvers are completed as planned and on schedule.

In addition, an MDS can be used to analyze performance trends and detect impending failures, thus reducing maintenance and resupply because small or impending failures are detected before any appreciable damage is done to the system. Detection of impending failures also allows the work to be performed during scheduled maintenance periods or at times of reduced crew workload.

2. Optimum Level of Complexity for a Malfunction Detection System

The complexity of the malfunction detection and fault isolation equipment depends on the highest failure level at which detection is required (see Table IV-7). The MDS must reliably detect a failure, isolate the component responsible for the failure down to the lowest selected replacement level, and prominently display the results to the crew so appropriate action can be taken. The malfunction detection, isolation logic, and display panels are single-function equipment whose space, weight, power requirements, maintenance, etc, must be directly charged to the APS. Therefore, a realistic assessment must be made to compare the benefits of an increased detection capability with the resulting increased equipment penalty incurred.

The complexity of automatic monitoring and control equipment runs parallel to the level of malfunction detection and display. As detection requirements increase, the crew will not, in general, be capable of reliably responding to all APS failures while still performing their other duties. Although output from the MDS could be relayed to ground control, this is undesirable for several reasons. First, ground communication links can fail, leaving the Space Station and crew in a tenuous position. Furthermore, the Space Station will develop procedures to be used for planetary missions where autonomous operation is required; therefore, a sophisticated MDS will require an automatic monitoring and control system (AMCS).

Table IV-7 Failure Categories in Malfunction Detection System

FAILURE CLASS	DESCRIPTION	DETECTION CAPABILITY	AUTOMATIC CONTROL
1	Critical Malfunctions That, If Ignored, Could Damage Space Station or Result in Injury to the Crew	Detect & Display All Critical Failures, & Identify Failed Component	Automatic Shutdown for All Critical Failures
2	Malfunctions That Seriously Degrade the Performance of the ACS &, If Ignored, May Become Critical Failures	Detect & Display Performance Characteristics & Other Class 2 Failure Information	Automatically Monitor Performance & Other Class 2 Variables. Take Appropriate Preprogrammed Action, e.g., Switch to Alternate Motor If Operating, or Take Motor Off Line If on Standby
3	Noncritical Failures That Do Not Seriously Affect Motor Performance but Could Progress to a Higher Order Failure	Detect & Display All Information Needed to Determine Class 3 Failures	Automatically Monitor All Class 3 Information & Analyze Trends to Predict Time of Failure & Schedule Maintenance
4	Motor Refurbishment Failures That Do Not Affect Motor Performance or Crew Safety	Most Failures, e.g., Jammed Door, Require No Detection Equipment. A Pressure Gage Is Sufficient for Most of the Rest	Generally Not Required or Necessary

An AMCS for Class 1 failures would provide automatic shutdown. For Class 2 failures, it could be programmed to take several courses of action, depending on the type and degree of failure and the condition of the motor (e.g., operating, on standby, etc) at that time. Class 3 automatic control would require the AMCS to provide trend analysis for all possible failures, predict the time of the failure, schedule corrective maintenance, and perform all Class 1 and 2 automatic functions. Since Class 4 failures are all noncritical and occur during refurbishment, no automatic control should be required.

Automatic monitoring and control equipment for the APS can be integrated into the overall Space Station AMCS. Although this will allow some commonality in the computational and interface equipment, the degree of commonality will depend on a number of factors, and could be quite low if the Space Station AMC requirements are high during attitude control maneuvers. Therefore, the level of automatic control will depend on the level of MDS capability selected, on the crew time required to monitor the displays, and on the cost of providing an AMCS in terms of space, weight, and maintenance.

3. Candidate Malfunction Detection Methods

Candidate malfunction detection methods for the four ignition systems are outlined in Table IV-8.

a. Failures during Ignition - All ignition failures are Class 2 because they prevent motor ignition and thereby seriously affect motor performance. None are capable of becoming Class 1 failures.

An oxidizer control valve failure could be detected by a valve position indicator or by a pressure gage in the injector or the chamber. The valve position indicator is preferred since it provides the simplest and most positive indication of valve failure.

The propane-initiated precombustor can malfunction due to a defective spark source or trip valve, or due to a depleted propane supply. The spark plug and induction coil could be checked by measuring induced voltage and current, the trip valve could be checked by a position indicator, and the butane supply could be monitored by a pressure gage.

Table IV-8 Malfunction Detection and Repair during Motor Ignition

COMPONENT FAILURE	FAILURE CLASS	SYMPTOMS	CANDIDATE DETECTION METHODS	CANDIDATE REPAIR PROCEDURES
Oxidizer Valve Fails Closed	2	Motor Fails to Ignite	• Valve Position Indicator* • Injection Pressure Transducer • Chamber Pressure Transducer	Remove and Replace Valve: • Discard • Send to Repair Shop & Refurbish If Possible
Butane Initiated Precombustor				
• Defective Spark Plug/ Induction Coil	2	Motor Fails to Ignite	Induced Voltage & Current Check	Remove, Discard, & Replace
• Malfunctioning Trip Switch	2	Motor Fails to Ignite	Valve Position Indicator	Remove & Replace: • Discard • Repair If Possible
• Depleted	2	Motor Fails to Ignite	• Butane Pressure Gage* • Visual Check • Ignition Counter	Remove & Discard Expended Butane Can; Replace with New Can
Pyrogen Hot Gas Igniter				
• Faulty Squib	2	Igniter Fails to Fire; Motor Fails to Ignite	Continuity Check	Replace Squib
• Premature Igniter Firing	2	Igniter Fires into Inert Fuel Grain	Chamber Pressure Transducer Followed by Squib Continuity Check	Replace Igniter
Electrically Heated Oxidizer Line				
• Tungsten Heater Burned Out	2	Motor Fails to Ignite	Resistance & Current Check	Replace Heating Element
• Capacitor Failure	2	Motor Fails to Ignite	Voltage Check	Replace & Discard Old Capacitor
Spark-Initiated Precombustor				
• Flow Splitter Valve Closed	2	Motor Fails to Ignite	• Valve Position Indicator	Remove & Replace Valve: • Discard • Repair If Possible
• Depleted Precombustor Fuel Grain	2	Motor Fails to Ignite	• Trip Wire	Remove & Replace Precombustor Fuel Grain
• Spark Source	2	Motor Fails to Ignite	• Precombustor Thermocouple • Induced Current & Voltage Check	Remove & Replace

*Preferred method.

The pyrogen hot gas igniter has two failure modes -- a faulty squib (which can be determined by a continuity check) and a premature ignition (which can be detected by a chamber pressure pulse and confirmed by a squib continuity check). The igniter supplies warm fuel-rich products that combine with the oxygen during ignition. A premature firing will have no effect on the inert fuel grain.

The electrically heated precombustor oxidizer line can malfunction due to a burned out tungsten element or a capacitor failure. The tungsten element will be partially consumed during each ignition. This process can be monitored by periodic resistance checks, and the gas heating can be evaluated by measuring current and calculating i^2R during capacitor discharge. Capacitor integrity and energy storage can be determined by a voltage check.

The spark-initiated precombustor is a small hybrid gas generator that supplies warm, fuel-rich gases to burn with the main oxidizer flow. The precombustor grain is small enough to ignite with a spark. Possible failure modes include a malfunctioning flow splitter valve, a depleted precombustor fuel grain, and a faulty spark source. A valve failure could be detected by a position indicator, a depleted fuel grain could be identified by a trip wire, and a faulty spark source, by a precombustor thermocouple or an induced voltage and current check. The latter is a more precise indication of spark characteristics, but a thermocouple would provide a valuable indication of precombustor operation.

b. Failures during Motor Operation - Malfunction detection methods during motor operation are outlined in Table IV-9. The oxidizer valve can either close prematurely or fail to close, both of which are Class 2 failures. If the oxidizer valve closes prematurely, the motor shuts down early. If the oxidizer valve fails to close, the motor continues firing, requiring the main oxidizer control valve to be closed; to reduce this latter possibility, the oxidizer valve will be designed to fail closed. Both of these failure modes can be detected either by a valve position indicator or by an injection pressure transducer. Detection with a valve position indicator is the preferred method. The injector can be designed for a nearly unlimited life, but some oxidation or erosion may occur and increase the oxidizer flow, thrust, and chamber pressure. This is a Class 3 failure but should be monitored. Measurements of increased thrust and reduced injector ΔP would indicate an eroding injector.

Table IV-9 Malfunction Detection and Repair during Motor Operation

COMPONENT FAILURE	FAILURE CLASS	MOTOR SYMPTOM(S)	CANDIDATE DETECTION METHODS	CANDIDATE REPAIR PROCEDURES
Oxidizer Valve Closes Prematurely	2	Motor Shuts Down Prematurely	-Valve Position Indicator* -Injection Pressure Transducer	Remove & Replace Valve: -Discard* -Repair If Possible
Oxidizer Valve Fails to Close	2	Motor Continued Operating - Close Main Oxidizer Valve		
Injector Erodes	3	Thrust & P_c Increase	-Injection & Chamber Pressure Transducers -Load Cell	-Monitor F & P_c. When Values Reach Predesignated Limit, Remove, Replace, & Discard Injector
Forward Closure Seal Fails	1 (2 on Parallel Transfer Concept)	Automatic Shutdown	-Trip Wire Seal -Thermocouple	-Replace Seal; Replace Forward Closure/ Case If Damaged
Forward Closure Comes Loose	1 (2 on Parallel Transfer Concept)	Automatic Shutdown - Redundant Latch Holds Closure on & Maintains Seal	-Continuity Check	-Resecure Forward Closure; Check for Defective Retention Mechanism
Fuel Grain Depletion (Except Moving Grain Concept)	2	Low Thrust & Low P_c - Automatic Shutdown	-Trip Wire* -Load Cell, P_c & Pin Transducers -Motor Case Thermocouples -E. T. Meter	-Replace Expended Fuel Grain
Moving Grain Concept Grain Jams or Fails to Move	2	Thrust & P_c Fall, Grain May Go Out	-Load Cell, P_c & Pin Transducers -Grain Position Indicator*	-Remove & Inspect Grain
Grain O-Ring Seal Fails	2	Thrust & P_c Rise	-Load Cell, P_c & Pin Transducers	-Replace Seal
Aft Closure Burnthrough	1	Thrust & P_c Fall, Automatic Shutdown	-Load Cell, P_c & Pin Transducers* -Motor Case Thermocouples	-Remove & Replace Motor Case & Nozzle Assembly
Throat Erosion	3	Increased Thrust, Lower P_c	-Load Cell, P_c & Pin Transducers	-Monitor F, P_c, & Pin, Replace Case/ Nozzle Assembly before Throat Burnthrough
Exit Cone Burnthrough	2	Reduced Thrust, Constant P_c	-Load Cell, P_c Transducer* -Thermocouple	-Remove & Replace Motor Case & Nozzle Assembly
Electrical System Failure (Loose Plug, Broken Wire, etc)	2	Valve Power Failure or Open in Grain Depletion Line Will Cause Motor Shutdown	-Continuity & Voltage Checks	-Repair in Place -Replace Forward Closure & Repair Electrical Failure in Onboard Workshop
Pressure System Leaks or Ruptures	2	Gradual Loss of Pressure	-Pressure Transducer	-Remove & Replace during Resupply Since Pressurant Supply Is Redundant
Oxidizer System Leaks or Ruptures	2	Gradual Loss of Pressure	-Pressure Transducer	-Remove & Replace during Resupply Since Oxidizer System Is Redundant

*Preferred method.

A forward closure seal failure or a forward closure retention failure is normally a Class 1 failure. (Class 2 in the parallel transfer concept, since the motor remains outside the Space Station). Either event will result in motor shutdown. A redundant forward closure latch will be provided on all designs to prevent the forward closure from coming loose. Movement of the forward closure would break a contact to signal shutdown. Leaks around the forward closure seal could be detected by a trip wire seal or a thermocouple in the forward closure cover.

Fuel grain depletion is a predictable failure mode based on firing time, although trip wires, motor case thermocouples, and thrust/P_c measurements are more accurate indicators. A trip wire is the preferred detection method since it is a specific fail-safe indication of fuel depletion. Though fuel depletion is a benign failure mode in that it only reduces performance, it is accompanied by rapidly falling thrust and chamber pressure, which are also symptoms of an aft closure burnthrough. In addition, continued operation after fuel is deplete exposes the motor to oxidizer-rich combustion products. Therefore, the motor will be shut down when the trip wire indicates fuel depletion.

The moving grain concept has several additional failure modes. If the grain jams, the oxidizer will not mix properly with the fuel gases. Thrust and chamber pressure may fall, and the grain may eventually be extinguished. A grain position indicator would provide a direct confirmation for this type of failure, and is the preferred detection method. The moving grain is propelled by a pressure drop across the grain, which is maintained by an O-ring seal. If this seal fails, oxidizer can leak around the grain. This will increase motor mass flow, O/F ratio, and aft closure/nozzle boundary layer temperature. Increased thrust and pressure provide the best indication of this failure.

An aft closure burnthrough is the primary Class 1 failure for the hybrid system. Although the chambers can be designed for extended operation and will be replaced after completion of their expected operating life, the possibility of a burnthrough exists. Fortunately, such a failure is readily detectable. The 222-N (50-lb_f) motors have a throat diameter of about 15 mm (0.6 in.) at P_c of 689 kN/m^2 (100 psia). An aft closure burnthrough of this size will halve the chamber pressure and nearly halve the thrust. Therefore, a rapid drop in chamber pressure and thrust will signal an automatic shutdown of the motor.

Two other similar failures are throat erosion and an exit cone burnthrough. Throat erosion can easily be detected by a gradual decrease in chamber pressure and an increase in thrust. This is a Class 3 failure since throat erosion can be monitored and the chamber can be replaced before burnthrough occurs. Exit cone burnthrough will result in decreasing thrust with no change in chamber pressure. Due to the reduced pressure in the exit cone, this is a Class 2 failure. The motor would be shut down if thrust fell below a certain level. Thermocouples on the thruster pad could serve as backup indicators of nozzle or aft closure burnthrough on the underside of the motor.

Electrical system failures would be detected by open or shorted circuits due either to loose plugs or to broken wires. Depending on the circuit, an electrical failure would either shut the motor down automatically or force a shutdown due to the loss of motor performance and malfunction detection information.

Oxidizer and pressurant depletion are predictable, based on tank pressures. Tank leakage or rupture can also be determined from the tank pressure. The use of redundant subsystems makes it possible to isolate the leak or rupture and repair it at a later time.

c. Failures during Standby - Candidate detection methods during standby are outlined in Table IV-10. Leaks are the primary failure modes. Although GOX can leak into the Space Station through several paths, including the quick disconnect, oxidizer valve, and oxidizer line, the total leakage should not appreciably raise the partial pressure of oxygen in the Space Station. Any substantial leak could be detected by a flowmeter in the oxidizer line, an on-site visual bubble test using a leak detection solution, or an auditory check.

If the sparked propane ignition system is selected, a propane leak is possible, which is potentially more serious. Although the amount of propane required for ignition is small and propane is not particularly toxic, the presence of propane in the cabin atmosphere is undesirable. Therefore, a chemical sniffer should be installed in each of the two ACS assembly rooms to check for possible leaks.

In the movable tube and nozzle cap designs, cabin air can leak to space through the forward closure seal or the external motor seal. The former is considerably more serious since it indicates a possible Class 1 failure on the next firing. Since

Table IV-10 Malfunction Detection and Repair during Standby

COMPONENT FAILURE	FAILURE CLASS	CANDIDATE DETECTION METHODS	CANDIDATE REPAIR PROCEDURES
Oxygen Leaks within the Space Station Quick Disconnect Leak Oxidizer Valve Fitting Leak Other Line Leaks	3	● Flowmeter ● Onsite Visual (Bubble Test) or Auditory Check* ● Use Main Oxidizer Valve to Isolate Motors between Tests & a Line Pressure Transducer to Measure Leakage	Noncritical Failure Mode, Check during Scheduled Maintenance
Butane Leak within the Space Station		● Automatic Sniffer* ● Olfactory Check by Crew	Inspect Propane Can & Trip Switch Seals to Isolate Leak; Replace Bad Seal
Cabin Air Leak Past External Motor Seal	3	Vacuum Pressure Gage	Monitor Leak; Replace Seal during Next Grain Replacement or Schedule an Earlier Replacement if Leakage Rate is Too High
Cabin Air Leak Past Internal Motor Seal	2	Vacuum Pressure Gage	Take Motor Off Line & Schedule Seal Replacement
Electrical System Failure (Loose Plug, Broken Wire, etc)	3	Continuity & Voltage Checks	Take Motor Off Line & Schedule Maintenance: ● Repair in Place ● Replace Forward Closure Assembly & Repair Electrical Failure in Onboard Workshop

*Preferred method.

an individual motor may go weeks or months between firings, seal failures will most likely occur during standby. Therefore, each motor could have an electronic vacuum pressure gage (VPG) that would be turned on during standby to measure the hardness of vacuum (down to 10^{-3} torr or lower) inside the chamber (to detect forward closure seal failures) and possibly in a labyrinth seal outside the external motor seal. Based on the extremely low failure rates for the motor seals, a VPG is probably not justified for the external motor seal. However, the absolute safety requirement makes a VPG advisable for the motor seal. Electrical system failures during standby can be detected by voltage and continuity checks.

Malfunction detection of the oxidizer feed assembly is based on automatic pressure monitoring. Pressure transducers located downstream of the pressurant spheres, downstream of the check valve assembly, and downstream of the vaporizer assembly permit isolation of the failure, as well as activation of the proper crossover valves to compensate for a failure. System condition is indicated on a control panel (Fig. IV-1) that consists of an assembly schematic with warning lights for all major portions or modules of the assembly. Three warning lights are associated with each module: green for the operating path; white for standby; and red for a failure.

d. Failures during Motor Refurbishment - Candidate malfunction detection methods during motor refurbishment are outlined in Table IV-11.

Movable tube refurbishment failures involve seal failures around the motor, door, and refurbishment tube -- all of which are detectable by a pressure gage on the refurbishment container -- and jammed door or retraction mechanisms, which are obvious without automatic detectors.

Parallel transfer concept failures include outer and inner door seal failures, which are detectable with a pressure gage, and failures of the motor pad retraction or rotation mechanisms, which are detectable by a visual check via portholes or by a position indicator; a visual check is preferred.

The nozzle cap approach has five potential seal failures and a potential jamming of the cap extension mechanism. Failures of the nozzle cap seal and cap holding mechanism are detectable by a cap pressure gage; seal failures on the cap extension mechanism, the motor pad, and the external motor seal are all detectable by a vacuum pressure gage.

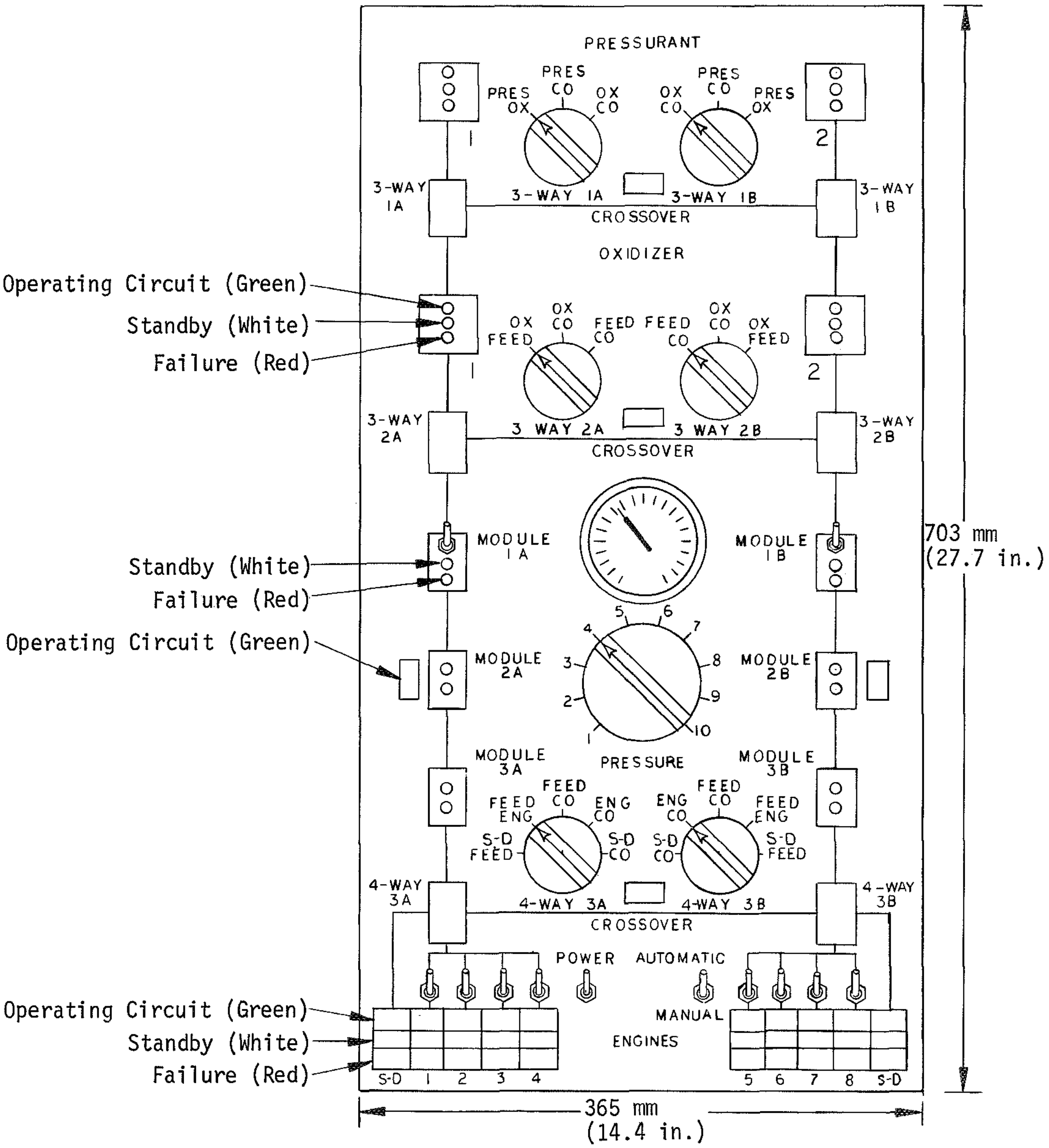


Fig. IV-1 Oxidizer Feed System Control Panel

Table IV-11 Malfunction Detection and Repair during Motor Refurbishment

COMPONENT FAILURE	FAILURE CLASS	MOTOR SYMPTOMS	CANDIDATE DETECTION METHODS	CANDIDATE REPAIR PROCEDURES
Motor Refurbishment Concepts				
Movable Tube Concept				
Failure of External Motor Seal	3	Refurbishment container cannot be repressurized		Retract motor & repair seal
Failure of Sliding Door Seal	4	Cabin air leaks to space during refurbishment	Refurbishment container pressure gage	After motor refurbishment (unless leak rate is unacceptable), return door to stored position, remove cover, & replace seal
Failure of Refurbishment Tube Seal	4	Cabin air leaks to space during motor retraction	Refurbishment container pressure gage	Repressurize and remove container; replace seal
Failure of Motor Extension & Retraction Mechanism	4	Failure before motor is retracted	Check out retraction mechanism before installing refurbishment container	Use a backup refurbishment container
	4	Failure with motor half retracted	Motor will not retract/extend	IVA required for this repair. Depressurize ACS room & remove motor & refurbishment container
Failure of Sliding Door Mechanism	4	Failure before motor is retracted	Lubricate & check out door movement before retracting motor	Dismantle door assembly. Remove & replace door retraction mechanism
	4	Failure with door half closed	Door jammed	IVA required for this repair. Depressurize ACS room, remove motor, & replace door assembly
Parallel Transfer Concept				
Failure of Outer Door Seal	4	Cabin air leaks to space during motor refurbishment	Refurbishment container pressure gage	Reverse motor position & replace seal
Failure of Inner Door Seal	4	Cabin air leaks into refurbishment container during depressurization	Refurbishment container pressure gage Onsite auditory check	Repressurize container & replace seal
Failure of Motor Pad Retraction Mechanism	4	Refurbishment container will not hold pressure	Visual check Position indicator	IVA required to repair retraction mechanism. Depressurize ACS room, disassemble refurbishment container, & repair retraction mechanism
Failure of Motor Pad Rotation Mechanism	4	Refurbishment container will not hold pressure	Visual check Position indicator	IVA required to repair rotation mechanism. Depressurize ACS room, disassemble refurbishment container, & repair/replace retraction mechanism
Nozzle Cap Approach				
Failure of Cap Seal	4	Cap will not hold pressure	Cap pressure gage	IVA required. Depressurize ACS room, retract motor pad, & repair seal
Failure of Cap Holding Mechanism	4	Cap will not hold pressure	Cap pressure gage	IVA required. Depressurize ACS room, retract motor pad, & repair cap holding clamp
Failure of Cap Extension Seal	3	Cabin air leaks to space	Vacuum pressure gage	IVA required. Depressurize ACS room, retract motor pad, & repair seal
Failure (Jamming) of Cap Extension & Turning Bar	4	Motor cannot be refurbished	Extension bar jammed	IVA required. Depressurize ACS room, retract motor pad, & release extension bar
Failure of Motor Pad Seal	3	Cabin air leaks to space	Vacuum pressure gage	IVA required. Depressurize ACS room, retract motor pad, & repair seal
Failure of External Motor Seal	4	Cabin air leaks to space	Vacuum pressure gage	Attach nozzle cap & replace seal
Forward Closure Concepts				
O-Ring Seal Failure	3	Motor will not hold pressure	Leak test using rubber nozzle plug -P_c transducer	Install new seal
Snap Ring Approach				
Broken Snap Ring Pliers	4	Pliers will not remove snap ring	Inspection	Use spare pliers
Double Bayonet Flange				
Broken or Damaged Bayonet Ring	4	Closure cannot be attached/ removed	Inspection	Replace forward closure, motor case, or both
Jammed or Malfunctioning Removal Tool	4	Closure cannot be attached/ removed	Inspection	Use spare removal tool. Repair or discard damaged tool
Bayonet Screw Flange				
Stripped Threads	4	Closure cannot be attached/ removed	Inspection	Replace forward closure, motor case, or both
Broken or Damaged Bayonet Ring	4	Closure cannot be attached/ removed	Inspection	Replace forward closure, motor case, or both
Pin				
Jammed Pin	4	Closure cannot be attached/ removed	Inspection	Use pin retraction tool
Damaged Retainer Strap or Wire	4	Cannot attach strap or wire	Inspection	Replace strap or wire
Bolted Flange				
Screw Thread Failure	4	Cannot attach or remove bolt or nut	Inspection	Use bolt & nut removal tools
Elongated Bolt Holes	4	Closure movement	Inspection	Replace closure

Failure modes for the five forward closure concepts primarily involve jammed or broken components, and do not require automatic detection equipment.

4. Candidate Repair Procedures

One objective of an MDS is to provide warning of impending motor failures so that they can be corrected during routine maintenance (Table IV-12) or so that additional maintenance can be performed before the motor has been rendered inoperable. Repair is defined as any unscheduled maintenance, in response to an unpredicted failure, that is required to return the system to normal operation.

There are three principal levels of repair:

1) Repair a failed part in place;
2) Replace and send the failed part to an onboard work shop for possible recycling;
3) Replace and discard the failed part.

The level of repair depends on comparing the effort, facilities, and manhours required to recycle the part with the resupply effort required to replace it.

Candidate repair procedures for the ignition systems were outlined in Table IV-7. Failed oxidizer control valves would be replaced. Bad seals could be repaired onboard the Space Station, but a malfunctioning actuation system would probably be considered unrepairable.

With the sparked propane system, the spark plug and propane can be discarded; but an attempt would be made to repair or recalibrate a faulty trip valve. On the other hand, the pyrogen ignition system is completely disposable; squib or other igniter failures would be repaired by discarding and replacing the failed part. Similarly, the electrically heated oxidizer line ignition system would require no refurbishment equipment. Burned out heating elements and failed capacitors would be discarded and replaced.

The flow splitter valve for the spark-initiated precombuster would be repaired in the same manner as the oxidizer control valve. Only seal failures could be repaired onboard. The precombuster grain and spark source would both be discarded and replaced when grain depletion or spark source failure occurred.

Table IV-12 Scheduled Maintenance

COMPONENT	LUBRICATION	CALIBRATION OR ADJUSTMENT	REMOVE & REPLACE	PRESSURE TEST OR LEAK CHECK	VISUAL INSPECTION	ELECTRICAL CHECKOUT	SCHEDULED MALFUNCTION DETECTION	
Forward Closure Retention								
Snap Ring	O-Ring	N/A	O-Ring	Pressure Check to Verify Integrity of O-Ring & Snap Ring	Snap Ring	N/A	N/A	Maintenance Will be Accomplished during Refurbishment
Double Bayonet	O-Ring	N/A	O-Ring	Pressure Check to Verify Integrity of O-Ring & Bayonet Ring	Attachment Flange	N/A	N/A	Maintenance Will be Accomplished during Refurbishment
Bayonet/Screw Flange	O-Rings Springs Screw Threads	N/A	O-Rings	Pressure Check to Verify Integrity of O-Rings & Attach Flange	Attachment Flange	N/A	N/A	Maintenance Will be Accomplished during Refurbishment
Pin	Pin	N/A	• Pin • Strap or Wire Retention	Pressure Check to Verify Integrity of O-Ring & Pins	• Pins • Strap or Wire Retention	N/A	N/A	Maintenance Will be Accomplished during Refurbishment
Bolted Flange	Bolt & Nut Threads	N/A	Bolts & Nuts	Pressure Check to Verify Integrity of O-Ring & Bolts	Bolts & Nuts	N/A	N/A	Maintenance Will be Accomplished during Refurbishment
Nozzle Throat	N/A	N/A	Motor Case	Pressure Check to Verify Integrity of Motor	Nozzle Throat Dia.	N/A	Nozzle Throat	Maintenance Will be Accomplished during Refurbishment
Refurbishment								
Movable Tube	• Retraction & Extension Mechanism • Sliding Door Ball Bearing • Three-Way Pressure Valve	Retraction & Extension Mechanism	Seals at Least Every 24 Months	• Refurbishment Tube & Seals • Pressure Valve	Seals	Retraction & Extension Mechanism	N/A	Maintenance Will be Accomplished before Refurbishment
Parallel Transfer	• Retraction & Extension Mechanism • Turning Mechanism	• Retraction & Extension Mechanism • Turning Mechanism	Seals at Least Every 24 Months	• Refurbishment Chamber & Seals • Pressure Valve	Seals	• Retraction & Extension • Motor & Circuit • Turning Motor & Circuit	N/A	Maintenance Will be Accomplished before Refurbishment
Nozzle Cap	• Cap Turning & Extending Mechanism • Cap Locking Mechanism	• Retraction & Extension Mechanism • Turning Mechanism	• Seals Every 24 Months • Work Area Will Have to be Evacuated	• Cap Seal • Pressure Valve	Seals	• Retraction & Extension	N/A	Maintenance Will be Accomplished before Refurbishment
Motor Grain	N/A	N/A	Care Should be Taken in Assembling Grain to Motor to Insert Grain in the Proper Direction	N/A	Grains	Verify Fuel Depletion Detection Wires Are Not Broken	Fuel Depletion Detection System	Maintenance Will be Accomplished during Refurbishment

Candidate failure modes for operational failures were outlined in Table IV-8. Oxidizer control valve actuation failures would be repaired by discarding and replacing the valve. Injector erosion failures would be repaired during scheduled maintenance by discarding and replacing the injector. Forward closure seal failures or a loose forward closure during operation would be repaired immediately by replacing the seal or resecuring the forward closure and checking for damage to the forward closure. Expended fuel grains will be replaced. The approximately 5% of residual fuel would be added to Space Station waste (in the movable grain design, there is no residual fuel). Jammed moving grains would be removed, inspected, trimmed if possible, repositioned, and reinstalled. Aft closure burnthroughs, throat erosion, and exit cone burnthroughs would require discarding and replacing the case/nozzle assembly. Some electrical failures (e.g., a bad contact or loose plug) could be repaired in place; most of the rest could be repaired in a refurbishment area.

Repair procedures during motor standby were described in Table IV-9. Fittings would be checked for oxygen leaks during scheduled maintenance. Propane leak warnings would trigger prompt checks to identify the source of the leak and replace the failed trip valve or butane can. Very small cabin air leaks past the external motor seal would normally be repaired during the next scheduled maintenance. Cabin air leaks past the main motor seal would result in the motor being taken off line to preclude a seal failure during the next firing. Maintenance would be scheduled to replace the seal and return the motor to an active standby condition. Electrical failures would be handled in a similar manner: the motor would be held off line until proper functioning could be restored.

Repair procedures during motor refurbishment were outlined in Table IV-10.

Most movable tube refurbishment failures can be repaired in a shirtsleeve environment. The refurbishment tube and sliding door seals and retraction mechanisms can be checked before refurbishment. A malfunctioning component could either be repaired or replaced. An external seal failure would be repaired by retracting the motor and replacing the seal. There is an extremely small possibility of the motor or door retraction mechanism jamming, despite a prerefurbishment check. If this happens, the APS room could be depressurized at a convenient time and the jammed refurbishment mechanism could be replaced via IVA. This would not alter the operational status of the other motors.

The parallel transfer concept has redundant seals that virtually eliminate the possibility of a cabin leak. The access door or motor pad seals can be replaced without resorting to IVA. However, a failure of either the retraction mechanism or the motor pad rotation mechanism would require IVA for repair.

The nozzle cap approach has five failure modes that require internal vehicular activity for repair. Failure of the cap seal, the cap extension seal, or the motor pad seal will require IVA for replacement. In addition, jamming of the cap holding mechanism or cap extension bar would require IVA. Failure of the external motor seal could be replaced by securing the nozzle cap and withdrawing the motor.

The five forward closure concepts have widely different repair requirements. All five are subject to cut or defective O-rings, which would be replaced. Broken snap ring pliers would require spare pliers. Jamming of the forward closure was considered unlikely in the snap ring, pin, or bolted flange concepts. However, in the double bayonet and bayonet/screw approaches, a broken or damaged bayonet ring or stripped threads are possible. These failures would be repaired by discarding and replacing the forward closure, the case, or the entire motor assembly.

The repair sequence for the selected conceptual OFA is described in Table IV-13.

D. MAINTENANCE

Maintenance is limited to scheduled maintenance, which is a preventive measure to keep all systems, subsystems, and components in a predetermined condition. A filter replacement would be a typical scheduled maintenance item. Maintenance by repair or replacement will return a defective system to its desired operational capabilities.

Scheduled maintenance has two objectives: to discover incipient malfunctions and to prevent malfunctions and breakdowns.

Table VII-8 Repair Procedures for Oxidizer Feed Assembly

PRESSURANT MODULE

Burst Disc or Relief Valve

1. Isolate Failure
2. Remove Vent Line
3. Remove Base Fitting
4. Remove & Store Part
5. Install New Part
6. Attach Base Fitting
7. Attach Vent Line

Pressurant Tank

1. Isolate Failure
2. Remove Fill Line
3. Remove Relief Line
4. Remove Transfer Line
5. Remove Four Quick-Release Fasteners
6. Remove & Store Tank
7. Install New Tank
8. Attach Four Fasteners
9. Attach Transfer Line
10. Attach Relief Line
11. Attach Fill Line

Three-Way Valve

1. Isolate Failure
2. Bleed Down Pressurant
3. Remove Pressure Transducer
4. Remove Transfer Line to Oxidizer Tank
5. Remove Crossover Line
6. Remove Electrical Line
7. Remove Bolts Holding Three-Way Valve in Place
8. Remove & Store Valve
9. Install New Valve
10. Attach Retaining Bolts
11. Attach Electrical Line
12. Attach Crossover Line
13. Attach Transfer Line to Oxidizer Tank
14. Attach Pressure Transducer

Pressure Transducer

1. Isolate Failure
2. Bleed Down Pressurant
3. Remove Electrical Line
4. Remove Transfer Line
5. Remove Transducer from Valve Fitting
6. Remove & Store Transducer
7. Install New Transducer
8. Attach Transducer to Valve Fitting
9. Attach Transfer Line
10. Attach Electrical Line

OXIDIZER MODULE

Oxidizer Tank

1. Isolate Failure
2. Remove Pressurant Line
3. Remove Transfer Line
4. Remove Relief Line
5. Remove Fill Line
6. Remove Six Quick-Release Fasteners
7. Remove & Store Tank
8. Install New Tank
9. Attach Six Fasteners
10. Attach Fill Line
11. Attach Relief Line
12. Attach Transfer Line
13. Attach Pressurant Line

Burst Disc or Relief Valve

1. Isolate Failure
2. Remove Vent Line
3. Remove Base Fitting
4. Remove & Store Part
5. Install New Part
6. Attach Base Fitting
7. Attach Vent Line

Three-Way Valve

1. Isolate Failure
2. Bleed Down Oxidizer
3. Remove Pressure Transducer Fitting
4. Remove Transfer Line to Control Components
5. Remove Crossover Line
6. Remove Electrical Line
7. Remove Bolts Holding Three-Way Valve in Place
8. Remove & Store Valve
9. Install New Valve
10. Attach Retaining Bolts
11. Attach Electrical Line
12. Attach Crossover Line
13. Attach Transfer Line to Control Components
14. Attach Pressure Transducer

Pressure Transducer

1. Isolate Failure
2. Bleed Down Oxidizer
3. Remove Electrical Line
4. Remove Transfer Line
5. Remove Transducer from Valve Fitting
6. Remove & Store Transducer
7. Install New Transducer
8. Attach Transducer to Valve Fitting
9. Attach Transfer Line
10. Attach Electrical Line

CONTROL COMPONENTS

Module 1 - Shutoff Valve & Check Valves

1. Isolate Failure
2. Isolate System Using Three-Way Valve
3. Bleed Down Residual Oxidizer
4. Remove Electrical Line
5. Remove Fitting on Shutoff Valve
6. Remove Fitting on Check Valve
7. Remove & Store Module
8. Install New Module
9. Attach Fitting on Check Valve
10. Attach Fitting on Shutoff Valve
11. Attach Electrical Line

Pressure Transducers

1. Isolate Failure
2. Bleed Down Residual Oxidizer
3. Remove Electrical Line
4. Remove Both Fittings
5. Remove & Store Transducer
6. Install New Transducer
7. Attach Both Fittings
8. Attach Electrical Line

Module 2 - Vaporizer, Relief Valve, & Burst Disc

1. Isolate Failure
2. Bleed Down Residual Oxidizer
3. Remove Fitting on Upstream Pressure Transducer
4. Remove Fitting on Downstream Pressure Transducer
5. Remove & Store Module
6. Install New Module
7. Attach Fitting on Downstream Pressure Transducer
8. Attach Fitting on Upstream Pressure Transducer

Module 3 - Filter & Regulators

1. Isolate Failure
2. Bleed Down Residual Oxidizer
3. Remove Fitting from Pressure Transducer
4. Remove Fitting from Three-Way Valve
5. Remove Four Quick-Release Fasteners
6. Remove & Store Module
7. Install New Module
8. Attach Four Fasteners
9. Attach Fitting to Three-Way Valve
10. Attach Fitting to Pressure Transducer

The following scheduled maintenance functions have been considered in this study:

1) Servicing:
    a) Lubrication,
    b) Calibration,
    c) Adjustment,
    d) Cleaning;
2) Routine removal and replacement;
3) Inspection:
    a) Leak test,
    b) Pressure check,
    c) Visual inspection,
    d) Electrical checkout verification.

When the control motors are operating, malfunction detection will be performed by the Space Station crew and equipment.

Maintenance of the control motors falls into one of the following areas:

1) Ignition devices;
2) Forward closure attachment devices;
3) Motor refurbishment devices;
4) Motor grains;
5) Oxidizer feed assembly.

These are discussed in detail in the following subsections.

1. Ignition Devices

a. Butane or Propane Spark-Initiated Precombuster - A butane or propane-filled canister is attached to a trip valve. The trip valve pulses, allowing a quantity of gas to mix with the oxidizer flowing through the oxidizer control valve. The gas mixture is ignited by a spark plug, and the hot gas mixture is injected into the motor, igniting the grain.

Scheduled maintenance is performed during motor grain refurbishment. At this time, the spark plug, spark plug gasket, gas canister, and seal are replaced. Then the trip valve is lubricated and calibrated, and the oxidizer valve is lubricated. Once the oxidizer valve is closed and the injector nozzle is plugged, the ignition system is leak-tested.

b. Pyrogen Hot Gas Igniter - The pyrogen igniter must be reloaded after each ignition. The pyrogen igniter considered for use on the spin/despin motor requires a single refurbishment cycle. Scheduled maintenance is performed concurrently with the refurbishment function. The igniter is refurbished with a fresh squib and propellant cartridge, the seal at the igniter-to-closure interface is replaced, the oxidizer control valve is lubricated, and the electrical cable is checked. After servicing, the oxidizer control valve is closed, the oxidizer injector nozzle is plugged, and the system is leak-tested. The operation of the squib electrical cable is checked before ignition.

c. Electrically Heated Precombuster - The oxidizer is heated before being injected into the combustion chamber. During motor grain refurbishment, the heater heating element is replaced and the operating capability of the electrical control cable is verified. The oxidizer control valve is lubricated and the electrical control cable operation verified. The oxidizer control valve closed with the oxidizer injector plugged and the system leak-tested.

d. Spark-Initiated Precombuster - A small quantity of oxidizer is allowed to flow from the oxidizer control valve through the PMM precombuster grain. A surface spark ignites the precombuster grain, which exhausts into the motor chamber and combines with the oxidizer to ignite the motor grain.

Scheduled maintenance is performed concurrently with refurbishment. At refurbishment the PMM grain, the spark source battery, the tungsten electrodes, and the seals are replaced, the oxidizer control valve is lubricated, and the electrical control cable operation is verified. After refurbishment, the oxidizer control valve is closed, the injection nozzle is plugged, and the ignition system is leak-tested.

2. Forward Closure Attachment Devices

a. Snap Ring - A snap ring plier is used to help assemble the forward closure to the motor case. During refurbishment, the forward closure O-ring seal is replaced. After being assembled, the motor is pressure tested to verify the integrity of the O-ring and snap ring.

b. Double Bayonet - In the double bayonet concept, a ring actuated by a hand grip tool is used to attach the forward closure to the motor case. During refurbishment, the forward closure O-ring seal is replaced. After being assembled, the motor is pressure tested to verify the integrity of the O-ring and the bayonet ring.

c. Combination Bayonet and Screw Attachment - The forward attachment flange is in two parts: a bayonet external ring engages the motor case and is held in position by four springs; the closure flange is screwed to the motor case. During refurbishment, the forward closure O-ring seal is replaced and the springs and threads on the closure are lubricated. After assembly, the motor is pressure tested to verify the integrity of the O-ring and closure attachment.

d. Pin - The forward closure is attached and held to the case by four radial pins that incorporate either a strap, wire, or tape retention design. A pin extraction tool is used to extract the pins during refurbishment. The flange will have an alignment key to facilitate aligning the closure holes to the case holes. During refurbishment, the forward closure O-ring seal is replaced. After assembly, the motor is pressure tested to verify the integrity of the O-ring.

e. Bolted Flange - The forward closure is bolted in four places to the case. Small hand tools are required to remove and install the attachment bolts and nuts. During refurbishment, the forward closure O-ring seal is replaced. After assembly, the motor is pressure tested to verify the integrity of the O-ring.

3. Motor Refurbishment Devices

Each of the three refurbishment concepts considered below offers a shirtsleeve environment for the replacement of motor grains.

a. Movable Tube - A tube with sliding door is attached beneath the motor to be refurbished. When the motor is retracted, the sliding door seals the motor opening in the outer skin. Access to the motor is through an access door at the bottom of the tube. Before opening the access door, the pressure within the tube is equalized to that within the cabin of the Space Station.

Before attaching the refurbishment tube, a visual inspection is made of the seals on the sliding door and on the access door, as well as the ball bearing rollers on the sliding door. The seals will be replaced if they appear worn or brittle. The ball bearing rollers will be lubricated. Once every 24 months, the seals will be replaced. The retraction and extension mechanism will be checked for proper operation, adjustment, and lubrication. The pressurization valve will be checked for operation, and lubricated if necessary. Once the movable tube is in place, the crew will pressure check the tube and verify the integrity of the seals.

b. Parallel Transfer - The motor attached to the outer skin panel is lowered into a refurbishment chamber. The motor and panel are reversed, positioning the motors on the inside of the chamber when the skin panel is extended back into position. The refurbishment of the grain is accomplished through a chamber access door.

Before refurbishment, the crew will visually inspect the skin panel reverse seal and the access door seal and replace the seals if they are worn or brittle. The seals will be replaced at least every 24 months. The crew will also lubricate the retraction/extension and reversing mechanism and motors, verify the operation of the pressure valve, pressure check the chamber to verify the integrity of the chamber seal, and electrically verify the electrical control cable.

During refurbishment, the crew will visually inspect the motor side environmental seal and replace it if it is worn or brittle. This seal should be replaced at least every 24 months.

c. Nozzle Cap - In the nozzle cap concept, the motor is stationary and a movable nozzle cap rotates into position to seal the motor nozzle during refurbishment.

Before refurbishment, the operation of the pressure valve will be checked. The extension/retraction and rotation mechanisms will be lubricated. The cap locking mechanism will be lubricated. Seals will be replaced at least once every 24 months. To replace the seals, the motor room will be evacuated and the crew will wear protective clothing.

4. Motor Grains

The motor grains will be replaced during scheduled motor refurbishment. Before replacing a grain, a visual inspection will be made to determine if any discrepancies exist. The seal used with the moving grain concept will be replaced during each refurbishment. Care should be taken to insert the grain into the motor in its proper position. After refurbishment, the motor will be pressure checked to verify the integrity of the motor case.

5. Oxidizer Feed Assembly

A conservative approach has been followed for the OFA. We have assumed that each component of the assembly system will be replaced before its operating life is exceeded. This assumption has been incorporated in the scheduled maintenance estimates. Table IV-14 presents the estimated life limitations of the components that compose the various candidate oxidizer feed systems.

Valves are the most critical components in the feed system. It is believed that high-reliability valves can be obtained with a 3- to 5-year calendar life, depending on seal material and valve type. Cyclic lives in excess of 1 million cycles are obtainable. Therefore, we recommend that all valves be replaced either after 3 years in space or after a combined ground and space environment life of 5 years so that their calendar life is not exceeded.

The total useful life (terrestrial and spatial) of the transducers is 5 years, per NASA-MSC specification MSC-KA-6D-68-1. Assuming a 2-year life before launch, the spatial life of a transducer is 3 years. Martin Marietta's experience indicates that these estimates are essentially correct.

To minimize total maintenance time, identical components/modules that require replacement can be replaced at the same time, saving preparation and travel time. We assumed half of the filters are replaced after each pressurant and oxidizer resupply (every 6 months).

If all the components with 3-year lives were replaced during one maintenance period, available crew time might be exceeded. Therefore, we suggest that only half of the valves, components, and transducers be replaced at one period. The components in the half of the system that was active immediately after orbit insertion should be replaced first after 3, 6, and 9 years. Components in the initially redundant standby half of the APS should be replaced at 3½ and 6½ years.

Table IV-14 Estimated Life of Oxidizer Feed System Components

COMPONENT	SPATIAL LIFE LIMITATIONS			
	CYCLES	REF[*]	YEARS	REF[*]
Valves				
Solenoid Valves	100,000	a	3	b
Feedline	100,000	a	2	a
Check Valves	5,000	a	3	b
Pressure Relief Valve	3,000	a	3	b
Burst Disc	--	--	3	b
Pressure Regulators	5,000	a	2	a
Three-Way Valves	5,000[†]	c	3	b
Quick Disconnects	400	a	2	a
Pressurant Sphere [0-22,048 kN/m^2(0-3200 psig) - 0 = 1 cycle] & 1/2 Quick Disconnect	400	a	2	a
Filter Bodies (Change Filter Element Once a Year)	--	--	10	c
Propellant Tanks	100	a	10	c
Shell [0-1509 kN/m^2(0-219 psig) - (9 psig) = 1 cycle]	2,000	a	10	c
Transducers	--	--	3	d

[*] References:
- a. *Workshop Attitude Control System (WACS), Propulsion Module Component Description Document.* S&E-ASTN-PAS, 3-25-69.
- b. *Handbook of Long-Life Space Vehicle Investigations.* M-68-21. Martin Marietta Corporation, Denver, Colorado, December 1968.
- c. General Data Indication.
- d. *Experiment General Requirement Document - AAP.* MSC-KA-6D-68-1 (Rev B). EGRD useful life specification for transducers is 5 yr, assumed terrestrial life is 2 yr.

[†] Minimum.

Primary scheduled maintenance for the OFA consists of:

1) Checking the pressure in the system;
2) Replacing filter elements;
3) Testing the fittings for leaks.

Pressures are checked before and after each resupply. This is estimated to require 10 minutes per OFA, or 20 minutes per resupply. The total pressure-monitoring time per year is 80 minutes, assuming a resupply every 90 days. The crew times required for the remaining scheduled maintenance functions are presented in Table IV-15.

The total estimated scheduled maintenance time per year for the OFAs is 286 minutes.

E. ONBOARD SERVICING AND REPAIR

Onboard servicing and repair requirements for the hybrid APS have been evaluated in six primary areas. The location of the OFA on the Space Station was considered, as well as the subsequent layout of the lower deck of the Space Station, in order to determine the proper location of APS thrusters and maintenance facilities. Three motor pad configurations were designed to contrast the requirements of the three primary motor refurbishment concepts. Components and spares requirements were evaluated for candidate APS component designs. Required maintenance, repair, and handling equipment was examined and evaluated. Finally, refurbishment tasks and completion times were evaluated for the APS.

1. Space Allocation for Oxidizer Feed Assembly

Five conceptual designs were made to determine the optimum location of the OFA in terms of removal, compactness, and safety. Consideration was given to storing half the oxidizer and pressurant at each end of the Station to eliminate degradation of the operation of the assemblies in case of meteoroid impact. In all of the designs, the thruster modules were located at the aft end of the Station on the first deck level.

Table IV-15 Estimated Crew Time for Scheduled Maintenance

FUNCTION	CREW TIME PER OFA (minutes)
Review Procedures	4
Obtain Spares	3
Travel to Assembly	5
Remove Cover	10
Replace Filter	3
Tighten Fittings (1/2 minute Each)	58
Replace Cover	10
Return from Assembly & Stow Gear	5
Perform Administrative Functions	5
TOTAL PER ASSEMBLY	103

The concepts considered were:

1) Split assemblies located on the fifth deck, with lines running along the central tunnel [Fig. IV-2(a)];
2) Two assemblies located on the first deck, with lines along the outer wall and interior of the Station [Fig. IV-2(b)];
3) Two assemblies located on the fifth deck, with resupply lines along the central tunnel and feedlines along the outer walls [Fig. IV-2(c)];
4) Split assemblies located on the first deck, with the feed and resupply lines running along the outer wall [Fig. IV-2(d)];
5) Split assemblies located on the first and fifth decks, with feed and resupply lines running along the outer walls [Fig. IV-2(e)].

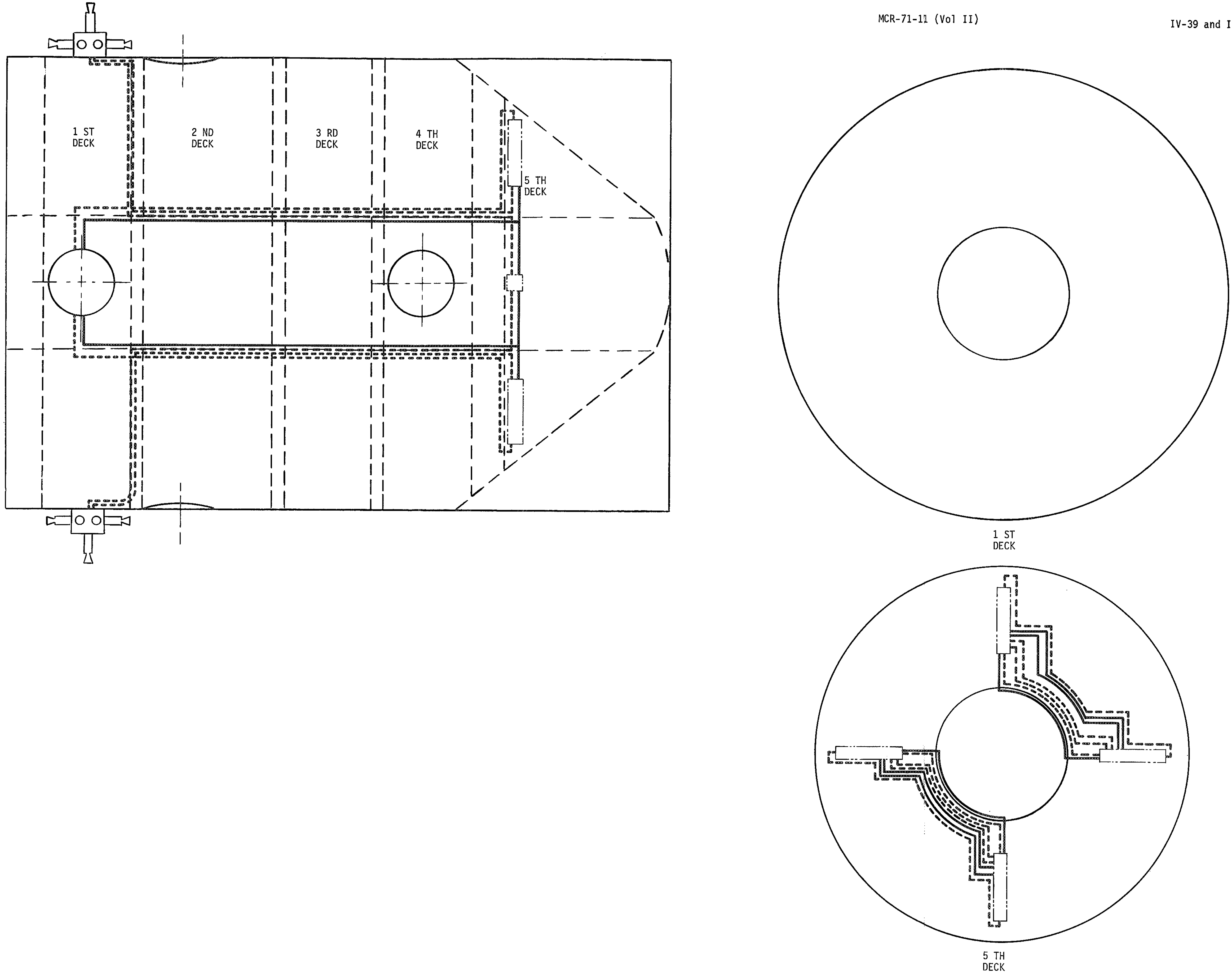
There are other combinations that can be considered, such as running lines along the central wall or outer wall for various deck combinations.

In the selected concept, the oxidizer assemblies are located on the first deck [Fig. IV-2(c)]. Redundancy is provided by having connections between the assemblies and by being able to resupply from either a side or the end docking port. This concept was selected because it was the simplest and involved the fewest number of lines. This approach minimizes the potential for leaks and meteoroid impacts, and also minimizes the volume required for the OFAs.

2. Propulsion Compartment Design

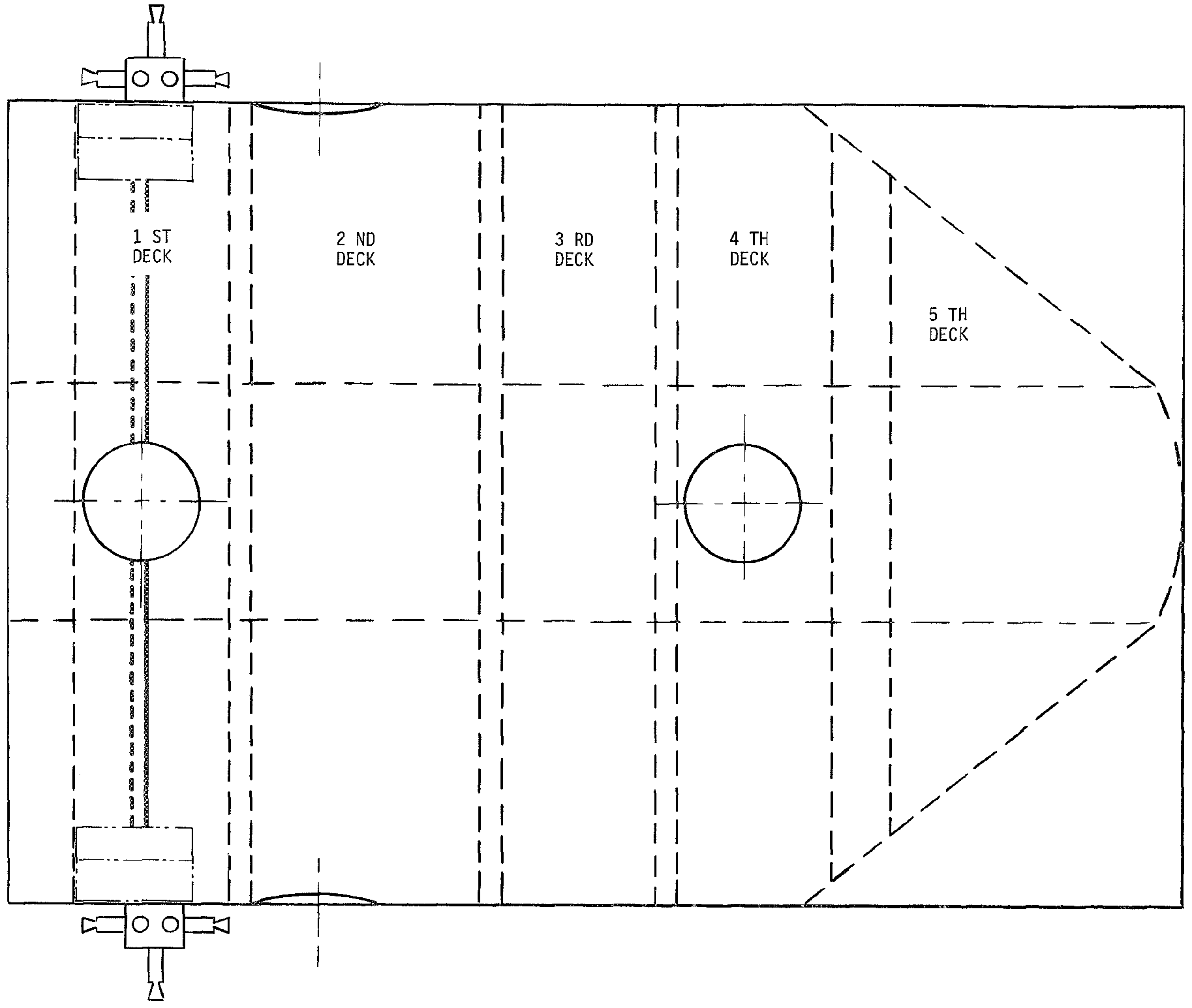
All maintenance, repair, and checkout of the hybrid APS will be accomplished in the two propulsion compartments shown in Fig. IV-3. The Space Station is 10 m (33 ft) in diameter and has a 3-m (10-ft) diameter access tube in the center. The floor-to-ceiling height is 2 m (80 in.). On the lower deck, two 1.5-m (5-ft) diameter docking access tubes, 180 deg apart, extend from the exterior wall to the central access tube.

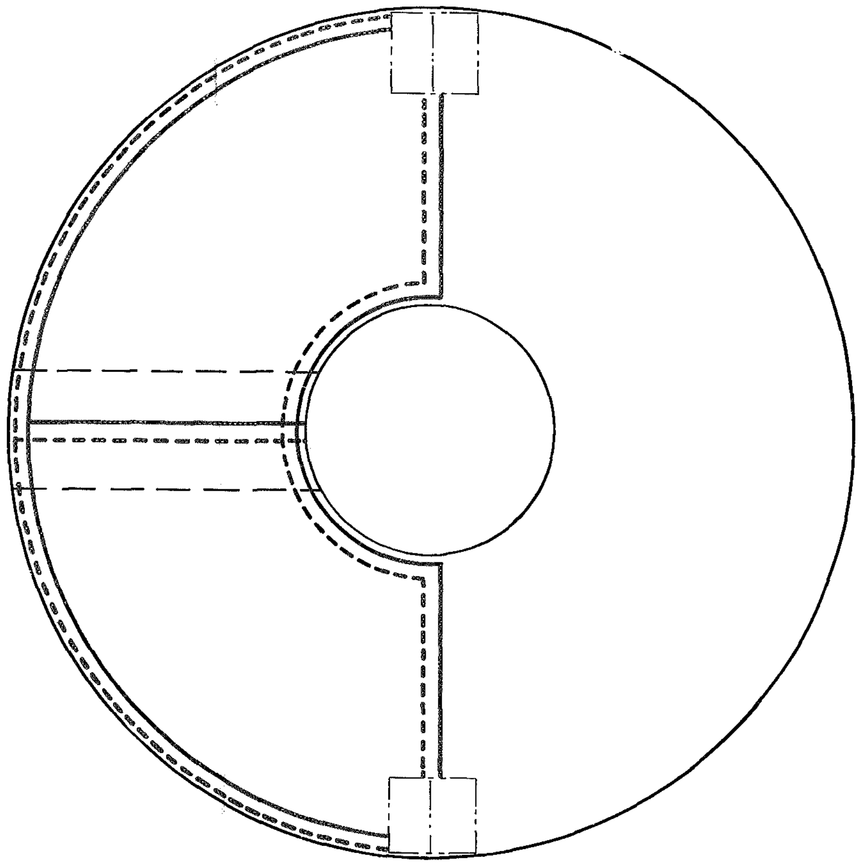
The lower deck has been sectioned into a propulsion handling/refurbishment area and an administrative area for each thruster pad.

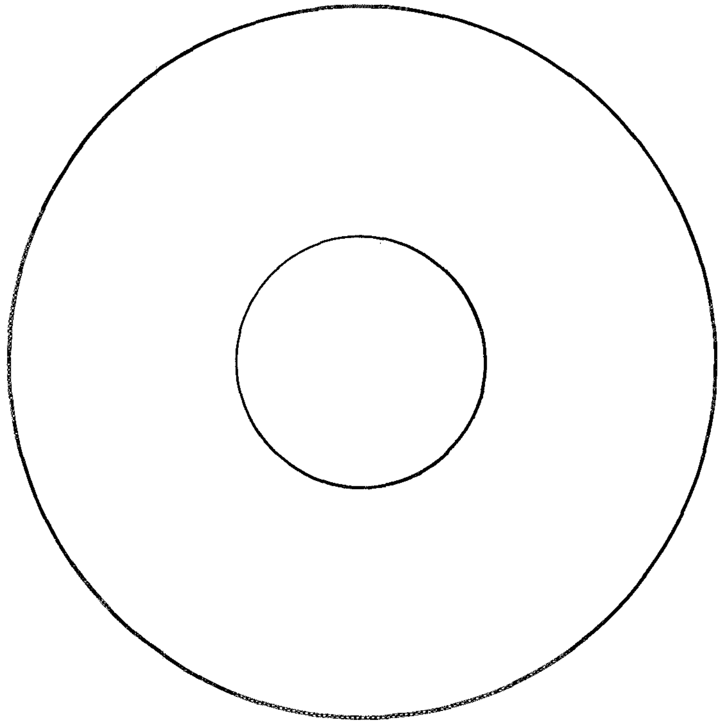


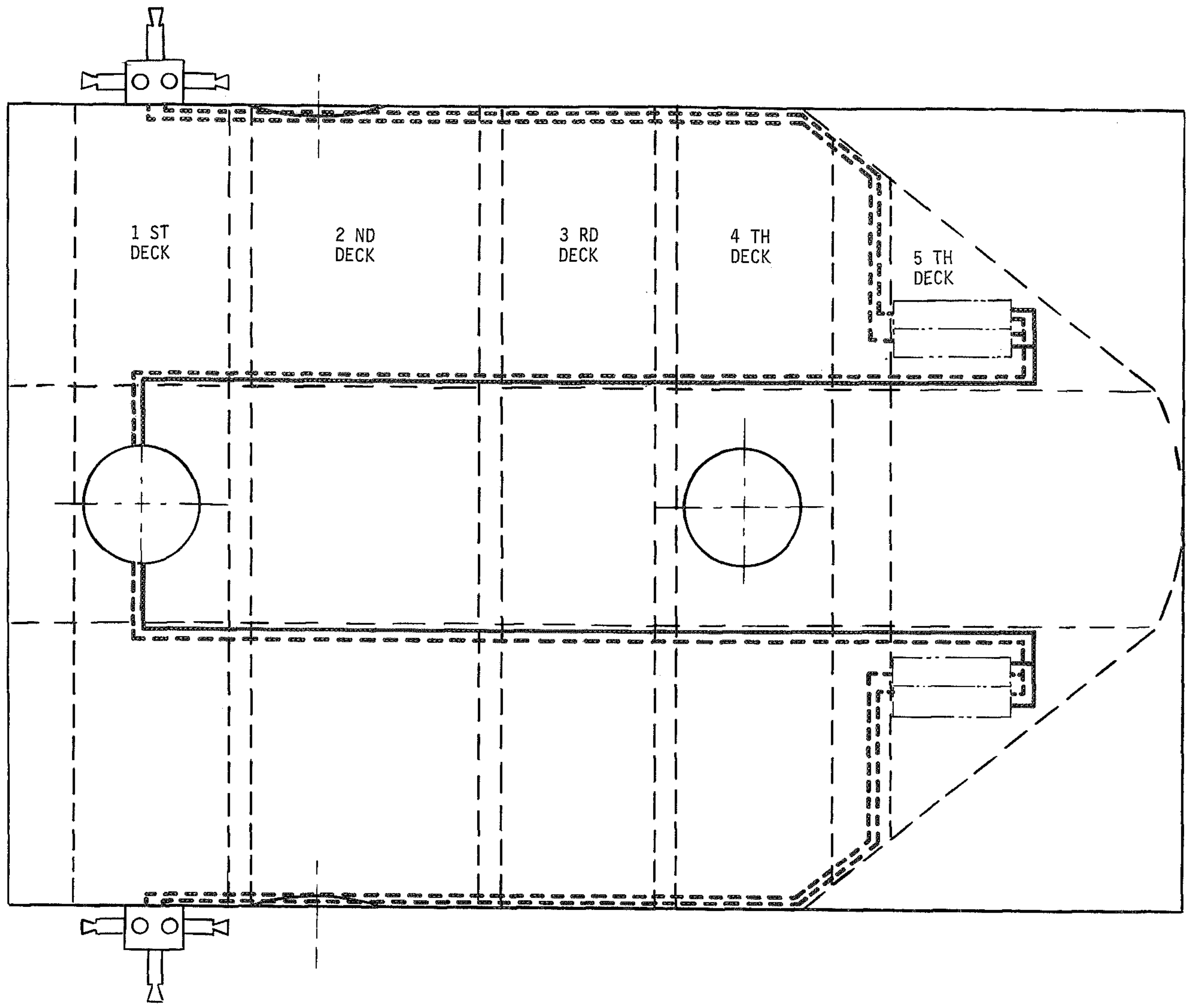
(a) Concept 1

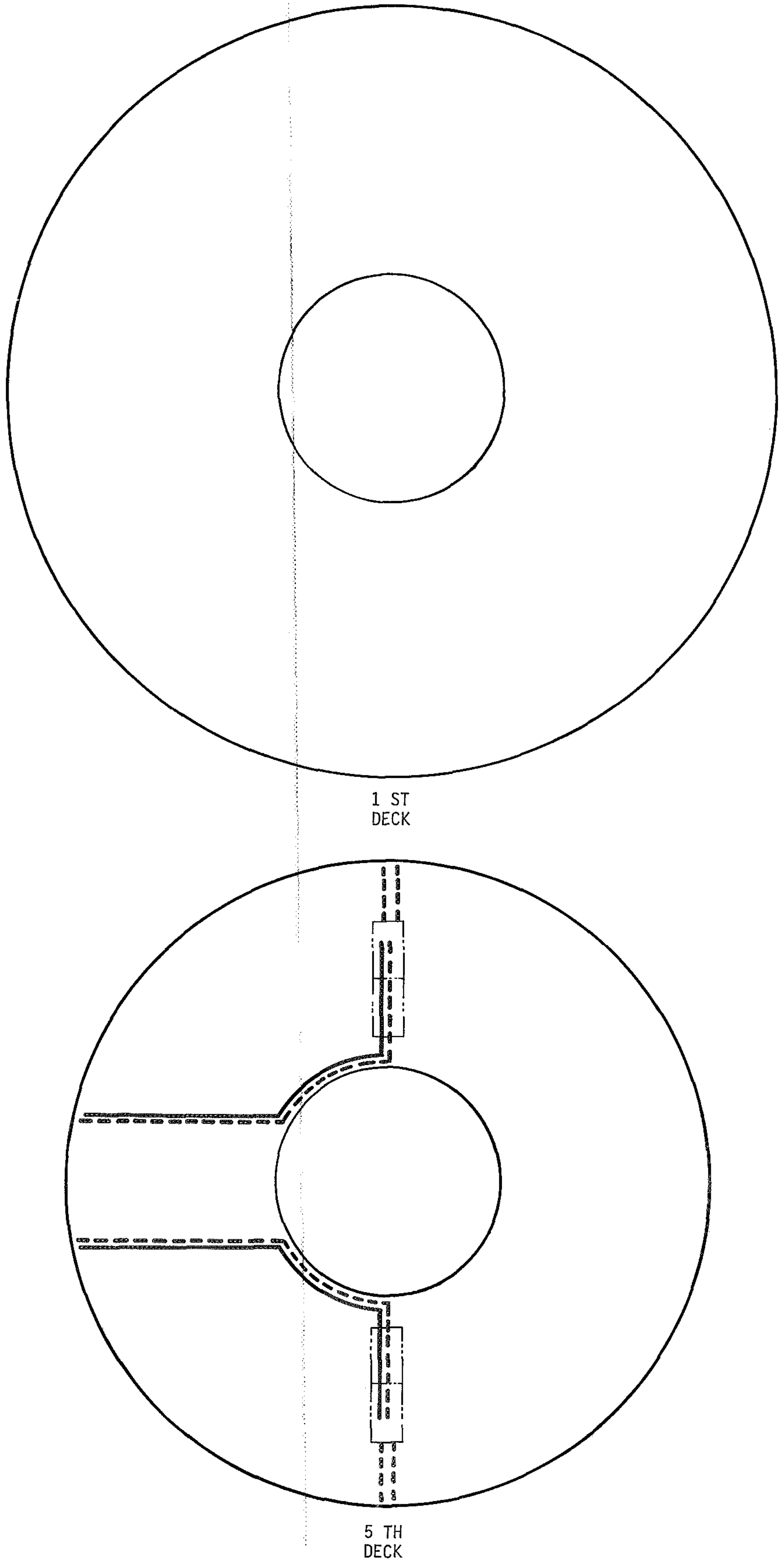
Fig. IV-2 Space Allocation for Oxidizer Feed System




1 ST
DECK

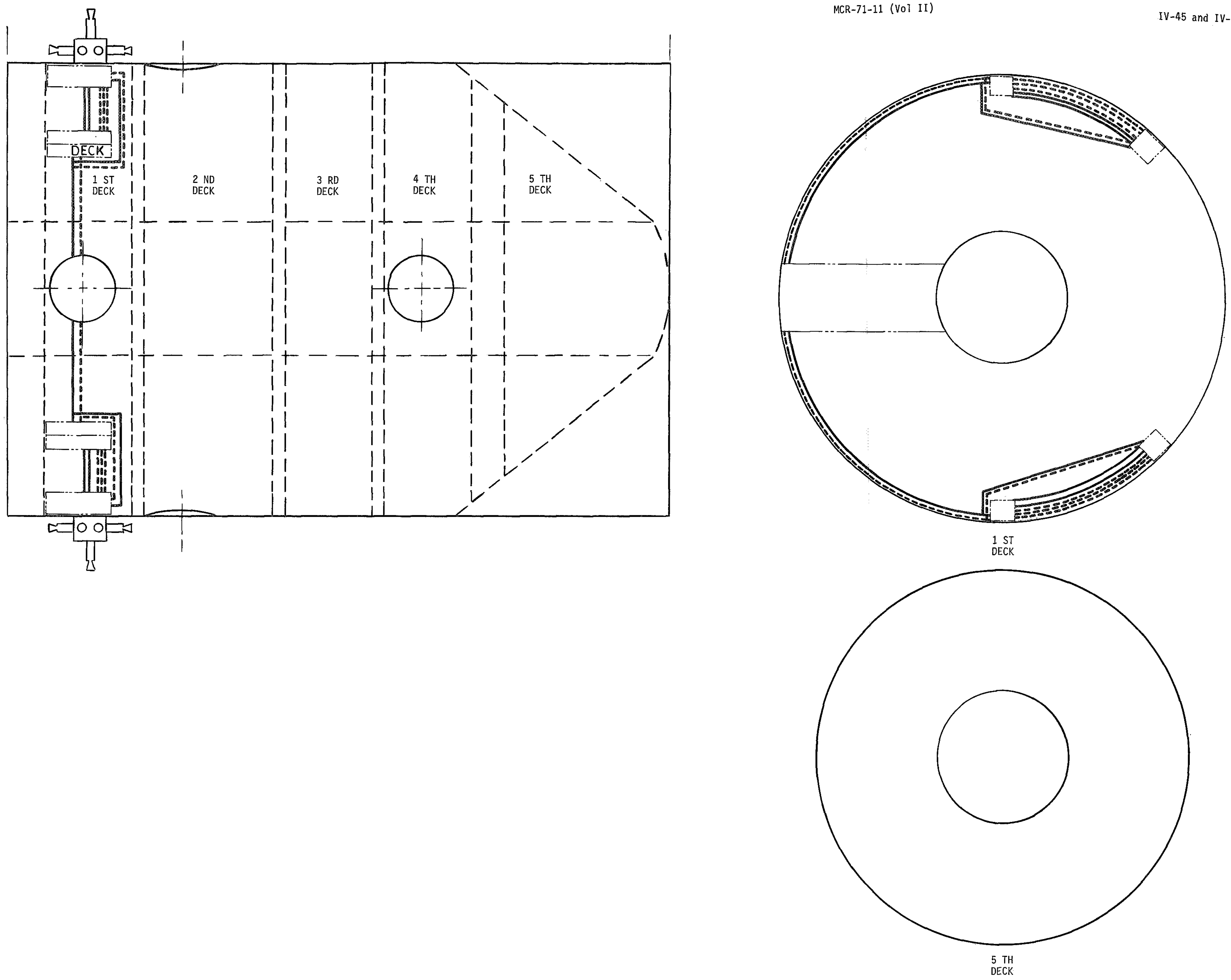

5 TH
DECK





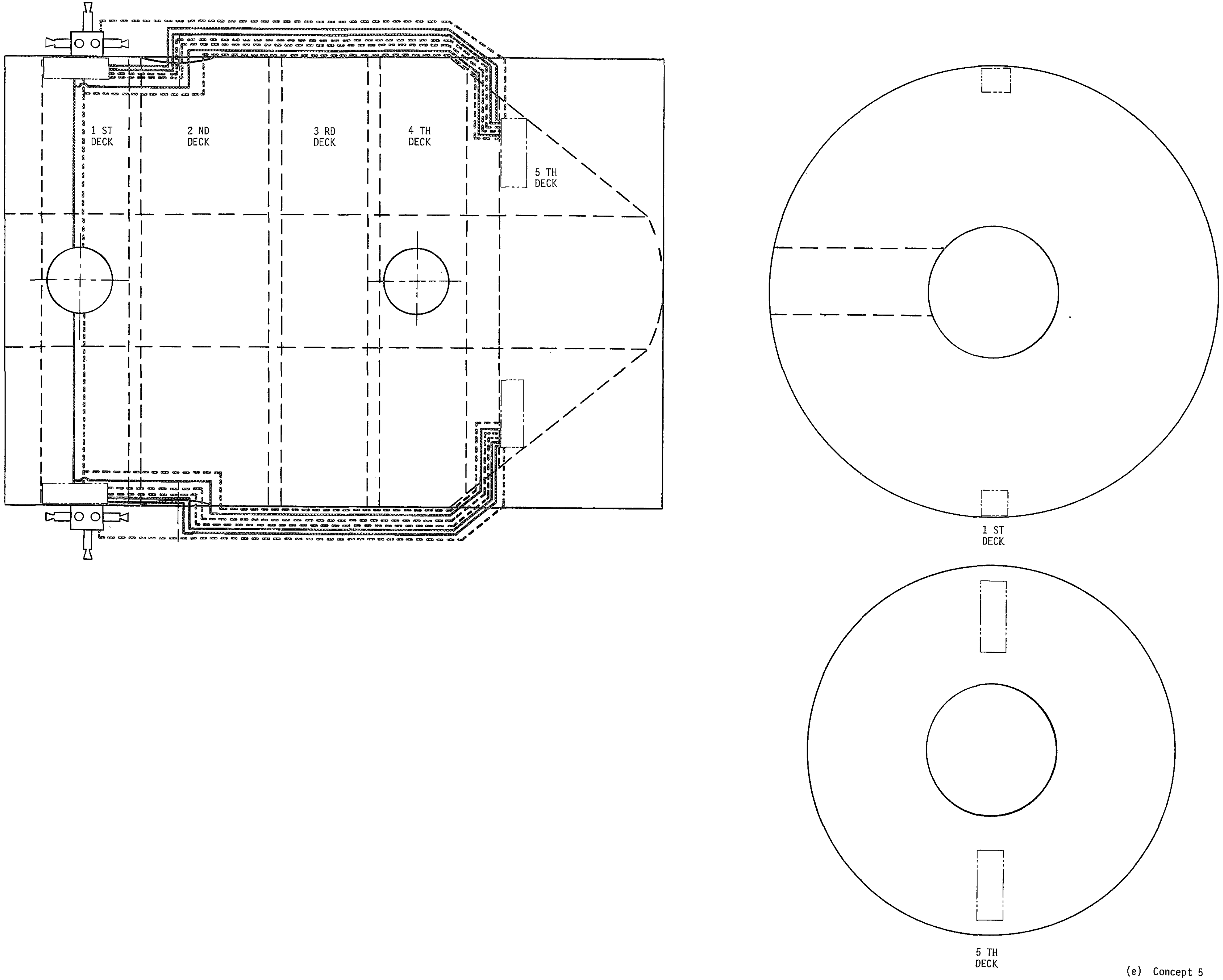
(c) Concept 3

Fig. IV-2 (cont)



(d) Concept 4

Fig. IV-2 (cont)



(e) Concept 5

Fig. IV-2 (concl)

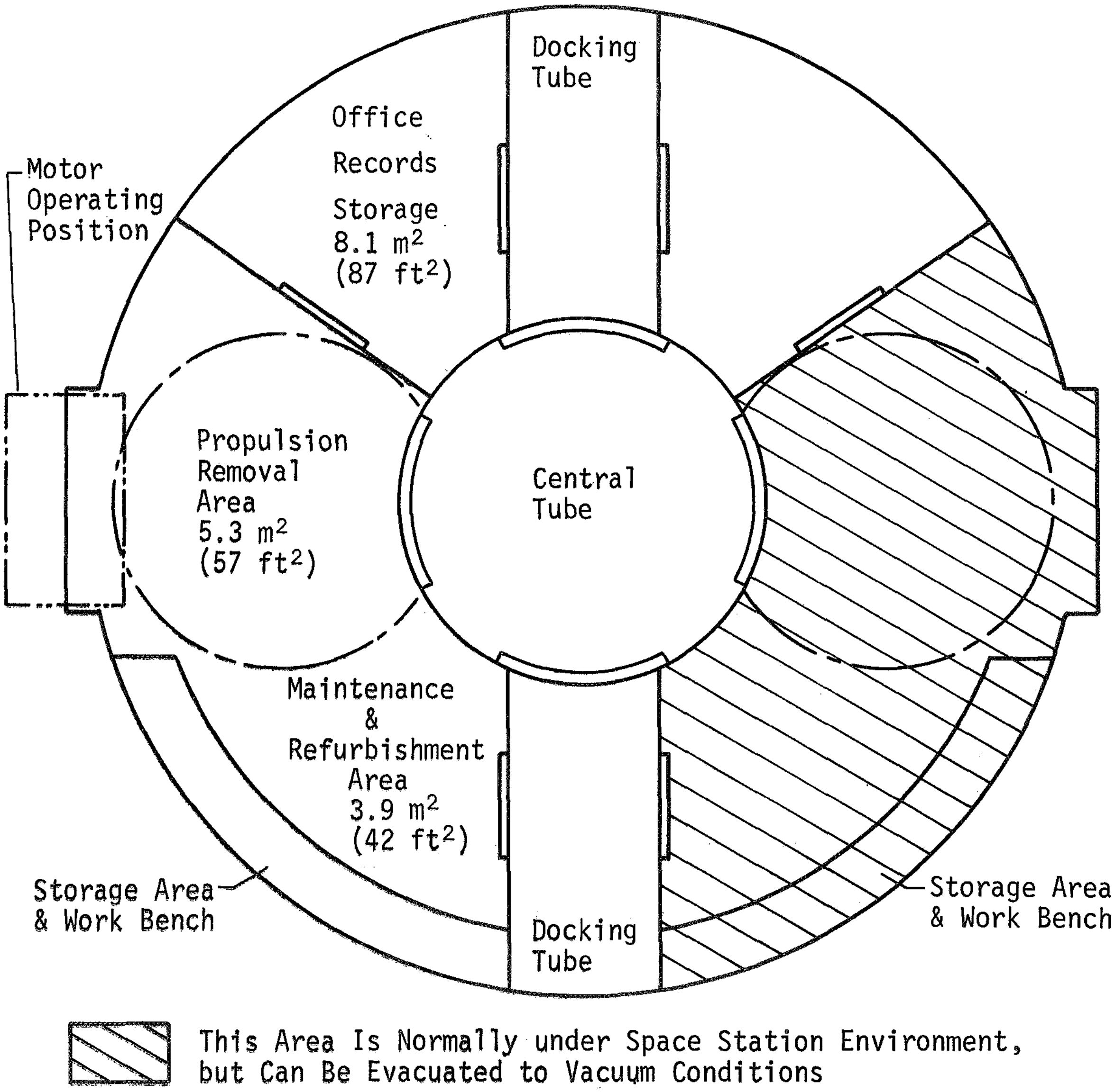


Fig. IV-3 Onboard Servicing Propulsion Compartment Layout
Scale: 1 in. = 4 ft

The refurbishment work area will be completely enclosed, providing for an evacuation of the area should IVA maintenance be required. The refurbishment work area provides for removal, installation, servicing, repair, and storage of APS motors and spare parts. A portion of the motor compartment, separate from the refurbishment work area, will serve as an administrative area for the storage of inventory records, maintenance procedure manuals, and will serve as the motor refurbishment observation area during IVA motor repair.

The spin/despin motors, because of their greater size, require more room during handling and servicing than the smaller attitude control motors. The space required in the motor compartment is, therefore, predicted on servicing the spin/despin motors. The spin/despin motor and tube assembly is approximately 1.37 m (4.5 ft) long, approximately 0.5 m (1.5 ft) in diameter, and weighs 127 kg (280 lb) fully loaded. The motor and refurbishment tube assembly is loaded onto a dolly and moved to the refurbishment area for servicing. The removal and installation area is 5.6 sq m (60 sq ft) and the servicing area is 3.7 sq m (40 sq ft).

A 2.8-sq-m (30-sq-ft) work table, used for servicing and adjustment, is provided in the refurbishment area. During standby operation of the ACS propulsion system, the refurbishment area can be used for other Space Station repair and service functions. Storage space is provided around the work table for replacement fuel grains, igniter parts, O-rings, spare motor cases, hand tools, valves, filters, and facility equipment.

3. Attitude Control Motor Facility Requirements

Sixteen APS motors control the pitch, yaw, and roll of the Space Station. Each motor is 178 mm (7 in.) in diameter, 762 mm (30 in.) long, and has a loaded weight of 16 kg (35 lb). The motors are mounted on two 8-motor pads, 180 deg apart. The 16 motors can be fired individually or in pairs to provide redundant control of pitch, yaw, and roll. After approximately 400 sec of operation, the motors will require new fuel grains and a general refurbishment and checkout. Three refurbishment concepts were considered and are discussed in the following three sections. Attitude control motor refurbishment spares are listed in Table IV-16.

a. Movable Tube Refurbishment Concept - The two candidate layouts for the movable tube thruster pads are shown in Fig. IV-4. The straight nozzle approach shown on the left uses a 2x2-m (80x80-in.) thruster pad that is raised 0.3 m (12 in.) to allow the eight ACS motors to be extended and retracted perpendicular to the pad and still point in their required directions. The canted nozzle approach shown on the right uses a flush 2.4x2-m (96x 80-in.) thruster pad. All APS motors are extended perpendicular

Table IV-16 Attitude Control Motor Refurbishment Facilities and Spares

REFURBISHMENT APPROACH	FACILITIES & EQUIPMENT	SPARES
Movable Tube	2 Raised Thruster Pads 2 x 2 x 0.3 m (80 x 80 x 12 in.) or 2 Flush 2x2.4-m (80x96-in.) Pads 2 Complete Refurbishment Tube & Door Assemblies	1 Spare Refurbishment Tube 1 Spare Door Assembly 12 Replacement External Motor Seals 2 Sets of Replacement Refurbishment Seals Door Seal Door Assembly Seal Refurbishment Tube Seal Refurbishment Tube Door Seal
Parallel Transfer	2 Flush Thruster Pads 2 x 2.3 m (80 x 90 in.)	
	16 Chambers	1 Spare
	32 Electric Motors	2 Spares
	48 Seals	6 Spares
	16 Motor Mounting Plates	1 Spare
	16 Retraction/Extension Mechanisms	1 Spare
	16 Reversing Mechanisms	1 Spare
Nozzle Cap	2 Raised Thruster Pads 1.8 x 1.8 x 0.3 m (69 x 69 x 12 in.)	
	16 Nozzle Caps	1 Spare
	16 Retraction/Extension Mechanisms	1 Spare
	16 Locking Mechanisms	1 Spare
	16 Nozzle Cap Seals	2 Spares
	16 Motor Attach Seals	2 Spares
	16 Skin Seals	2 Spares

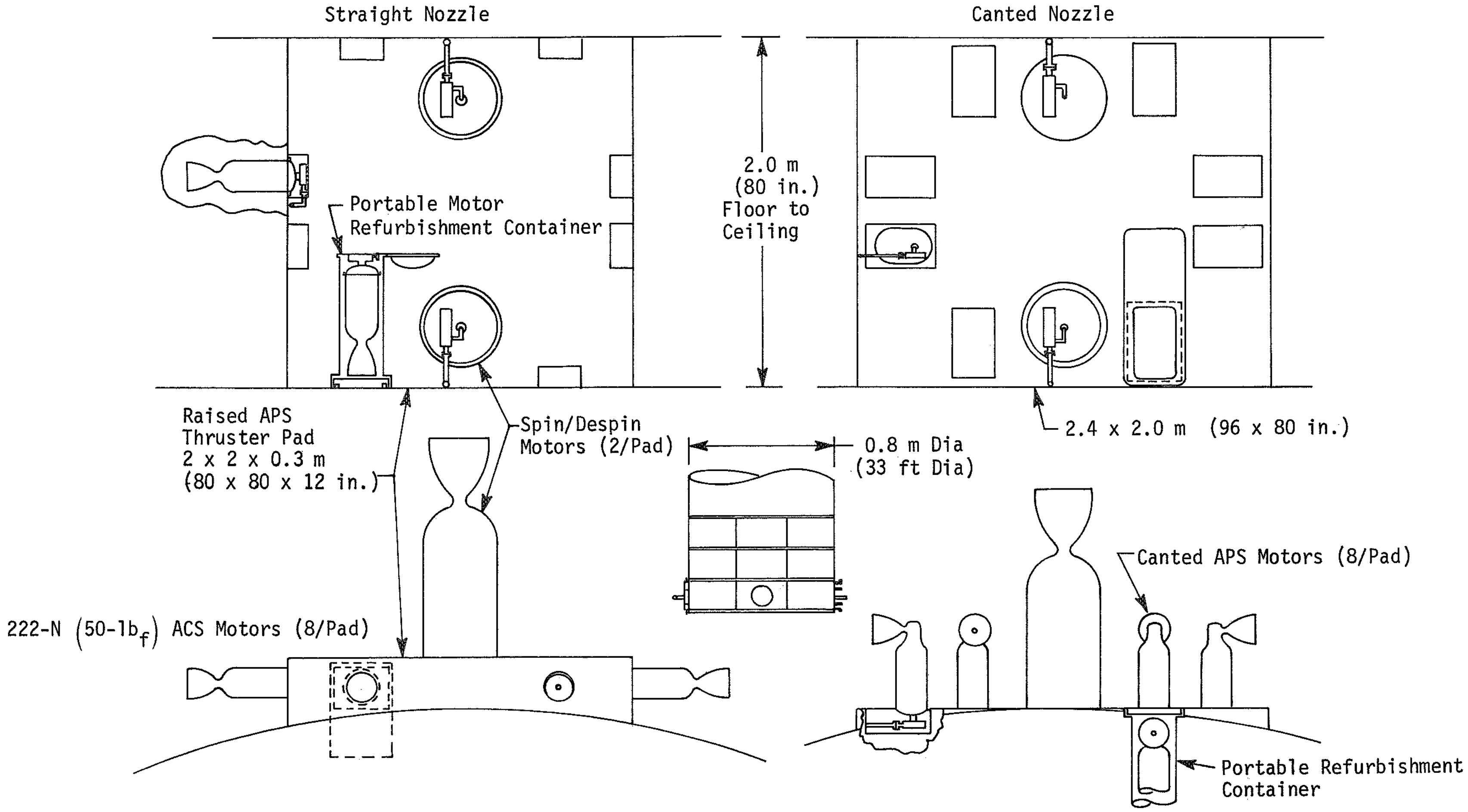


Fig. IV-4 Thruster Pad Designs for Movable Tube Refurbishment Concept to the top surface of the pad. The nozzles are oriented to provide thrust in the proper direction.

Both motor design approaches are refurbished in the same manner. During standby or motor operation, the forward closures, ignition system, oxidizer control valves, and electrical lines would be protected by a cover. During refurbishment, the cover would be removed and a sliding door assembly would be installed. A motor refurbishment container would be connected over the door assembly. The motor would then be withdrawn into the tube and the sliding door would be closed. The motor could then be refurbished in place (as shown) or moved to the maintenance area for inspection and repair. All components (the door assembly, the refurbishment tube, and the loaded motor) would weigh less than 111 kg $\left(25\ \mathrm{lb_m}\right)$ in a 0.7-g environment and could be easily handled by one man.

Major APS facilities required for the movable tube concept include thruster pads, refurbishment equipment, and spares. Both motor designs require two floor-to-ceiling thruster pads. The straight nozzle pad is only 2 m (80 in.) wide -- vs 2.4 m (96 in.) for the canted nozzle) -- but it is also raised 0.3 m (12 in.). This will require an aerodynamic fairing during launch. The thruster pads will have GOX, electrical, and instrumentation lines for each motor, as well as brackets to hold the refurbishment door assemblies.

Three sets of refurbishment containers and door assemblies are sufficient for the 16 APS motors. This would allow two simultaneous motor refurbishments, while holding one refurbishment tube and door assembly in reserve as a spare. Several sets of door and refurbishment container seals would be carried as replacements. Sixteen forward closure caps would also be required to protect the motor during operation and standby and to provide redundant forward closure retention.

b. Parallel-Transfer Refurbishment Concept - The parallel transfer thruster pad design is shown in Fig. IV-5. The APS motors are mounted on two mounting pads, 180 deg apart. Each pad is 2.3 x 2.0 m (90 x 80 in.) in area. In the standby or firing positions, the APS motors are extended above the mounting pad. During refurbishment, the motor is retracted and reversed in its own refurbishment chamber. These chambers extend 0.5 m (20 in.) into the motor compartment. After the chamber has been pressurized, the inner door can be opened to remove the motor.

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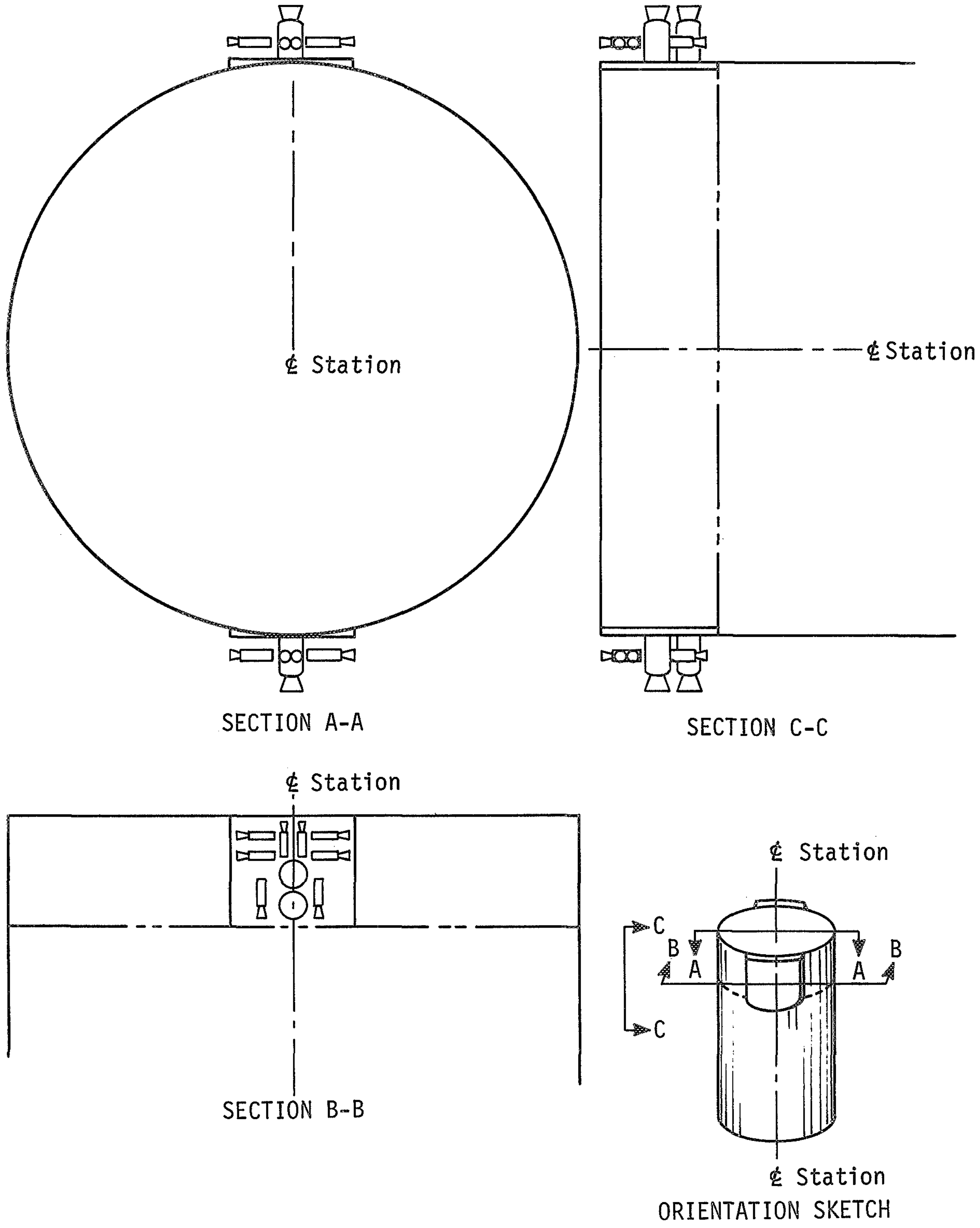
¢ Station
¢Station
SECTION A-A
SECTION C-C
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SECTION B-B
¢ Station
C
B
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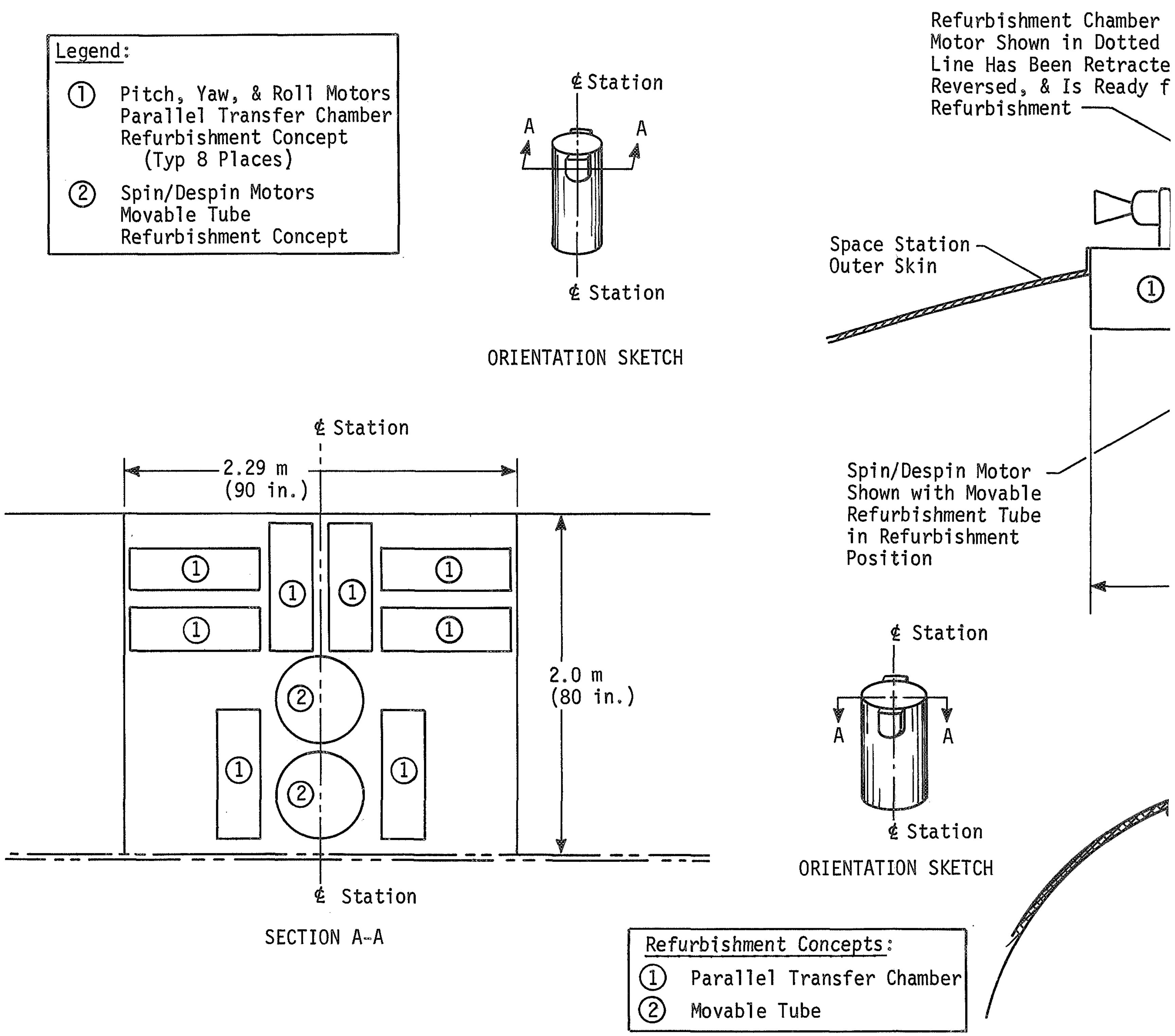
C
¢ Station
ORIENTATION SKETCH

1


Legend:
① Pitch, Yaw, & Roll Motors Parallel Transfer Chamber Refurbishment Concept (Typ 8 Places)
② Spin/Despin Motors Movable Tube Refurbishment Concept
¢Station
A
A
¢ Station
ORIENTATION SKETCH
¢ Station
2.29 m (90 in.)
2.0 m (80 in.)
①
②
¢ Station
SECTION A-A
Refurbishment Chamber Motor Shown in Dotted Line Has Been Retracte Reversed, & Is Ready f Refurbishment
Space Station Outer Skin
Spin/Despin Motor Shown with Movable Refurbishment Tube in Refurbishment Position
¢ Station
A
A
¢ Station
ORIENTATION SKETCH
Refurbishment Concepts:
① Parallel Transfer Chamber
② Movable Tube

2

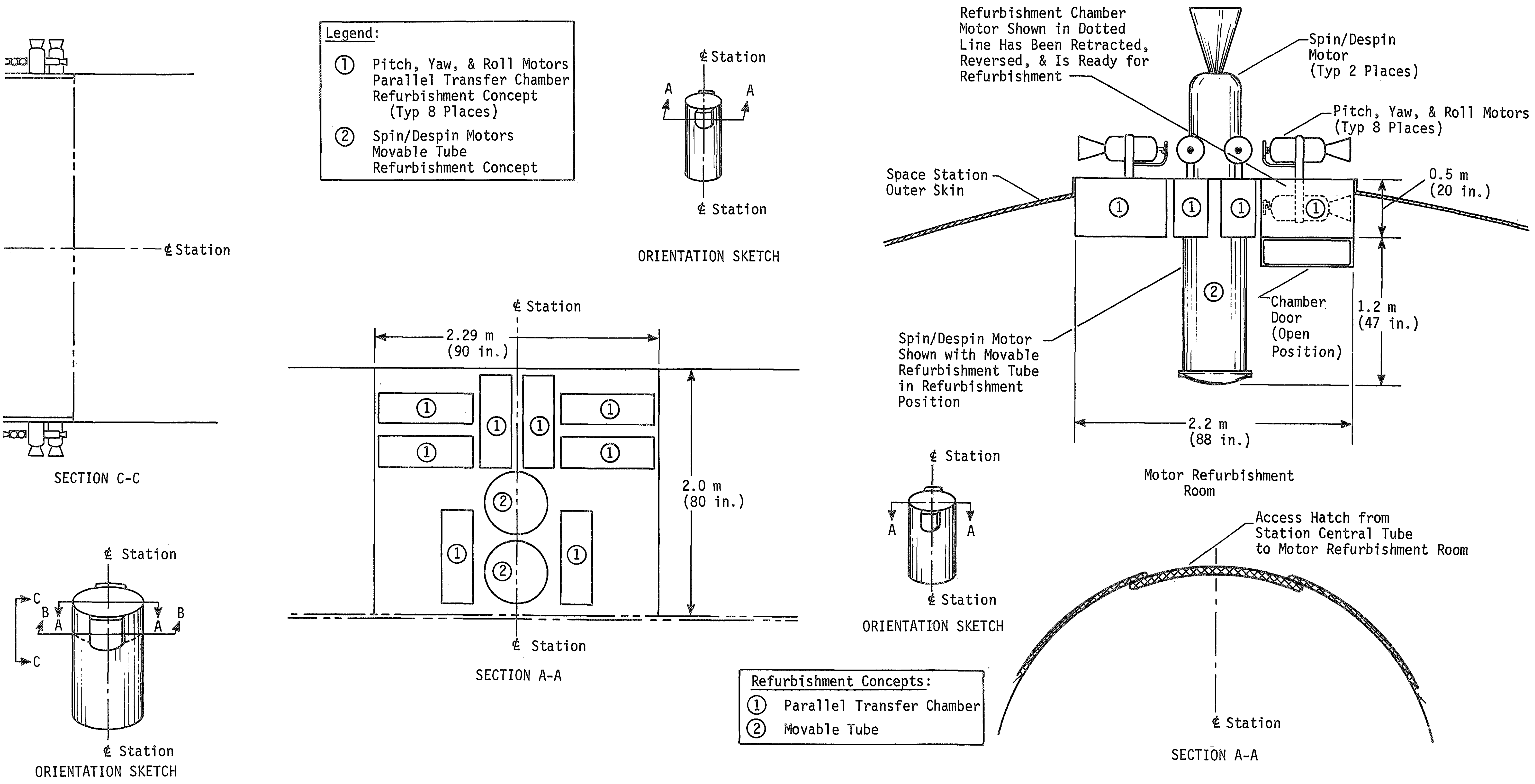


Fig. IV-5 Parallel-Transfer Concept

2

3

The mounting pads are plumbed to provide GOX to the APS motors. The oxidizer lines attached to the motors are flexible, allowing the motors to retract, extend, and reverse in the refurbishment chamber. The pads provide electrical cables for motor ignition, instrumentation, and operation of the retraction, extension, and rotation mechanism.

Each motor refurbishment chamber has a three-way valve to pressurize and depressurize the chamber during motor retraction.

There are eight refurbishment chambers per pad, one for each motor. Each chamber is 254 mm (10 in.) wide, 762 mm (30 in.) long, and 508 mm (20 in.) deep, and is permanently mounted beneath the motor pad. A door on the bottom of the chamber provides access to the inside of the chamber. The retraction/rotation system requires two electric motors, one motor for operating the retraction and extension mechanism and one for operating the rotation mechanism. The motors are connected so that either one can be used alone to provide power for retraction, rotation, and extension. Seals are provided on both sides of the mounting plate and the access door. The three seals are the same size and can be replaced in a shirtsleeve environment without evacuating the motor compartment.

A certain number of replacement parts will be needed as spares to back up the operation of the parallel-transfer refurbishment concept. The 16 refurbishment chambers are the same size and are interchangeable; one chamber will be provided as a spare. The 32 electrical motors that are used to extend, retract, and rotate the APS thrusters are interchangeable; two electrical motors will be provided as spares. The 48 chamber seals (three seals per chamber) are the same size and are interchangeable; six seals will be provided as spares. The 16 motor mounting plates, the 16 retraction/extension mechanisms, and the 16 reversing mechanisms require one spare unit each.

c. Nozzle Cap Refurbishment Concept - The design of the nozzle cap thruster pad is shown in Fig. IV-6. The APS motors are mounted on two mounting pads, 180 deg apart, that are 1.8 by 1.8 m (69 by 69 in.) in area. The mounting pads extend out from the Space Station about 0.3 m (12 in.). The APS motors are permanently mounted inside the pad so that the nozzle and aft closure are exposed outside the pad. During refurbishment, the motor nozzle is covered with a sealed nozzle cap. The cap is normally positioned alongside the nozzle during motor standby and firing.

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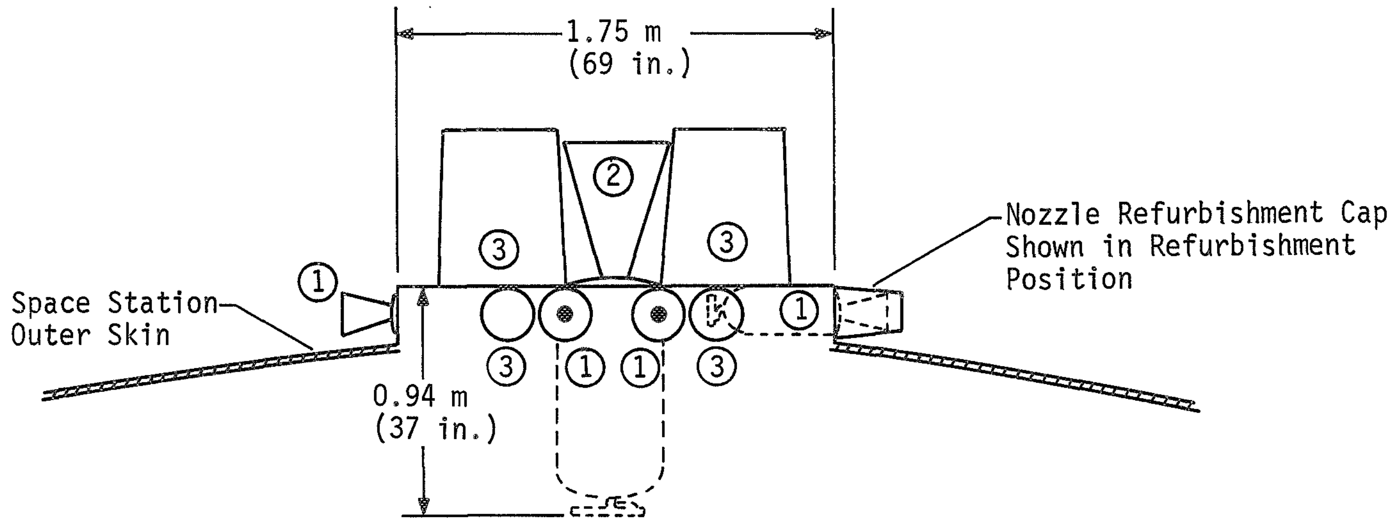
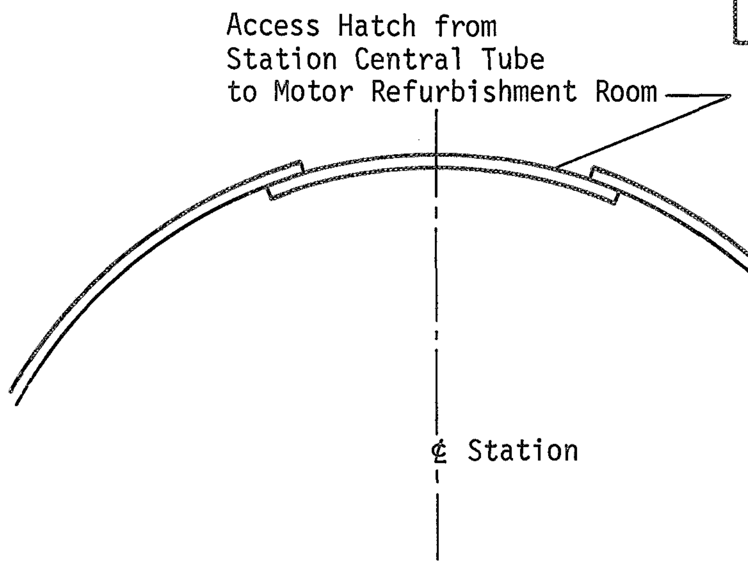
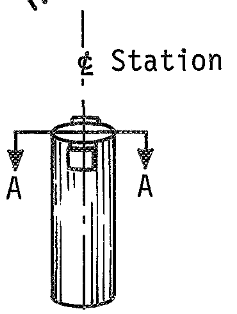


Motor Refurbishment Room

Legend:
- ① Pitch, Yaw, & Roll Motors (Typ 8 Places)
- ② Spin/Despin Motors (Typ 2 Places)
- ③ Nozzle Refurbishment Cap

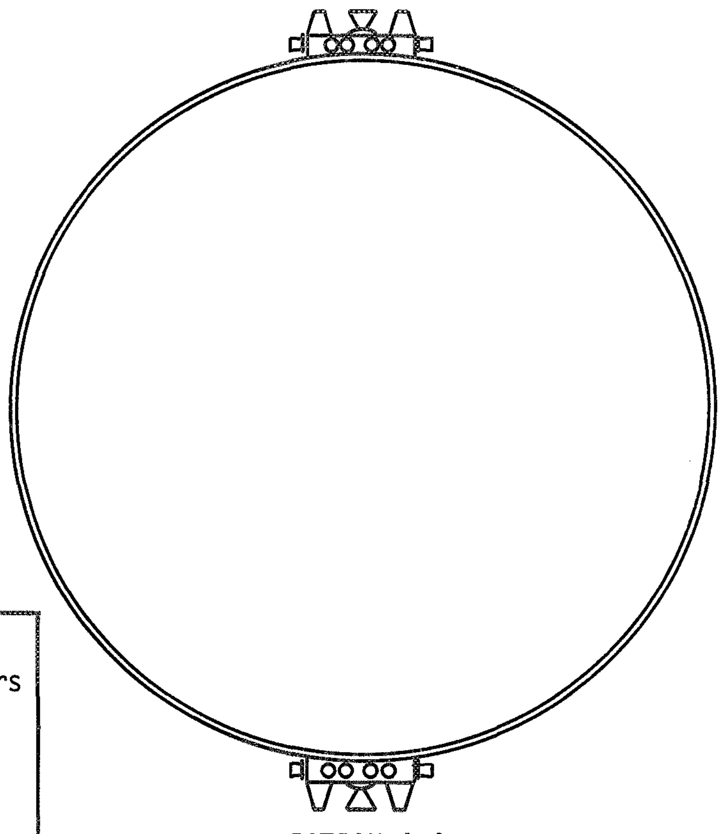


SECTION A-A

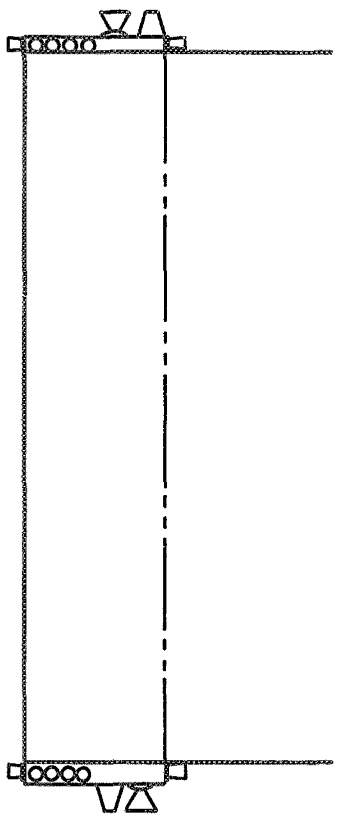


ORIENTATION SKETCH

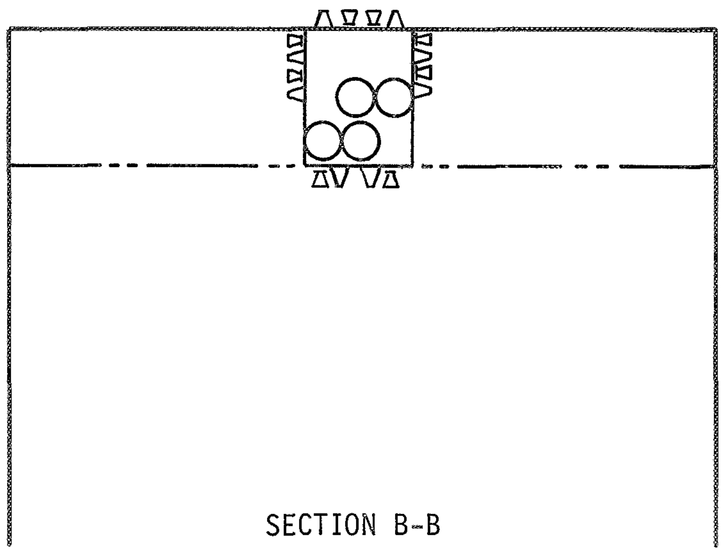
1



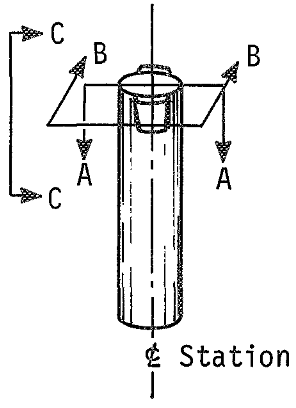
SECTION A-A



SECTION C-C



SECTION B-B



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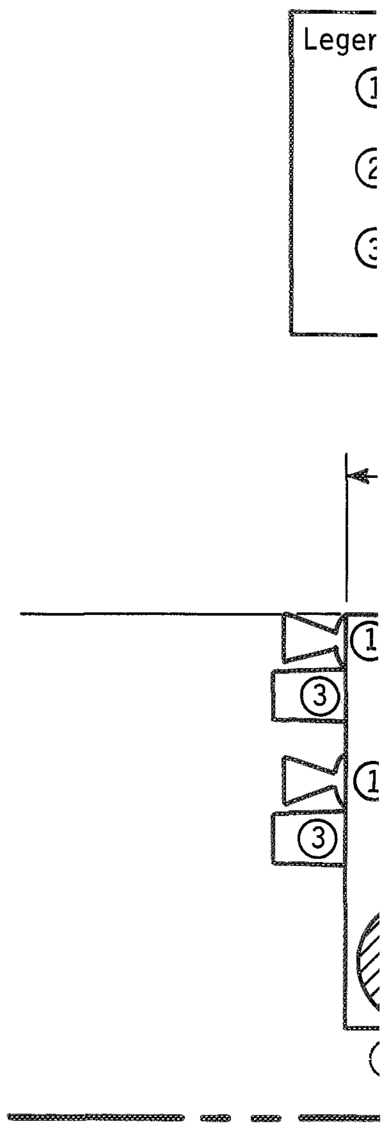


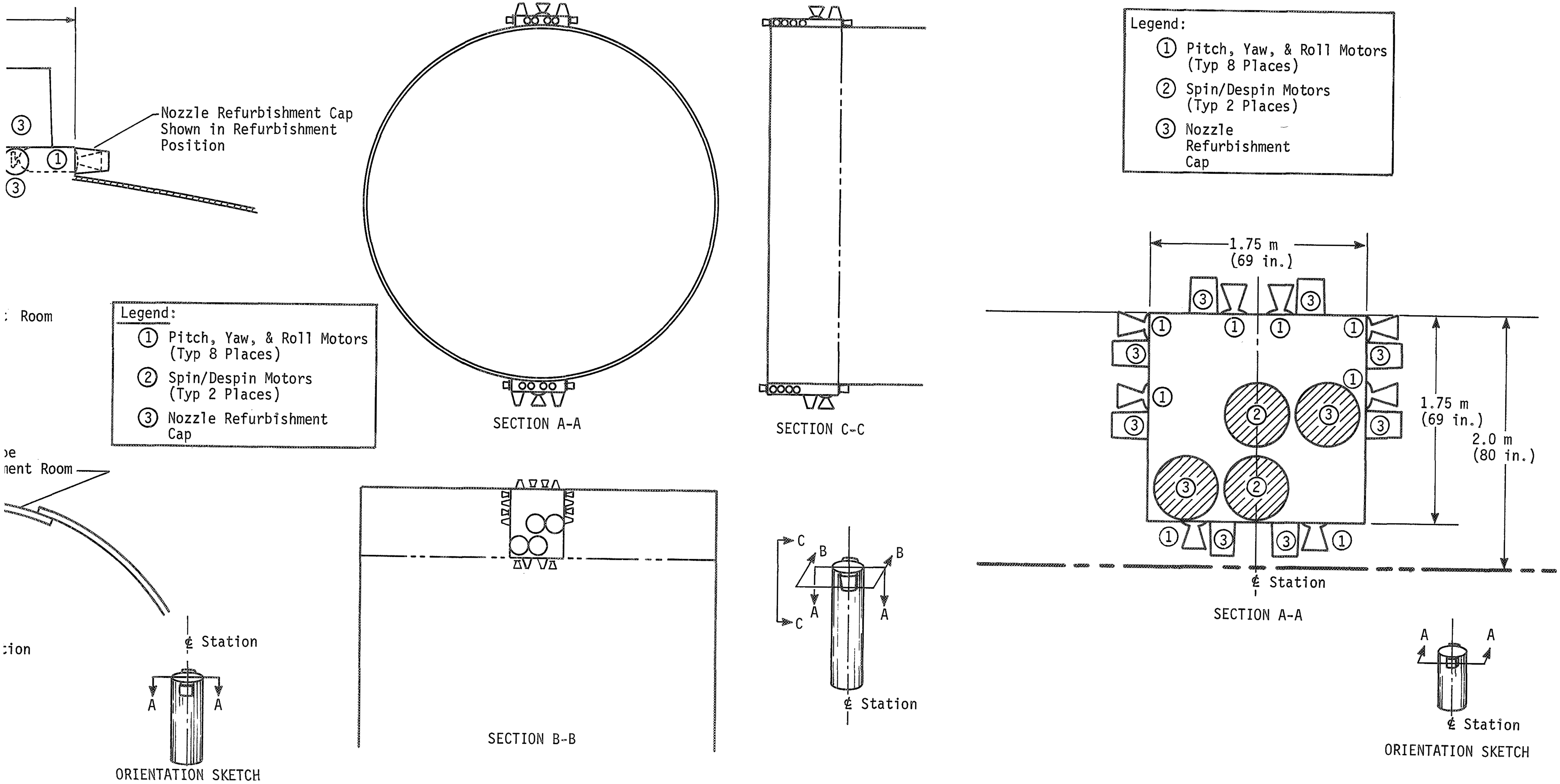


Fig. IV-6 Nozzle Refurbishment Cap Concept

Plumbing at the mounting pads provides GOX to the APS motors during firing.

There are eight nozzle caps per pad, one for each motor. Each cap is about 300 mm (12 in.) long and 250 mm (10 in.) in diameter, and can be extended, rotated, retracted, and locked in position over or beside a motor nozzle. Seals are provided to seal the motor during refurbishment.

The following replacement parts will be needed as spares to back up the operation of the nozzle cap refurbishment concept:

1) One nozzle cap;
2) One retraction/extension mechanism;
3) One locking mechanism;
4) Two nozzle cap seals
5) Two motor attachment seals;
6) Two skin seals.

4. APS Equipment and Spares

Regardless of the refurbishment concept, the APS will require storage and maintenance facilities for fuel grains, oxidizer control valves, ignition systems, forward closure/motor case assemblies, filters, regulators, etc.

a. ACS Motor Equipment and Spares Requirements - A list of required equipment and spares is given in Table IV-17. Storage facilities will be provided for 10 replacement fuel grains, each 203 mm (8 in.) in diameter x 356 mm (14 in.) long, and for 12 motor seals (10 replacements and two spares). These spares would provide a 40% margin over the total impulse required for the first 6 months. Two spare motor case and nozzle assemblies would be carried as spares, along with one forward closure for the snap ring, pin, and bolted flange designs and two closures for the double bayonet or bayonet/screw approach. Spare parts for the oxidizer control assembly would include two replacement oxidizer valves, two injectors, and two quick-disconnects.

Ignition system spares depend on the system selected. The propane system would require 11 propane cans, 12 spark plugs, and two spare trip valves. The heated oxidizer line system would require 12 replacement heating elements and two spare capacitors. The pyrogen ignition system is not suitable for the APS motors,

Table IV-17 Attitude Control Motor Facilities and Spares Requirements

COMPONENT	FACILITIES & EQUIPMENT	SPARES
Motors	16 Complete Thrust Chamber Assemblies Forward Closure Motor Case & Nozzle Assembly Oxidizer Control Valve Injection System Injector	2 Spare Forward Closures 2 Spare Motor Case & Nozzle Assemblies 2 Spare Oxidizer Control Valves 2 Spare Injectors 2 Spare Quick-Disconnects 10 Replacement Fuel Grains 203 mm (8 in.) in diameter by 355 mm (14 in.) long) 12 Replacement Motor Seals
Ignition Assemblies		
Propane System		11 Replacement Propane Cans 12 Replacement Spark Plugs 2 Spare Trip Valves
Oxidizer	12 DPST Ignition Relay	
Heated Line	12 Capacitors 2 Selector Switches	12 Replacement Heating Elements 2 Spare Capacitors & Relays 1 Spare Selector Switch
Pyrogen Igniter	Not Intended for ACS Motors	
Precombustor		12 Replacement Grains with Spark Electrodes 2 Spare Induction Coils
Forward Closure Retention Systems		
Snap Ring	2 Snap Ring Pliers	1 Spare Snap Ring Pliers 2 Spare Snap Rings
Double Bayonet	2 Forward Closure Removal Tools	1 Spare Tool 1 Spare Forward Closure 1 Spare Motor Case
Bayonet Screw		1 Spare Forward Closure 1 Spare Motor Case
Pin	2 Pin Removal Tools	1 Spare Removal Tool 1 Spare Forward Closure
Bolted Flange	Small Hand Tools	1 Spare Forward Closure

due to the large number of restarts. The precombuster design would require 12 replacement grains and two spare induction coils. The snap ring forward closure retention system, and both the double bayonet and the bayonet screw designs are impractical for use with the 406-mm (16-in.) diameter motors. The pin design requires a pin extractor, one spare extraction tool, four spare pins, one spare strap or wire retention hardware, and one spare forward closure. The bolted flange design requires small hand tools, four spare pairs of nuts and bolts, and one spare forward closure.

b. Spin/Despin Motor Equipment and Spares Requirements - The spin/despin system uses three 1112-N $\left(250\text{-lb}_f\right)$ motors, each delivering 1/3 of the total impulse required for a spin or despin maneuver. Before a spin/despin maneuver, all three motors are loaded and two are extended into firing position. The first motor is fired, then retracted and replaced by the third motor while the second motor is firing. After the maneuver, the motors are retracted, replaced by motor hole covers, refurbished, moved on a handling dolly to the opposite side of the Space Station, and installed for the next spin/despin maneuver.

Spin/despin facility spares are shown in Table IV-18. Spares include one each of the following: forward closure, motor case/nozzle assembly, oxidizer valve, injector, and quick-disconnect. Four additional fuel grains (three replacements and one spare) each 406 mm (16 in.) in diameter and 784 mm (31 in.) long, would be provided to complete the first spin/despin cycle (6 months). One spare motor hole cover and four replacement seals would be provided, along with dolly spares.

The propane ignition system would require one spare propane can, one spare spark plug, and one spare trip valve. The heated oxidizer line would require one spare heating element and one spare capacitor. The pyrogen ignition system (assuming the spin/despin motors would operate in a burn-to-completion mode), would require three replacement igniters and one spare igniter. The precombuster system would require one spare grain and one spare induction coil. The snap ring forward closure retention system would require two snap ring pliers and one spare snap ring. The double bayonet design would not be attractive for the larger diameter spin/despin motors. A manually turned single bayonet or bayonet screw would offer alternative retention systems and would require no spares.

The spin/despin motors could be used with any of the APS thruster pad designs. Both the movable tube and the nozzle cap

Table IV-18 Spin/Despin Motor Facilities and Spares

COMPONENT	FACILITIES & EQUIPMENT	SPARES
Motors	3 Complete Thrust Chamber Assemblies Forward Closure Motor Case & Nozzle Assembly Oxidizer Control Valve Ignition System Injector Fuel Grain	1 Spare Forward Closure 1 Spare Motor Case & Nozzle Assembly 1 Spare Oxidizer Valve 1 Spare Injector 1 Spare Quick Disconnect
	4 Motor Hole Covers	4 Replacement Grains 406 mm (16 in.) in Diameter by 784 mm (31 in.) long - 5 Segments
	1 Motor Handling Dolly	1 Spare Motor Hole Cover 4 Motor Hole Cover Seals & Dolly Spares
Ignition Assembly		
Propane System		1 Spare Propane Can 1 Spare Spark Plug 1 Replacement Trip Valve
Heated Oxidizer Line		1 Spare Heating Element 1 Spare Capacitor
Pyrogen Ignitor (Single Burn Mode)		3 Replacement Igniters 2 Spare Igniters
Precombustor		1 Spare Grain With Spark Electrodes 1 Spare Induction Coil
Forward Closure Retention Systems		
Snap Ring	Not Practical for 406-mm (16-in.) Diameter	
Double Bayonet	Not Practical for 406-mm (16-in.) Diameter	
Bayonet/Screw	Not Practical for 406-mm (16-in.) Diameter	
Pin	Pin Extraction Tool	1 Spare Extraction Tool 4 Spare Pins 1 Spare Strap or Wire Retention Hardware 1 Spare Forward Closure
Bolted Flange	Small Hand Tools	4 Spare Pairs of Nuts & Bolts 1 Spare Forward Closure
Refurbishment Facilities		
Movable Tube	Use APS Pads 1 Complete Refurbishment Tube & Door Assembly	1 Spare Refurbishment Tube & Door Assembly 1 Spare External Motor Seals 1 Set of Replacement Refurbishment Seals Door Seals Door Assembly Seal Refurbishment Tube Seal Refurbishment Tube Door Seal
Nozzle Cap	2 Nozzle Cap Assemblies Nozzle Cap Holding Clamp Assembly Nozzle Cap Cap Extension Bar	2 Spare Sets of Seals Cap Pad Holding Clamp Extension Bar 1 Spare Cap 1 Spare Clamp 1 Spare Extension Bar

approach would be acceptable for motor refurbishment. The movable tube approach would require two refurbishment tube and door assemblies (including one spare), one spare external motor seal, and one spare set of refurbishment seals. The nozzle cap approach would require two nozzle cap assemblies, spare parts for a third assembly, and two complete sets of seals.

c. Oxidizer Feed Assembly Equipment and Spares Requirements - The selection of onboard spares was based on the reliability analysis discussed in Subsection IV-B-4 and on the following criteria:

1) Components whose failure would adversely affect crew safety. No components meet this criterion;
2) Components whose failure would degrade mission success;
3) Components with a high failure probability.

Based on the above criteria, the following reserve of spares at launching was established:

1) Two 3-way valves;
2) Two control valves;
3) Two relief valves;
4) Two control regulators;
5) Two filters.

Equipment is required to remove fluid from a system to perform inflight maintenance. This can be accomplished through purging, inverse pumping, or by the vacuum cleaner technique.

Means must be provided for disposing of contaminated fluid and components that have been replaced. Such items will probably be stored until the logistics craft resupply interval.

Fluid fittings for inflight maintenance must seal after repeated assemblies and disassemblies. The threads must not gall, and the seal must be reparable; require simple tools for assembly, and provide reasonable sealing characteristics.

New methods are required to remove and replace fittings and to repair tubing. The method and the tools must be adaptable to both partial and zero gravity, must be simple, provide control of contamination, be compatible, and require minimum crew training.

5. Maintenance, Repair, and Handling Equipment

The auxiliary propulsion compartment provides a comfortable shirtsleeve environment. This compartment will have adequate lighting, a ventilation system that will keep the oxygen supply fresh and clean, a temperature and humidity control. Safety and emergency equipment, such as a fire extinguisher and life support suit, will be provided. A two-way communication system with other compartments of the Space Station will also be provided.

Because the spin/despin motors are too large to be conveniently refurbished or repaired by hand, a mobile dolly will be provided. This dolly can also be used by the crew as a stepladder during gravity operation and as an anchor during weightless operation. In addition, it can be tied down in the work area and used as a work stand for servicing the APS motors.

A work area and a work table are provided in the propulsion compartment. This work area will be used to refurbish the APS. The work table can be used to service and repair smaller parts and to calibrate and adjust mechanisms. Tiedowns have been provided in both the work area and work table to hold component parts stationary during weightless servicing and repair. The work area will provide for pressure and leak check operations. An electrical patch board will be used to check out and verify electrical components during and after servicing. Space will be provided around the work table for storing motor grains, igniter parts, spare parts, and tools. The area around the motor installation pad and the work area is enclosed to provide evacuation capability should IVA be required for APS repair.

A separate administrative area is provided to store inventory records and maintenance procedure manuals, and to observe propulsion performance. This area shall have cabinetry files and an observation window for observing activity in the motor servicing enclosure.

The propulsion system will require servicing and refurbishment according to both a scheduled and nonscheduled plan. The type of equipment needed to maintain and service the APS is shown in Table IV-19.

A nonflammable silicone grease is used to lubricate the oxidizer control valve, the ignition canister trip valve, and the refurbishment extraction/contraction mechanism. O-rings and threads will be lubricated with nonflammable lubricants before being assembled.

Table IV-19 Onboard Servicing and Repair of APS Motors

CONCEPT	LUBRICATE	CALIBRATION OR ADJUSTMENT	REMOVE & REPLACE	PRESSURE TEST OR LEAK CHECK	VISUAL INSPECTION	ELECTRICAL CHECKOUT	SCHEDULED MALFUNCTION DETECTION	FACILITY
Ignition								
Butane or Propane Spark-Initiated Precombuster	Grease Gun (Silicone)	Small Hand Tools	Spark Plug Wrench	Leak Detection Solution Oxidizer Injector Plug	Flashlight	Oscillo-scope Power Source Vacuum Tube Volt Meter	Oxidizer Injector Removal & Installation Tool	Refurbishment Compartment
Pyrogen Hot Gas Igniter (Single Shot)	Grease Gun (Silicone)	N/A	Squib Removal & Installation Tool Igniter Removal & Installation Tool	Leak Detection Solution Oxidizer Injector Plug	Flashlight	Power Source VTVM	Oxidizer Injector Removal & Installation Tool	Refurbishment Compartment
Electrically Heated Precombustor	Grease Gun (Silicone)	N/A	Small Hand Tools	Leak Detection Solution Oxidizer Injector Plug	Flashlight VTVM	Power Source VTVM	Oxidizer Injector Removal & Installation Tool	Refurbishment Compartment
Spark-Initiated Precombustor	Grease Gun (Silicone) Oil Can	N/A	Special Wrench to Remove & Install PMM Charge	Leak Detection Solution Oxidizer Injector Plug	Flashlight VTVM	Power Source VTVM	Oxidizer Injector Removal & Installation Tool	Refurbishment Compartment
Forward Closure Retention								
Snap Ring	O-Ring Lube (Silicone)	N/A	Snap Ring Pliers	Nozzle Plug Pressure Gage Leak Detection Solution	Flashlight Magnifying Glass	N/A	N/A	Refurbishment Compartment
Double Bayonet	O-Ring Lube (Silicone)	N/A	Hand Grip Removal & Installation Tool	Nozzle Plug Pressure Gage Leak Detection Solution	Flashlight Magnifying Glass	N/A	N/A	Refurbishment Compartment
Bayonet/Screw Flange	O-Ring Lube (Silicone) Thread Lube	N/A	N/A	Nozzle Plug Pressure Gage Leak Detection Solution	Flashlight Magnifying Glass	N/A	N/A	Refurbishment Compartment
Pin	Silicone Lube	N/A	Pin Extractor	Nozzle Plug Pressure Gage Leak Detection Solution	Flashlight Magnifying Glass	N/A	N/A	Refurbishment Compartment
Bolted Flange	Thread Silicone Lube	N/A	Small Hand Tools	Nozzle Plug Pressure Gage Leak Detection Solution	Flashlight Magnifying Glass	N/A	N/A	Refurbishment Compartment
Nozzle Throat	N/A	N/A	Small Hand Tools	Nozzle Plug Pressure Gage Leak Detection Solution	Micrometer Flashlight	N/A	N/A	Refurbishment Compartment
Refurbishment								
Movable Tube	Grease Gun Bearing Grease	Small Hand Tools Gage	Small Hand Tools	Pressure Gage Leak Detection Solution	Flashlight Magnifying Glass	Power Source	N/A	Refurbishment Compartment
Parallel Transfer	Grease Gun	Small Hand Tools Gage	Small Hand Tools	Pressure Gage Leak Detection Solution	Flashlight Magnifying Glass	Power Source VTVM	N/A	Refurbishment Compartment
Nozzle Cap	Grease Gun	Small Hand Tools Gage	Protective & Life Support Clothing & Equipment	Pressure Gage Leak Detection Solution	Flashlight Magnifying Glass	N/A	N/A	Refurbishment Compartment
Motor Grain	N/A	N/A	N/A	N/A	Flashlight Magnifying Glass	N/A	Fuel Depletion Detection System	Grain Storage Area
Oxidizer Feed Assembly								
Pressurrant Tank	N/A	N/A	Small Hand Tools	Pressure Gage	Flashlight	N/A	Low Tank Pressure	Oxidizer Feed Compartment
Oxidizer Tank	N/A	N/A	Small Hand Tools	Pressure Gage	Flashlight	N/A	Low Line Pressure	Oxidizer Feed Compartment
Regulators	N/A	Small Hand Tools Gage	Small Hand Tools	Leak Detection Solution	Flashlight	N/A	N/A	Oxidizer Feed Compartment
Filters	N/A	N/A	Small Hand Tools	Leak Detection Solution	Δ P Button	N/A	Differential Pressures	Oxidizer Feed Compartment
Control Valves	N/A	N/A	Small Hand Tools	Leak Detection Solution	Flashlight	N/A	N/A	Oxidizer Feed Compartment

The ignition trip valve and the refurbishment extension and retraction mechanisms are calibrated and adjusted using inspection hand tools. Certain special hand tools will be required to remove and replace component parts. A spark plug wrench will be used to replace ignition spark plugs. The pyrogen igniter will require a removal and installation tool. A special tool will be used to remove and install the PMM igniter charge in the spark-initiated precombustor igniter concept. Depending on which forward closure retention concept is used, a snap ring pliers, pin extractor, small hand tools, or hand grip removal and installation tool will be required. A fluid decontamination and removal tool will be required for the oxidizer feed system.

After propulsion servicing and refurbishment, pressure leak checks will be made to determine the integrity of seals. A pressure gage and leak detection solution will be needed to perform the check on the refurbishment chamber. A nozzle plug is needed to perform a check of the motor. The pressure gage and leak detection solution are required for the OFA.

A flashlight and magnifying glass are needed to perform a visual inspection of the forward closure retention concept, the OFA, and movable tube and parallel-transfer refurbishment concepts.

An electrical patchboard, connecting the motor electrical system to electrical checkout equipment, will be provided in the motor servicing compartment. An oscilloscope, power source, and a vacuum tube voltmeter will be required.

6. Time Requirements for APS Motor Refurbishment

Propulsion refurbishment times and schedules have been evaluated for the ACS motors, the spin/despin motors, and the OFA. Three principal APS motor refurbishment approaches are described in terms of required tasks and completion time. Spin/despin refurbishment is similarly discussed. Since spin/despin maneuvers are relatively short, they require more intensive maintenance by the crew. However, several procedures are discussed that permit the crew to postpone part of the spin motor refurbishment to reduce crew workload during these maneuvers.

a. ACS Motor Refurbishment Time Requirements - Each ACS motor will be refurbished after every 400 sec of operation, which occurs, on the average, every 2 years. During refurbishment, the motor case and closure will be visually inspected, new O-rings will be installed, the igniter assembly will be refurbished, and a new fuel grain will be installed in the motor. Tables IV-20 thru IV-22 give a function time analysis for the three candidate refurbishment concepts.

b. Spin/Despin Motor Refurbishment Schedule Concepts - The spin/despin motors will use either the nozzle cap or movable tube concept for maintaining Space Station environment during servicing and refurbishment operations. Considering a refurbishment interval beginning at the termination of motor operation and ending when the motor is ready for refire, the nozzle cap approach requires a 30-minute servicing interval, and the movable tube, a 45-minute servicing interval (see Tables IV-23 and IV-24).

To accomplish a spin or despin maneuver, a total impulse of 3,078,168 N-sec (692,000 lb-sec) is required. The baseline design makes use of three motors, each providing 1/3 of the total required impulse. The three-motor concept was determined to be an optimum system. Using one or two motors requires large, hard-to-handle grains; and using more than three motors requires handling and storing many small grains.

The maneuver motors can be refurbished during a spin or despin, or during the period before the next scheduled spin or despin. Refurbishing after the maneuver allows the crew to remain at their duty stations until completion of the maneuver. Refurbishing after the maneuver also allows the use of both the spin and despin refurbishment areas simultaneously.

There are certain advantages to refurbishing during a maneuver. First, refurbishment during despin allows the work to be done in a positive gravity environment. Second, after any spin or despin operation, there is a set of motors ready for firing. Also, if there are waiting periods between the three motor firings in a spin/despin maneuver, it would be advantageous to refurbish the motors during the maneuver.

Four possible refurbishment approaches have been considered. Two deal with refurbishment during motor operation, and two with refurbishment during the period between spin and despin maneuvers.

Table IV-20 Refurbishment of ACS Motors Based on Movable Tube Concept

TIME (minutes)	REFURBISHMENT TASK
0.5	Remove Operating Shroud
0.5	Disconnect Oxidizer Line at Quick Disconnect
1.0	Attach Refurbishment Tube & Door Assembly
0.5	Depressurize Tube & Retract Motor
0.5	Close Environment Door Assembly
1.0	Equalize Internal Tube Pressure
1.0	Check Environment Door Seal by Observing Tube Pressure for 1 Minute
3.0	Remove Tube & Motor as One Assembly & Position for Servicing
1.0	Tie Down in Refurbishment Area
1.0	Remove Forward Closure
5.0	Visually Inspect Forward Closure & Replace O-Ring Seals
5.0	Refurbish Igniter Assembly
2.0	Remove Residual Fuel from Case
5.0	Visually Inspect Case
1.0	Insert New Fuel Grain in Case
1.0	Attach Forward Closure
1.0	Unstrap
3.0	Position & Attach Motor Tube Assembly to Motor Pad
1.0	Evacuate Tube
0.5	Open Environment Door Assembly
0.5	Extend Motor
1.0	Remove Refurbishment Tube
2.0	Check Environmental Seal for Sealing Integrity
0.5	Connect Oxidizer Line at Quick Connect
0.5	Attach Operating Shroud
41.0	

Table IV-21 Refurbishment of ACS Motors Based on Parallel Transfer Concept

TIME (minutes)	REFURBISHMENT TASK
1.0	Open Access Door & Visually Inspect Environment Seals
0.5	Disconnect Oxidizer Line
0.5	Close Access Door & Depressurize Refurbishment Chamber
0.5	Retract, Rotate, & Extend Motor Until Chamber is Sealed
0.5	Repressurize Refurbishment Chamber
1.0	Check Environment Seals by Observing Chamber Pressure for 1 Minute
1.0	Remove Motor from Chamber
1.0	Move Motor to Refurbishment Area & Tie Down
0.5	Remove Forward Closure
5.0	Visually Inspect Forward Closure & Replace O-Ring
5.0	Refurbish Igniter Assembly
2.0	Remove Residual Fuel from Motor Case
5.0	Visually Inspect Case
0.5	Insert New Fuel Grain
0.5	Attach Forward Closure
3.0	Unstrap Motor & Position for Installation in Chamber
0.5	Inspect Chamber Environment Seal
1.0	Install Motor in Chamber
1.0	Close Access Door & Evacuate Chamber
1.0	Retract, Rotate, & Extend Motor
0.5	Repressurize Chamber
1.0	Check Environment Seals by Observing Chamber Pressure for 1 Minute
0.5	Open Access Door, Connect Oxidizer Line, & Close Door
33.0	

Table IV-22 Refurbishment of ACS Motors Based on Nozzle Cap Concept

TIME (minutes)	REFURBISHMENT TASK
0.5	Disconnect Oxidizer Line at Quick Disconnect
1.0	Position Nozzle Cap over End of Nozzle & Lock in Position
1.0	Equalize Motor Internal Pressure
1.0	Check Environment Seal by Observing Motor Pressure for 1 Minute
1.0	Remove forward Closure
5.0	Visually Inspect Closure & Replace O-Ring
5.0	Refurbish Igniter Assembly
2.0	Remove Residual Fuel from Case
5.0	Visually Inspect Case
1.0	Insert New Fuel Grain in Case
1.0	Attach Forward Closure
1.0	Evacuate Motor Case
1.0	Remove Nozzle Cap
2.0	Check Environmental Seal for Sealing Integrity
0.5	Connect Oxidizer Line at Quick Disconnect
28.0	

Table IV-23 Refurbishment of Spin/Despin Motors Based on Nozzle Cap Concept

Fire Motor 15.5 minutes
Refurbish after 15-minute Cooldown

TIME (minutes)	REFURBISHMENT TASK
0.5	Disconnect Oxidizer Line at Quick Disconnect
1.0	Position Nozzle Cap over End of Nozzle & Lock in Position
1.0	Equalize Motor Internal Pressure
1.0	Check Environment Seal by Observing Motor Pressure for 1 Minute
1.0	Remove Forward Closure
5.0	Visually Inspect Closure & Replace O-Ring
5.0	Refurbish Igniter Assembly
2.0	Remove Residual Fuel from Case
5.0	Visually Inspect Case
1.0	Insert New Fuel Grain in Case
1.0	Attach Forward Closure
1.0	Evacuate Motor Case
1.0	Remove Nozzle Cap
2.0	Check Environmental Seal for Sealing Integrity
0.5	Connect Oxidizer Line at Quick Disconnect
28.0	

Table IV-24 Refurbishment of Spin/Despin Motors Based on Movable Tube Concept

Fire Motor 15.5 minute
Refurbish after 15-minute Cooldown

TIME (minutes)	REFURBISHMENT TASK
0.5	Remove Operating Shroud
0.5	Disconnect Oxidizer Line at Quick Disconnect
1.0	Attach Refurbishment Tube & Door Assembly
0.5	Depressurize Tube & Retract Motor
0.5	Close Environment Door Assembly
1.0	Equalize Internal Tube Pressure
1.0	Check Environment Door Seal by Observing Tube Pressure for 1 Minute
3.0	Remove Tube & Motor as One Assembly & Position for Servicing
3.0	Remove Motor from Tube & Tie Down
1.0	Remove Forward Closure
5.0	Visually Inspect Forward Closure & Replace O-Ring Seals
5.0	Refurbish Igniter Assembly
2.0	Remove Residual Fuel from Case
5.0	Visually Inspect Case
1.0	Insert New Fuel Grain in Case
1.0	Attach Forward Closure
3.0	Unstrap & Insert Motor Case in Refurbishment Tube
3.0	Position & Attach Motor/Tube Assembly to Motor Pad
1.0	Evacuate Tube
0.5	Open Environment Door Assembly
0.5	Extend Motor & Repressurize Tube
1.0	Remove Refurbishment Tube
2.0	Check Environmental Seal for Sealing Integrity
0.5	Connect Oxidizer Line at Quick Connect
0.5	Attach Operating Shroud
43.0	

1) Minimum Refurbishment during Spin Operation

    a) Two Loaded Motors in Spin Position, One Loaded Spare Motor - The first spin motor is fired. Before firing the second motor, the first motor is removed and replaced with the spare motor. The second motor and the spare (third) motor are then fired. All three motors are then refurbished and positioned prior to the despin operation (see Fig. IV-7).

    b) Two Loaded Motors in Spin Position, One Loaded Motor in Despin Position - The first spin motor is fired, removed, and refurbished. During the firing of the second spin motor, the refurbished motor is installed into its firing position. After firing the second spin motor, the refurbished motor is fired as the third spin motor to complete the maneuver. The two fired motors are then refurbished before the despin. One refurbished motor and the unused motor are oriented in a despin position, and the other refurbished motor is oriented in a spin position (see Fig. IV-7).

2) Maximum Refurbishment during Spin Operation

    a) Two Loaded Motors in Spin Position, One Loaded Spare Motor - The first spin motor is fired. Before firing the second motor, the first fired motor is removed and the spare motor is installed in its place. The first motor is then refurbished and positioned for the despin. Next, the second spin motor is fired, refurbished, and positioned for despin. The third spin motor (or spare) is fired, refurbished, and positioned as the spare despin motor (see Fig. IV-8).

    b) Two Loaded Motors in Spin Position, One Loaded Motor in Despin Position - The first spin motor is fired. Before firing the second motor, the first fired motor is removed and refurbished. During firing of the second spin motor, the refurbished motor is reinstalled in a spin position. Before firing the third spin motor, the second fired motor is removed, refurbished, and positioned for despin operation. The third spin motor is then fired, removed, refurbished, and reinstalled in the spin position (see Fig. IV-8).

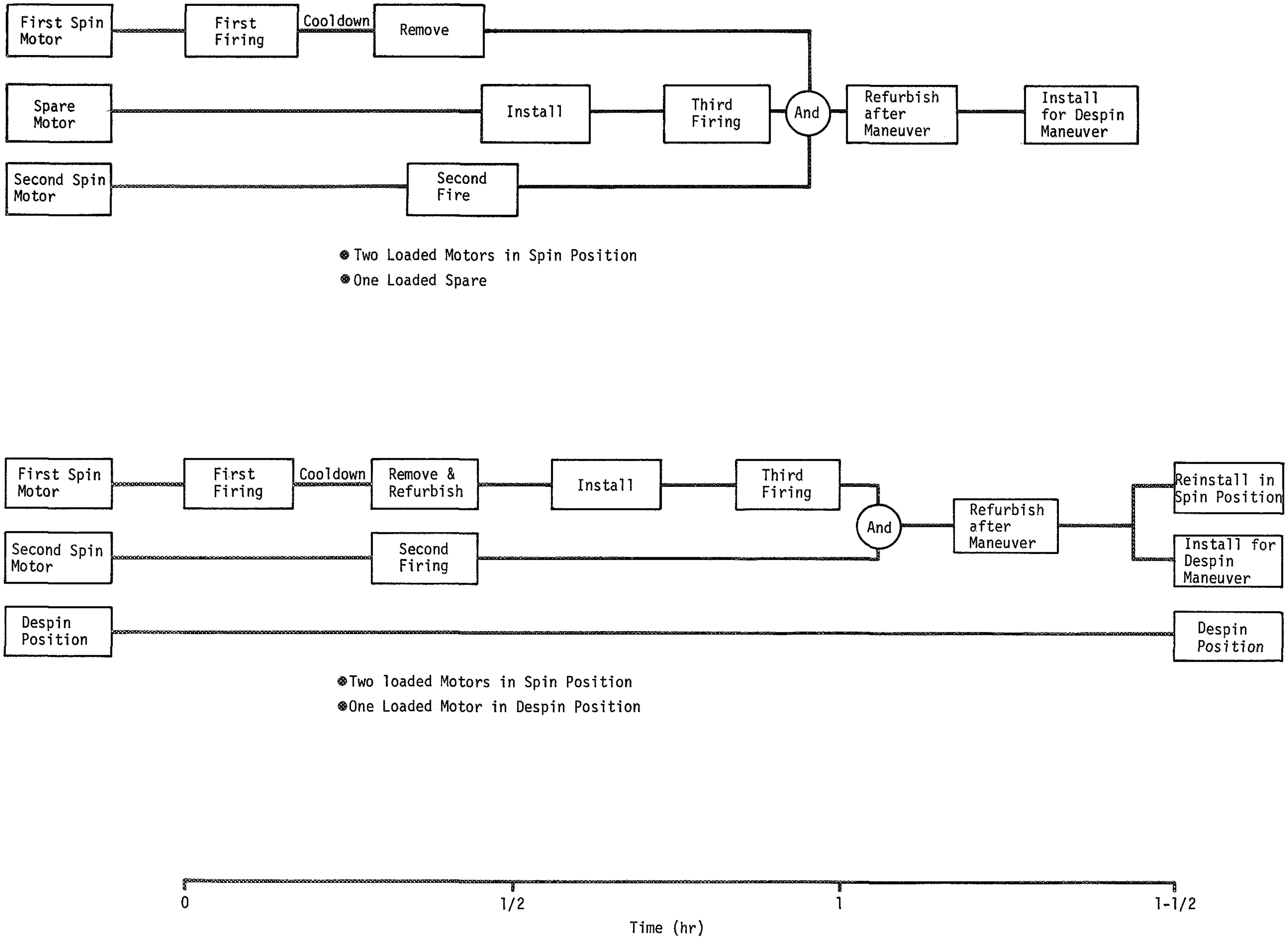


Fig. IV-7 Minimum Refurbishment during Maneuvers

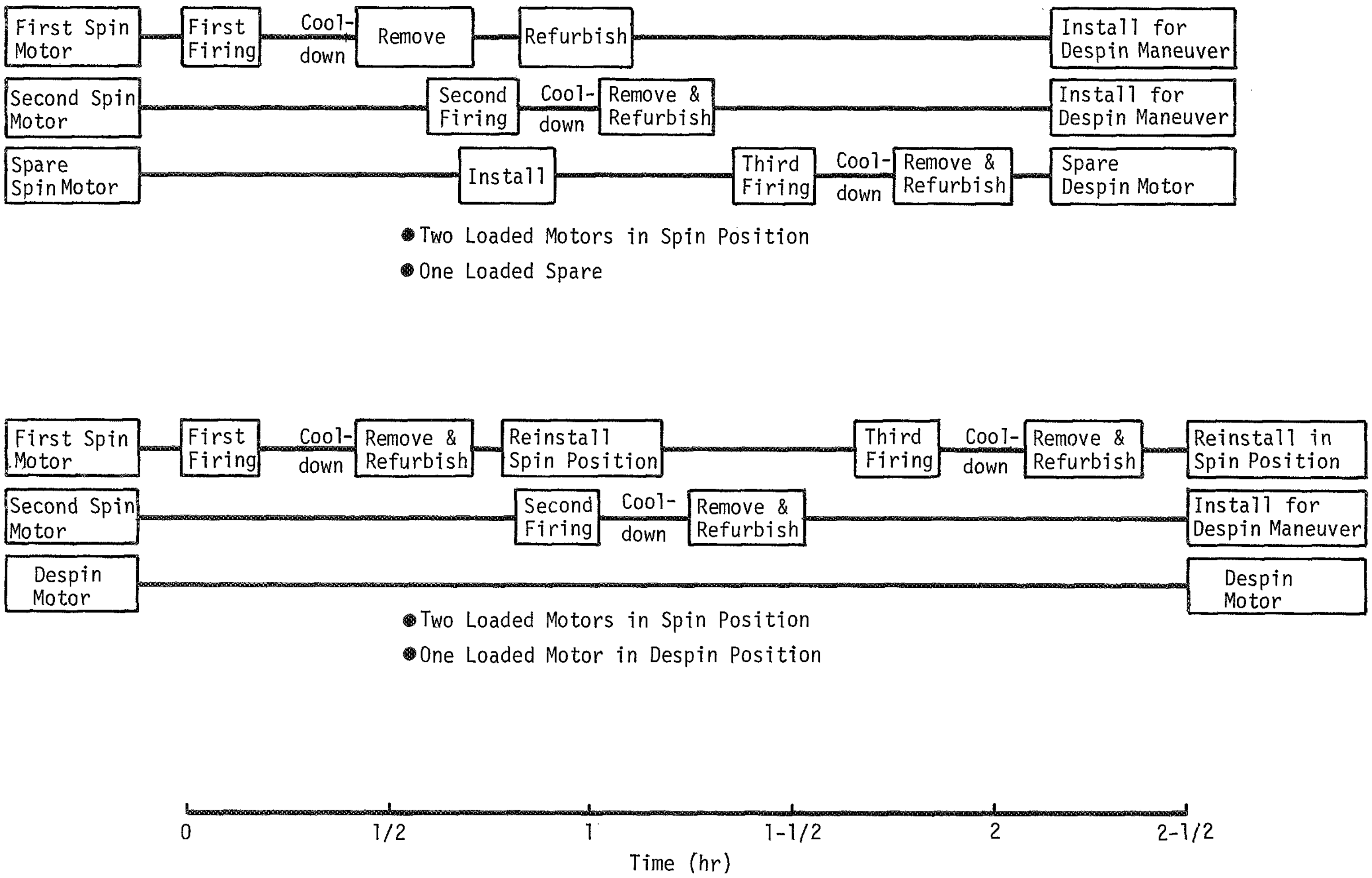


Fig. IV-8 Maximum Refurbishment during Maneuver

Table IV-25 compares the minimum total time required to accomplish a spin or despin. If motor refurbishment is performed after the maneuver but before the next maneuver, a spin or despin maneuver can be accomplished in 1 to 1½ hr. If the refurbishment is done simultaneously with the maneuver, a maneuver time of 2 to 2½ hr is required.

c. Oxidizer Feed Assembly Time Requirements - Tables IV-26 thru IV-29 present the estimated unscheduled maintenance time per year for the selected OFA and its components. The estimates assume that completely failed components, such as valves, are removed and replaced. Lower-tier items such as valve poppets are not replaced once the component is installed in the oxidizer feed system. The times required for each maintenance task were estimated for a modular, internally mounted concept that requires no EVA, and were calculated as:

1) The times required to perform the individual tasks necessary to replace components were estimated and then summed to obtain the average total replacement time. For example, the average total time to replace a helium sphere is 54 minutes (Table IV-26);

2) The probability of each component failing during a year due to random failure was tabulated. These probabilities, in ppm/year, were taken from the reliability analysis presented in Subsection IV-B-4. The failure porbabilities include environmental and application adjustment factors;

3) The probable unscheduled maintenance time per component type in a subsystem is equal to the product of the replacement time, number of components, and probability of component failure;

4) The sum of the unscheduled maintenance times for components in a subsystem equals the unscheduled maintenance time for that subsystem. For example, the average estimated unscheduled maintenance time required for the pressurization system is about 2.0 minutes per year. Obviously no maintenance can be performed in 2.0 minutes; however, over a period of years, the average maintenance time, prorated over the duration of the mission, will be 2.0 minutes for the pressurization subsystem.

Table IV-25 Comparison of Maximum and Minimum Refurbishment Times during Spin or Despin Operations

REFURBISHMENT CONCEPT	TIME (hr)
Minimum Refurbishment During Spin Operation	
Two Loaded Motors in Spin Position, One Loaded Spare Motor	
Nozzle Cap	1.1
Movable Tube	1.1
Two Loaded Motors in Spin Position, One Loaded Motor in Despin Position	
Nozzle Cap	1.3
Movable Tube	1.5
Maximum Refurbishment During Spin Operation	
Two Loaded Motors in Spin Position, One Loaded Spare Motor	
Nozzle Cap	1.9
Movable Tube	2.0
Two Loaded Motors in Spin Position, One Loaded Motor in Despin Position	
Nozzle Cap	2.4
Movable Tube	2.5

Table IV-26 Unscheduled Maintenance Time for the Oxidizer Feed Assemblies

ITEM	PRESSURANT				OXIDIZER				CONTROL				
	RELIEF VALVE & BURST DISC	PRESSURANT TANK	TRANSDUCER	3-WAY VALVE	OXIDIZER TANK	RELIEF VALVE & BURST DISC	TRANSDUCER	3-WAY VALVE	SHUTOFF & CHECK VALVES	VAPORIZER, RELIEF & CHECK VALVES	FILTER & REGULATOR	3-WAY VALVES	TRANSDUCER
Total Task Time, t (minutes)	43	54	46	50	58	43	46	50	44	41	45	45	43
Number of Parts, n	1	1	1	1	1	1	1	1	1	1	1	1	3
Probability of Part Failure, Q (ppm/yr)	6055	406	278	4000	3210	3715	172	2460	6120	3865	12,834	2460	172
Probability of Part Type Failure, nQ	6055	406	278	4000	3210	3715	172	2460	6120	3865	12,834	2460	516
Maintenance Time Per Year, nQt (minutes)	0.260	0.022	0.013	0.200	0.186	0.160	0.008	0.123	0.269	0.158	0.578	0.111	0.022

Subtotal 2.11 minutes

All Systems - 4 x Subtotal = 8.44 minutes/yr

Table IV-27 Unscheduled Maintenance Time for the Pressurant Subsystem

TASK	TIME (minutes)			
	RELIEF VALVE OR BURST DISC	PRESSURANT TANK	TRANSDUCER	3-WAY VALVE
Isolate Fault	1	1	1	1
Review Maintenance Procedure	3	3	3	3
Obtain Spare	3	3	3	3
Travel to Subsystem	5	5	5	5
Bleed Down Pressure	0	0	5	5
Remove Access Cover	3	3	3	3
Disconnect Instrumentation	0	0	1	1
Remove & Store Part	6	12	4	6
Install New Part	4	9	2	4
Connect Instrumentation	0	0	1	1
Replace Access Doors	3	3	3	3
Actuate System & Check Out OCS	5	5	5	5
Travel to Station & Stow Gear	5	5	5	5
Perform Administrative Functions	5	5	5	5
Total	43	54	46	50

Table IV-28 Unscheduled Maintenance Time for the Oxidizer Subsystem

TASK	TIME (minutes)			
	OXIDIZER TANK	RELIEF VALVE & BURST DISC	TRANSDUCER	3-WAY VALVE
Isolate Fault	1	1	1	1
Review Maintenance Procedure	3	3	3	3
Obtain Spare	3	3	3	3
Travel to Subsystem	5	5	5	5
Bleed Down Pressure	0	0	5	5
Remove Access Cover	3	3	3	3
Disconnect Instrumentation	0	0	1	1
Remove & Store Part	14	6	4	6
Install New Part	11	4	2	4
Connect Instrumentation	0	0	1	1
Replace Access Doors	3	3	3	3
Actuate System & Check Out OCS	5	5	5	5
Travel to Station & Stow Gear	5	5	5	5
Perform Administrative Functions	5	5	5	5
TOTAL	58	43	46	50

Table IV-29 Unscheduled Maintenance Time for the Control Subsystem

TASK	TIME (minutes)				
	SHUTOFF & CHECK VALVE	VAPORIZER, RELIEF & CHECK VALVE	FILTER & REGULATOR	3-WAY VALVE	TRANSDUCER
Isolate Fault	1	1	1	1	1
Review Maintenance Procedure	3	3	3	3	3
Obtain Spare	3	3	3	3	3
Travel to Subsystem	5	5	5	5	5
Bleed Down Pressure	3	2	2	2	2
Remove Access Cover	3	3	3	3	3
Disconnect Instrumentation	1	0	0	0	1
Remove & Store Part	4	4	6	6	4
Install New Part	2	2	4	4	2
Connect Instrumentation	1	0	0	0	1
Replace Access Doors	3	3	3	3	3
Actuate System & Check Out OCS	5	5	5	5	5
Travel to Station & Stow Gear	5	5	5	5	5
Perform Administrative Functions	5	5	5	5	5
TOTAL	44	41	45	45	43

Note that the maintenance times in Tables IV-26 thru IV-29 are average values. Should it become necessary to employ either EVA or suited IVA, these estimates must be modified. The "don protective clothing" task must be increased to 3 hr, which includes donning a pressure suit and breathing pure oxygen for 45 minutes. In addition, EVA and suited IVA require a buddy system, or two men. Furthermore, the task times in Table IV-26 must be multiplied by 2.5 to account for the lack of mobility in a pressure suit.

F. RESUPPLY METHODS AND PROCEDURES

Resupply for a hybrid orbital APS encompasses all the activities from terrestrial storage, inventory control, and ground handling to inflight removal of residual fuel and used motor components. The activities also include earth-to-orbit transfer, inorbit transfer, and transfer of material within the Space Station.

1. Resupply Methods for Nonliquids

a. Terrestrial Handling Procedures - Replacement fuel grains and other propulsion components will be stored at a facility near the transfer vehicle launch area. The resupply facility would contain a stock of replacement components, such as fuel grains, motor seals, and expendable ignition system supplies, to meet scheduled resupply requirements. There would also be a supply of motor case/nozzle assemblies, oxidizer control valves, refurbishment mechanisms, and other APS spares.

Replacement components would be stored and handled under procedures designed to maintain their operational capability. The oxidizer control valves, butane trip valves, filters, regulators, and instrumentation should receive careful handling and be protected from dust, salt spray, and extreme humidity and temperature. However, the motor cases, fuel grains, ignition system replacement parts, and seals can be stored under less restrictive conditions. Although no shelf life limitations are anticipated for propulsion components, any restrictions that develop will be carefully observed to ensure an available supply of component parts to meet all resupply requirements.

Before a resupply mission, the scheduled resupply components and any additional spares replacements requested since the last resupply will be selected from inventory, undergo a final inspection and be packaged for shipment to the Space Station.

b. Earth-to-Orbit Transfer - The packaged resupply components and spare replacements are compatible with the logistics vehicle and the launch environment. The size and weight of component packages shall conform with the storage capacity of the logistics vehicle. The packaging will protect the components from all launch environments, including accelerations, shock loads, and depressurization. The motor cases and fuel grains are rugged and require minimum packaging to survive the launch environment. Oxidizer valves, trip valves, and instrumentation will be more securely packed to prevent damage.

c. Logistics Vehicle-to-Space Station Transfer - Supplies can be transferred from the logistics vehicle by either direct docking of the logistics vehicle or by a packed pantry resupply approach. The Space Station will have several 1.5-m (5-ft) access ports. The logistics vehicle can be designed to mate with one of these access ports to provide direct pressurized transfer of supplies and personnel to the Space Station. Supplies can be transferred piece by piece (as conventional aircraft baggage) or in standardized modular containers. Containerization facilitates the transfer of supplies by reducing the number of packages. Although the containers introduce a weight and storage problem, they reduce the packing requirements of individual items.

The packed pantry concept offers a different approach to resupply. The logistics vehicle delivers a resupply module that mates with a Space Station access port. This module has been stocked with all the supplies required by the Space Station over the next 6 months.

This packed pantry approach offers four main advantages. It adds storage space, which frees other areas of the Space Station for more productive use. It also provides a centralized storage location that reduces the chance of duplicating supplies of the same article and simplifies inventory problems. Third, it relieves the crew from an intensive resupply task every 6 months by spreading the transfer of material over the 6-month period. Finally, it provides a centralized location for waste.

However, the packed pantry approach has two disadvantages -- parts availability and the risk of damage to propulsion components -- which make it less desirable for a hybrid APS. During propulsion refurbishment, and especially during repairs following a malfunction, it is important that all required ports be conveniently located and available in the refurbishment area. Trips back and forth to the pantry for parts would significantly add to the refurbishment time and could affect Space Station operation during a spin/despin maneuver. The second disadvantage lies in the fact that hybrid APS components are precision parts. Although the motor case and grain are rugged, they should only be handled by qualified personnel. Therefore, all APS refurbishment replacement parts should be safely stored in an APS refurbishment area, which should be off limits to nontechnical personnel.

d. Internal Transfer of Supplies - Supplies can be transferred within the Space Station as individual parts or in standardized storage containers. Large items, such as motor cases or fuel segments, could be handled separately without specialized containers. However, small items, such as filters, regulators, seals, valves, and ignition system supplies, could be more conveniently transported and stored in closed containers. These containers could slide along tracks in the access ports to facilitate transfer in a zero-g environment. They could easily be moved by one man without additional equipment. Following resupply, all APS replacement parts would receive an arrival inspection.

e. Waste Removal - The hybrid APS is not a prodigious generator of waste. Scheduled replacement of parts is shown in the resupply schedule in Table IV-30. Worn-out seals and ignition components, along with residual fuel compose almost all of the scheduled waste.

Residual fuel comes from two main sources -- the APS motors and the spin/despin motors. Fuel grains will have about a 5% residue after firing. Therefore, at a mixture ratio of 2.4, the APS motors will generate about 29.5 kg/0.028 m^3 $\left(65\ lb_m/ft^3\right)$ of charred fuel in 10 years of operation in the form of fuel shells 203 mm (8 in.) in diameter x 356 mm (14 in.) long x 1.27 mm (0.050 in.) thick. These charred, rubber-based fuel grains can easily be shredded with a knife and disposed of along with food and human wastes.

The spin/despin motors consume considerably more propellant 9,367 kg $\left(20{,}650\ lb_m\right)$ in 18 months than the APS motors. These

Table IV-30 Scheduled TCA Resupply Requirements

	ATTITUDE CONTROL MOTORS*
Motor Assembly	3 Fuel Grains, 203 mm (8 in.) in diameter by 355 mm (14 in.) Long 3 Replacement Motor Seals
Ignition Assemblies	
Butane System	3 Replacement Butane Cans 3 Replacement Spark Plugs
Heated Oxidizer Line	3 Replacement Heating Elements
Precombustor	3 Replacement Grains
Forward Closure Retention Systems	None
Refurbishment Approaches	
Movable Tube	3 External Motor Seals 1 Set of Refurbishment Seals
Parallel Transfer	9 Refurbishment Seals
Nozzle Cap	3 External Motor Seals
	SPIN/DESPIN MOTORS†
Motor Assembly	12 Replacement Grains, 406 mm (16 in.) in diameter by 787 mm (31 in.) long - 5 Segments 12 Replacement Motor Seals
Ignition Assemblies	
Butane System	12 Replacement Butane Cans 12 Replacement Spark Plugs
Heated Oxidizer Line	12 Replacement Heating Elements
Pyrogen Igniter	12 Replacement Igniters
Precombustor	12 Replacement Grains
Forward Closure Retention System	None
Refurbishment Approaches	
Movable Tube	12 External Motor Seals 2 Sets of Refurbishment Seals
Nozzle Cap	12 External Motor Seals

*Resupply required every 6 months.

†Semiannual requirements for the 6-month and 12-month resupply. Motors, spares, and support equipment may be removed after 18 months.

motors generate about 10.9 kg $\left(24 \text{ lb}_m\right)$ of residual fuel during each spin/despin maneuver, or about 109 kg $\left(240 \text{ lb}_m\right)$ in 18 months.

2. TCA Resupply Requirements

Resupply requirements are subdivided into two classes: scheduled resupply and unscheduled resupply. Scheduled resupply is based on the projected total impulse required and the parts replacement schedule. Any accelerated APS utilization or repairs resulting from component failures will require the use of spares. The spares requirements discussed in the previous section are sufficient to maintain full APS operation for at least 1 year, based on predicted failure rates. Spares used due to a component failure or to an anticipated failure detected through malfunction detection trend analysis would be replaced at the next resupply to maintain the required spares inventory.

The scheduled semiannual TCA resupply requirements shown in Table IV-30 were based on projected total impulse requirements.

3. Oxidizer Feed Assembly Resupply Requirements

The major resupply requirements for the selected OFA concept are the LOX and the helium pressurant. The amounts required are presented in Table IV-31.

a. Pressurant Resupply Techniques - The three resupply techniques evaluated in this study were:

1) Blowdown;
2) Bellows;
3) Modular replacement.

In a blowdown system pressurant is resupplied by equalizing the pressure between a high-pressure storage compartment onboard the logistics craft and the expended storage spheres onboard the Space Station. There are two advantages to this approach: a minimum of new technology is required, and the crew commitment during the resupply is minimal. The main disadvantage to this approach is that the requirement for transfer lines and associated compartments increases the weight of the system. In addition, residual pressurant remains onboard the logistics craft.

By using a bellows with a spring, motor, or manual drive, it is possible to expel almost all of the helium. However, the

Table IV-31 Consumable Resupply Requirements for the Oxidizer Feed Assemblies

TIME PERIOD	FUNCTION	RESUPPLY REQUIREMENTS LOX kg	LOX lb_m	HELIUM GAS kg	HELIUM GAS lb_m
0-10 days	Attitude Control Maneuvers, Docking Prior to CMG Activation	0	0	0	0
10-90 days	Attitude Control & Docking	0	0	0	0
3-6 months	Artificial-g Experiment 1	1210	2675.1	28	61.8
6-9 months	Artificial-g Experiment 2	1420	3141	32.8	75.8
15-18 months	Artificial-g Experiment 5	1420	3141	32.8	75.8
18 months - 10 years	Zero-g Station Attitude Control (every 180 days)	62	132.84	14.3	30.8
		7820	17299.1	402.0	887.0

life expectancy of a bellows is generally less than that of other systems, such as the blowdown system.

Another approach is to resupply pressurant by modular replacement of the gas storage spheres. This system is lightweight because no transfer lines and components are required and no residual pressurant is left onboard the logistics craft. Minor development of new technology is required for this approach in the areas of packaging, handling, and installation techniques. A larger crew commitment is also required with this approach.

The use of a permanent volatile liquid pressurization system eliminates routine pressurant resupply since the pressurant is recondensed during propellant servicing. The advantages of this approach are: (1) no resupply of pressurant is required; (2) minimum weight is obtained; (3) crew commitment during resupply is minimized; and (4) inflight maintenance requirements are reduced. Major disadvantages of this approach are the increased program cost and increased development risk due to heat storage material and ullage venting.

Another resupply approach uses a blowdown pressurization system, wherein the pressurant is recompressed during propellant servicing. Advantages of this approach are elimination of the resupply of pressurant, minimized requirements for crew commitment, and a reduction of the inflight maintenance requirements. The major disadvantages of this approach are the reduction in performance flexibility and additional development required.

b. Oxidizer Resupply Techniques - Resupply techniques considered in this study were those limited to the intermediate or subcritical pressure range for the LOX. High-pressure or supercritical transfer was not considered in this study because of three major difficulties associated with this technique:

1) Thermodynamic control of the receiver tank;
2) A large mass of residual fluid remaining in the supply tank;
3) A large structural weight penalty for the supply tank due to its operating pressure.

The kinds of intermediate pressure transfer systems considered were:

1) Surface Force System - Relies on surface tension differences between the liquid and vapor to orient or collect the liquid for transfer;
2) Positive Expulsion Systems - Provide an essentially impermeable barrier between the pressurant and fluid to be transferred;
3) Dynamic Force System - Forces the fluid to move in a manner such that the orientation of the liquid is known and transfer can be accomplished.

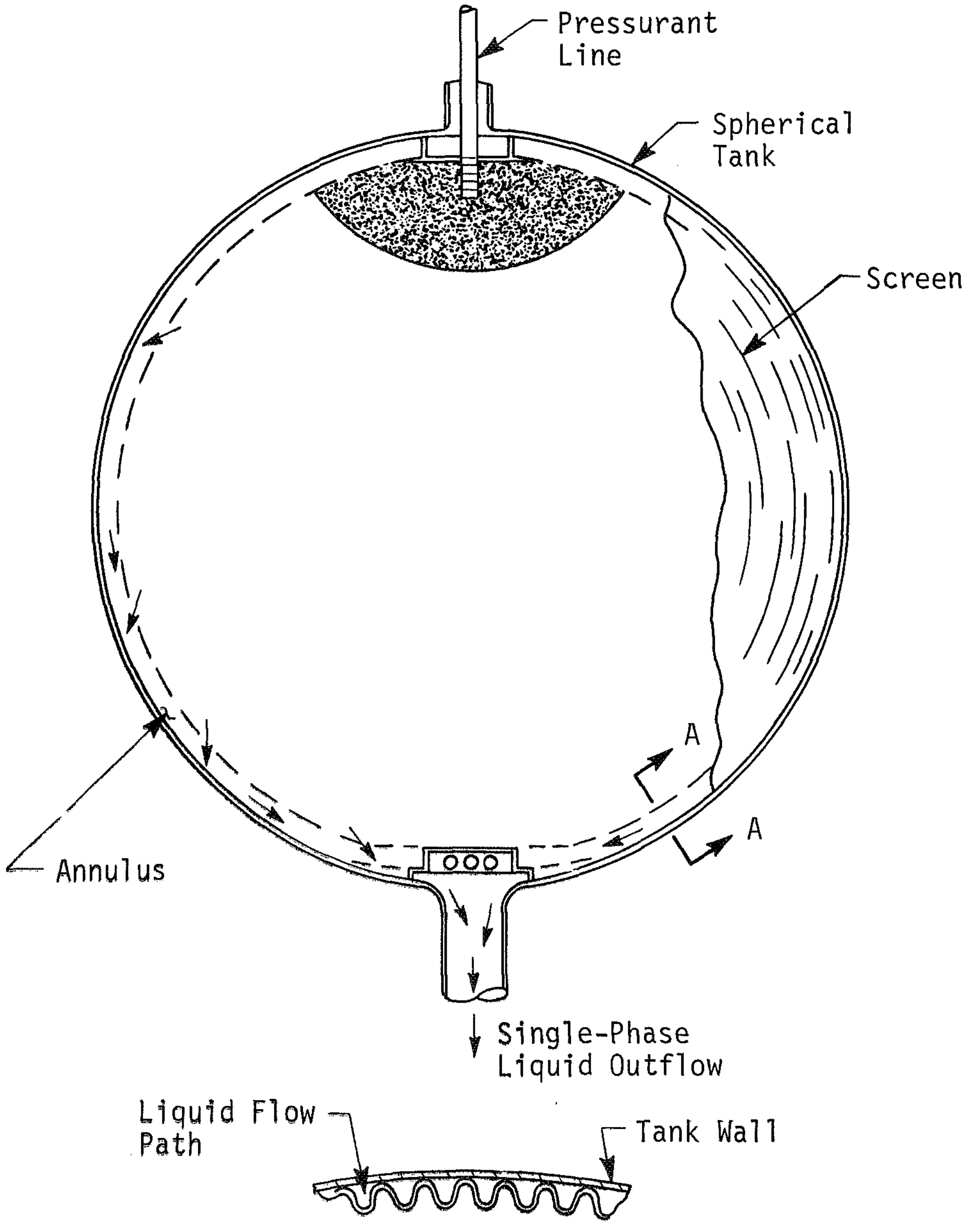
Modular replacement of the expended storage tanks was also considered.

The surface tension, or capillary containment system using screens, was preferred over the dielectrophoretic surface orientation system due to potential safety considerations. The use of oxygen, combined with a possible electrical breakdown, can result in a combustion hazard with the dielectrophoretic system.

The capillary system employs a single concentric screen tank (Fig. IV-9). The concentric screen or perforated plate is positioned near the tank wall to provide a liquid outflow path (annulus). The bulk liquid, on demand, flows through the foraminous materials, into the annulus, and out the tank. The liquid/gas interfaces at the individual pores of the material are stabilized by surface tension forces. This small differential pressure, on the order of 6.89 kN/m^2 (1 psia) or less, makes the preferential fluid path.

The major advantage of capillary devices is that they are lightweight, generally passive, and can be used for a number of cycles of operation. The propellant storage life of a surface tension device is excellent because of its lack of moving parts and its all-metal construction. Uncertainties in storage or mission duration due to seal leakage, bladder permeation, radiation, propellant effects on polymers, thermal cycling, etc, are eliminated by the use of capillary devices for long-duration missions.

A major problem in the transfer of the oxidizer with the capillary device is determining the quantity of commodity transferred and the amount remaining in the supply tank. This problem becomes extremely difficult under zero-g or low-g conditions because the location of the liquid and vapor phases is not sufficiently defined. Gaging systems presently under development



Note: A pleated screen is shown; an unpleated (flat) screen may also be used.

Fig. IV-9 Concentric Capillary Screen Concept include pressure-volume-temperature, acoustical, radioactive tracer gas, nuclear radiation attenuation, capacitance, positive displacement, density-volume, optical, radio-frequency, flowrate measurement, and point sensor. Venting requirements further increase the complexity of these systems.

Capillary devices have been used for noncryogenic propellant acquisition. The use of cryogenic fluids introduces thermodynamic and heat transfer problems outside the scope of this contract which can significantly influence the design of the transfer system.[*] Phenomena that must be considered include:

1) Gravity level requirements for vapor/liquid interface stability;
2) Vapor/liquid interface during draining and vapor ingestion;
3) Gas pressurant mass determination;
4) Transfer line chilldown;
5) Receiver tank thermodynamics and venting.

Positive expulsion devices considered were bladders, bellows, and diaphragm systems. Pistons present weight and moving seal problems, and thus, were not considered.

A significant amount of work has been accomplished with bladders (Fig. IV-10). Nonmetallic, folding-type bladders have been successfully used with earth-storable fluids. Cryogenic fluid expulsion presents problems in finding materials that are flexible at cryogenic temperatures and can be incorporated in a satisfactory design. Although considerable effort has been performed to develop materials and adhesives that are both flexible and compatible with LOX, and to develop satisfactory fabrication techniques, it is felt that such systems will only be good for up to 30 to 35 cycles on a reliable and repeatable basis.[†]

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[*] NASA is presently sutdying low-gravity propellant transfer under Contract NAS8-26236.

[†] *Handbook of Long-Life Space Vehicle Investigations (1967 and 1968).* M-68-21. Martin Marietta Corporation, Denver, Colorado, December 1968.

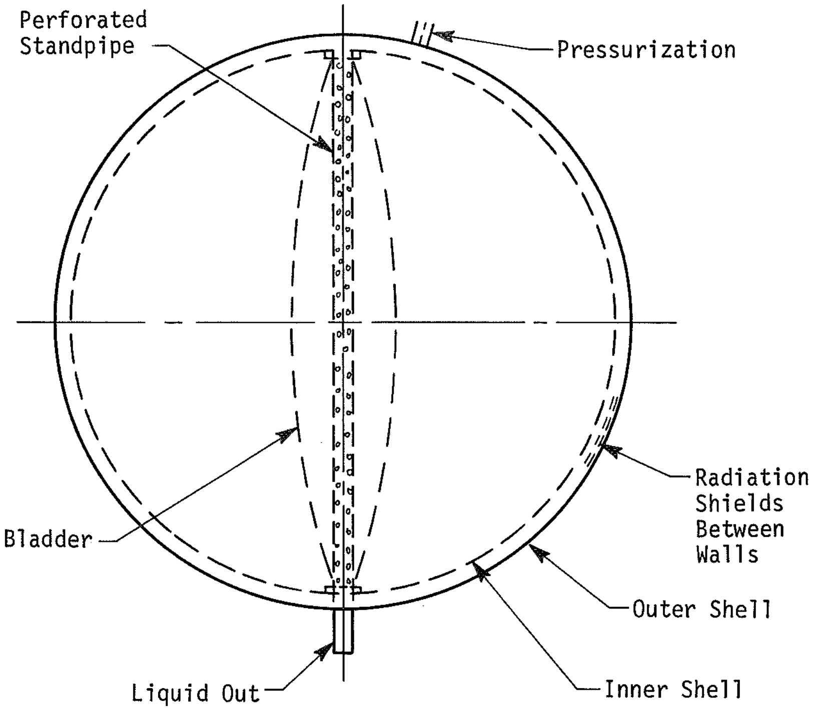

Fig. IV-10 External Pressurized Bladder

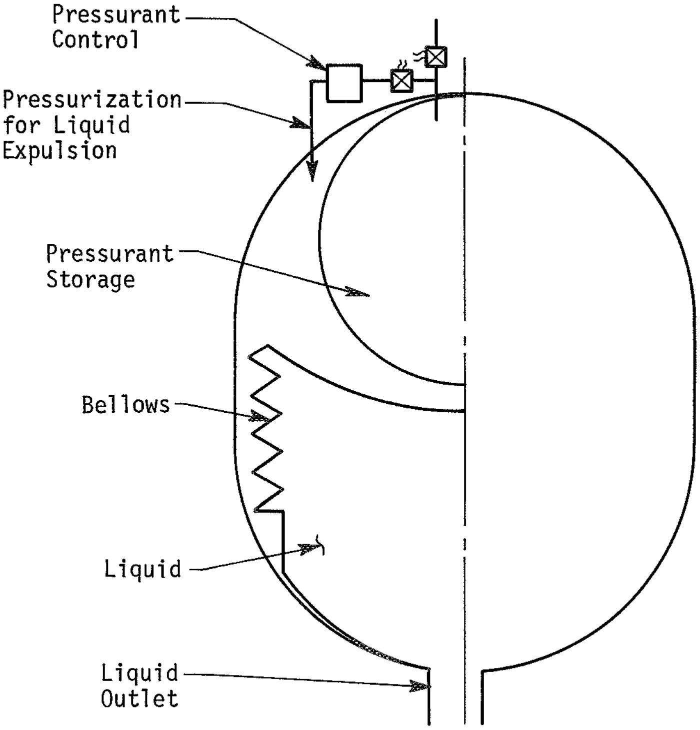

Fig. IV-11 Bellows Expulsion System

Formed metallic bellows (Fig. IV-11) are under development at Martin Marietta Corporation for cryogens.* The nested type of formed bellows offers potentially high reliability and high expulsion efficiency. Although it is generally 25% heavier than a basic system, the fluid quantity remaining, even at low gravity, can be determined by measuring the stroke of the bellows. Cycle life of 100 cycles should not be a problem.

Considerable effort has been devoted to both nonmetallic and metallic diaphragms. Polymeric positive expulsion diaphragms for cryogens have not operated successfully.† Convoluted metallic diaphragms are impermeable to propellants, and work well for one expulsion. Recycling results in severe metal working, which causes pinholing and failure in most cases.§

The dynamic force system of interest uses an internal paddle to provide a positive vortexing action to the fluid.† Although this concept (Fig. IV-12) is attractive, its complexity is beyond the scope of the subject contract. This concept does have the advantage of reduced residuals, but has a fairly large hardware weight penalty. In addition, the requirement for an internal tank motor or a tank passthrough for applying rotational motion to the paddle injection pumping would minimize hardware weight, but increase the total electrical power requirement and increase residual liquid. This concept also has a slow start-up.

One simple concept for the transfer of liquid cryogens is draining by linear or angular acceleration. Despite the simplicity of this approach, this transfer concept is flowrate-limited.

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*D. T. Corington and R. F. Fearn: *Cryogenic Metallic Expulsion Bellows Evaluation*. NASA, CR-725B, NASA-LeRC Contract NAS3-12017. Martin Marietta Corporation, Denver, Colorado, March 1969.

†J. A. Stark: *Study of Low-Gravity Propellant Transfer, First Quarterly Progress Report*. GDC 584-4-549, Contract NAS8-26236. General Dynamics Corporation, Convair Division, San Diego, California, September 28, 1970.

§*Handbook of Long-Life Space Vehicle Investigations (1967 and 1968)*. M-68-21. Martin Marietta Corporation, Denver, Colorado, December 1968.

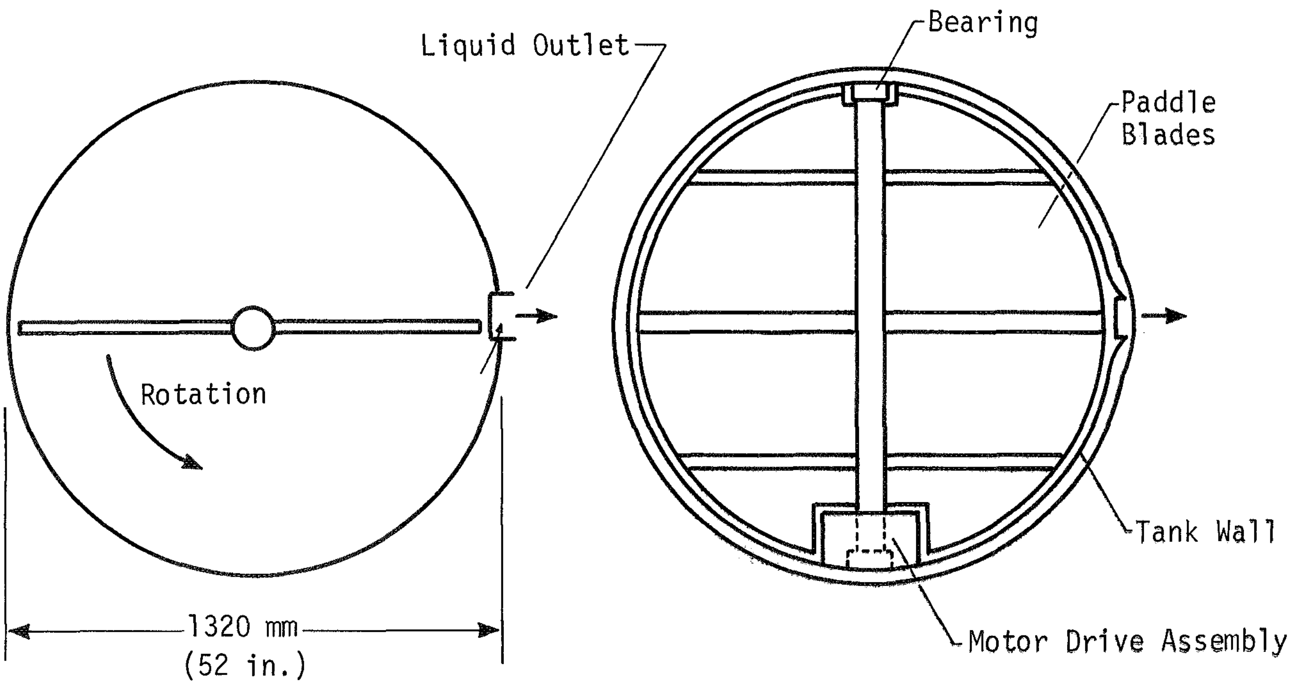

Fig. IV-12 Paddle-Type Vortex System

The weighted selection criteria presented in Section IV-A were used to quantitatively compare different candidate design approaches to establish the optimum design approach. Absolute safety and advanced technical status by 1975 were primary selection criteria. To achieve absolute safety, no propellant toxicity was allowed. No design was accepted that, through a single failure, could damage the Space Station or injure the crew. Furthermore, no design was accepted that, through any imaginable series of failures, could do catastrophic damage to the Space Station. Only designs that represent state-of-the-art 1975 technology were used.

Table V-1 shows the 11 selection criteria that were used to choose an optimum system. The candidate designs all satisfied the primary selection criteria.

Using the selection criteria, the candidate design approaches were rated separately for the ACS and spin/despin applications. The evaluation of the oxidizer feed systems used a technique that was somewhat different than that used for the TCA; this technique is explained in Section C of this chapter.

A. TCA SELECTION

Consideration was given to such factors as physical size, restart requirements, duration of operation, and ease of refurbishment. After considering the relative factors, a numerical rating was assigned to each candidate design, based on the selection criteria weighting factor. The design approach receiving the highest overall rating was selected.

1. Propellant Selection

The results of the candidate propellant system evaluation are shown in Table V-2. Safety, not unexpectedly, was the single most important criterion for propellant selection. Neither H_2O_2 nor NTO can meet the high degree of safety required for use on a manned Space Station. In the (CPF/PF)/(Li/LiH/PBD) system, both the oxidizer and the fuel introduce unacceptable handling and toxicity problems. Therefore, LOX or GOX are the only oxidizers that

Table V-1 Quantitative Space Station APS Selection Criteria

ITEM	WEIGHTING FACTOR	COMMENTS
Resupply Requirements	20	Simplicity of resupply operation, small size, and low weight of replacement parts/propellant.
Maintainability & Repair	15	Minimum number and complexity of maintenance and repair tasks.
Crew Requirements	15	Minimum manhours, flexibility of scheduling, and minimum training or special skills.
Commonality	10	Interchangeability of parts and spares between motors.
Onboard Equipment Requirements	10	Minimum handling equipment, service equipment, space requirements, and malfunction detection and automatic monitoring equipment.
Reliability	10	Minimum down time and maximum time between failures.
Space Station Interface Potential	5	Minimum modifications to the Space Station and no interference with other operations, experiments, etc.
Performance	5	High specific impulse and repeatable performance.
Weight	5	Minimum motor and equipment weight.
Growth	3	Flexibility of present system to handle increased total impulse requirements for build-up of Space Station.
Cost	2	Low motor, system development, and support costs.

Table V-2 Propellant Selection

PRIORITY	ITEM	WEIGHTING FACTOR	OXIDIZER →	LIQUID OR GASEOUS OXYGEN				H_2O_2	N_2O_4	ClF_5-ClO_3
			FUEL →	PLEXIGLASS (PMM)	PMM/PBD	TFTA/PBD	PE	PE	PMM/PBD	Li/LiH/PBD
1	Safety	Absolute		Yes	Yes	Yes	Yes	No	No	No
2	Technical Status in 1975	Absolute		Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	Supply Requirements	20		15	18	19	20	10	10	10
4	Maintainability & Repair	15		14	15	14	12	8	6	5
5	Crew Requirements	15		11	15	11	8	8	10	7
6	Commonality	10		8	8	8	8	5	5	5
7	Onboard Equipment Requirements	10		10	10	10	10	8	6	4
8	Reliability	10		10	10	10	10	8	8	8
9	Space Station Interface Potential	5		5	5	5	5	4	3	1
10	Performance	5		4	5	5	5	2	4	5
11	Weight	5		5	5	5	5	4	3	2
12	Growth Potential	3		3	3	3	3	2	2	2
13	Cost	2		2	2	2	2	1	1	1
		100		87	96	83	88	60	58	50

Selection: LOX/(PMM/PBD) for Spin/Despin;
GOX/(PMM/PBD) for ACS Motors.

meet the system requirement for absolute safety. A detailed study of operational requirements showed that only GOX could meet the short-pulse, multiple restart requirements expected for the attitude control motors. However, the spin/despin motors can operate in a single-burn mode, so the thermal transients associated with LOX will not adversely affect motor operation.

All four fuel systems considered with oxygen are state-of-the art. Each fuel system has its own maintenance, repair, and resupply requirements. The selected fuel, PMM/PBD, combines minimum resupply requirements with a low minimum regression rate to reduce maintenance and crew requirements. Polyethylene offers slightly higher performance, but requires a significantly higher · number of fuel grain replacements. Plexiglass delivers lower performance at a lower O/F ratio and has a somewhat shorter fuel replacement interval. Although TFTA/PBD is similar to PE in terms of performance and replacement interval, it introduces handling constraints not required for pure-binder fuel systems.

2. Fuel Grain Design

Five fuel grain concepts (Table V-3) were considered for use in the ACS and spin/despin motors. The conventional grain has a monolithic design with a cylindrical bore. The segmented design is also a conventional cylindrical bore grain that is cut into short cylindrical sections to facilitate grain handling. The multiple port grain is equivalent to several single-port grains fired in succession; this concept increases total impulse and extends the fuel replacement interval. The moving grain concept uses a solid, cylindrical, end-burning fuel grain; oxidizer feed pressure acting on the forward end of the grain holds the grain against the aft closure and advances it as the fuel surface regresses. The trash grain uses Space Station waste products pressed into a monolithic or segmented grain.

The multiple port, moving grain, and trash grain concepts would require development programs to be operational by 1975. The conventional monolithic (or segmented) cylindrical port grains have been used in hybrid target vehicles and demonstration motors and represent current technology. The smaller ACS motors will use the monolithic conventional grain design, and the larger spin/despin motors will use the segmented conventional grain design to facilitate handling.

Table V-3 Selection of Fuel Grain Design

PRIORITY	ITEM	WEIGHTING FACTOR	CANDIDATE APPROACHES									
			CONVENTIONAL MONOLITHIC GRAIN		SEGMENTED		MULTIPLE PORT		MOVING GRAIN		TRASH*	
			ACS	SPIN	ACS	SPIN	ACS	SPIN	ACS	SPIN	ACS	SPIN
1	Safety	Absolute	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	Technical Status in 1975	Absolute	Yes	Yes	Yes	Yes	Possible	Possible	Possible	Possible	Possible	Possible
3	Supply Requirements	20	20	15	18	19	18	15	20	20	20	20
4	Maintainability & Repair	15	13	14	10	13	10	11	12	10		
5	Crew Requirements	15	15	10	10	15	10	10	12	9		
6	Commonality	10	8	8	9	10	8	8	10	10		
7	Onboard Equipment	10	10	5	10	9	8	7	10	8		
8	Reliability	10	10	10	9	9	10	10	5	5		
9	Space Station Interface Potential	5	5	4	5	5	5	4	3	3		
10	Performance	5	5	5	5	5	4	4	5	5		
11	Weight	5	5	5	5	5	5	5	4	3		
12	Growth Potential	3	3	2	3	3	3	3	3	3		
13	Cost	2	2	2	1	1	1	1	0	0		
		100	96	80	85	94	82	78	84	76	High	High

*A waste fuel system must be compared to the equipment and manpower required to handle waste and perform ACS maintenance. The commonality achieved here should result in a significant reduction in overall maintenance, repair, and resupply requirements.

Selection: Monolithic, Single-Port Fuel Grain for ACS Motors;
Segmented Fuel Grain for Spin/Despin Motors.

3. Ignition System Selection

The four ignition systems considered for the hybrid ACS are ranked in Table V-4. The spark ignition system mixes a light hydrocarbon gas (e.g., butane or propane) with GOX and sparks the mixture; the resulting hot, oxidizer-rich gases heat the fuel grain and initiate hybrid combustion. The heated oxidizer system uses an electric heating element to preheat the oxidizer to approximately 809°K. The precombustor igniter is actually a small spark-ignited hybrid gas generator that supplies warm, fuel-rich products to mix and combust with the main oxidizer stream. Similarly, the pyrogen igniter is a solid gas generator that injects hot, fuel-rich products into the main oxidizer stream.

Selection of the ignition system was primarily based on technical status. Butane and propane spark-ignition systems have been used successfully for years at UTC with GOX on hybrid demonstration and test motors. Similarly, pyrogen igniters have been developed at UTC for hybrid systems, and have been used successfully on a number of motors. Compared to these two proved ignition systems, the heated oxygen system and the precombustor system are only very promising concepts. Therefore, although a comparative ranking of these approaches (Table V-4) showed that the heated oxygen ignition system was superior for the ACS motors, only the pryogen and spark ignition systems were considered for final selection.

The complexity of the pyrogen ignition system increases rapidly for multiple-start applications, but the complexity of the spark ignition system is nearly independent of the number of starts. The pyrogen system would require a separate igniter for each restart, which makes it unacceptable for the ACS motors. However, a pyrogen igniter can provide a safe, compact, reliable ignition system for the spin/despin motors. The spark ignition system is ideal for the ACS motors, where frequent starts are required. Once the spark system and the propane feed system have been provided, the number of restarts is limited only by the size of the propane supply. The spark ignition system could probably be used with LOX on the spin/despin motors since the initial oxidizer flow will probably be gas; however, since the injector would be sized for LOX, this system might not provide reliable ignition. Based on these considerations and the quantitative ratings shown in Table V-4, the pyrogen system was selected for the spin/despin motors and the sparked gas system was selected for the ACS motors.

Table V-4 Ignition System Selection

PRI-ORITY	ITEM	WEIGHTING FACTOR	PROPANE SYSTEM		HEATED OXYGEN SYSTEM		PRECOMBUSTOR SYSTEM		PYROGEN IGNITER SYSTEM	
			ACS	SPIN	ACS	SPIN	ACS	SPIN	ACS	SPIN
1	Safety	Absolute	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
2	Technical Status in 1975	Absolute	Yes	Probable	Probable	Probable	Probable	Probable	Yes	Yes
3	Resupply Requirements	20	16	12	18	20	16	12	0	18
4	Maintainability & Repair	15	12	10	13	13	12	10	5	15
5	Crew Requirements	15	12	10	14	15	12	10	0	15
6	Commonality	10	10	10	10	10	10	10	10	10
7	Onboard Equipment Requirements	10	7	5	9	7	7	5	10	10
8	Reliability	10	9	6	9	8	8	8	10	10
9	Space Station Interface Potential	5	4	3	4	4	4	3	5	5
10	Performance/Reproducible Ignition	5	5	2	5	4	4	3	5	5
11	Weight	5	4	1	5	3	4	1	0	5
12	Growth Potential	3	3	3	2	2	3	3	3	3
13	Cost	2	2	1	2	2	2	1	2	2
		100	84	63	91	88	82	66	50	98

Selection: Sparked Propane System for ACS Motors;
Pyrogen Ignition System for Spin/Despin Motors.

4. Forward Closure Attachment Design

Five candidate designs were considered for use in attaching the forward closure to the motor case. The first design uses a standard snap ring that locks the closure to the case. The second design uses a double bayonet concept, in which a ring locks the closure to the case; a special hand grip tool can be used to facilitate assembly. In the third design, the closure attaches to the case and is held in place by a spring-loaded bayonet; the closure is locked in place through a flange that screws into the motor case. The fourth design uses several radial pins to attach and hold the forward closre and case together; a strap, wire, or tape retention design holds the pins in place. The fifth design is simply a bolted flange concept using four bolts to hold the forward closure to the case.

The snap ring, bayonet, and screw designs are not practical for use with the large [about 406 mm (16 in.) in diameter] spin/despin motors. However, these attachments were considered for use with the smaller ACS motors.

In rating and evaluating attachment concepts, consideration was given to the motion needed to attach the closure and to the physical size of the closure. Considering a zero-g environment, installing a snap ring using a ratchet or snap ring pliers is superior to the rotary motion required to attach a bayonet or screw flange. A special hand tool could be designed to facilitate installation of a bayonet design. This tool would have to be developed and maintained in operational condition.

A snap ring pliers is an off-the-shelf, reliable tool requiring little or no maintenance. Another advantage of the snap ring design is the elimination of a jammed closure during motor servicing due to installation alignment and and cross threads. The 178-mm (7-in.) diameter ACS motors are large enough to accommodate the snap ring attachment.

The radial pin attachment concept is a reliable, easy-to-use method of attaching the forward closure of the larger spin/despin motors. A pin attachment has an advantage over the bolted flange concept since no rotary motion or torque is required to install the pins. The spin concept will require a pin extraction tool to facilitate the removal of the pins during motor refurbishment. A strap using a suitcase-type latch will be used to hold the pins in position during motor standby operation. As an added precaution to accidentally opening the latch and unstrapping the pins, the latch can be cotter-keyed in the closed position.

The attachment concepts were rated as shown in Table V-5. The shear pin design offers the greatest safety, as well as high reliability, low maintenance, and minimum crew requirements, and was selected for both the ACS and spin/despin motors.

5. Motor Refurbishment Concept

Three refurbishment approaches were considered for servicing the ACS and spin/despin motors. All three concepts provide for a shirtsleeve environment during motor servicing.

The first concept uses a movable attachment tube. During refurbishment, the tube is used to retract and extend the motor. During standby and firing, the tube is in storage or used to service another motor. Two tube sizes are required: one tube is used to service the smaller ACS motors, and the other tube, to service the larger spin/despin motors.

The second concept uses a permanently mounted chamber for each motor. The motor is retracted into the chamber and rotated. A door in the bottom of the chamber provides access to the motor for servicing.

In the third concept, a cap is positioned over the end of the nozzle and the motor is serviced while attached in its operational position.

Since the spin/despin motors are oriented radially with respect to the Space Station axis, the movable tube and nozzle cap are the only two applicable motor refurbishment approaches for the spin/despin motors. Note that the nozzle cap extends well beyond the thruster pad and may present a problem during launch.

The three motor refurbishment concepts are rated in Table V-6. All three approaches are considered safe and state-of-the-art. The movable tube approach held the highest rating for both the ACS and spin/despin motors. It scored highest in maintenance, onboard equipment, reliability, and weight. The parallel transfer approach scored highest in crew requirements, but ranked low in onboard equipment and weight. The nozzle cap approach was not outstanding in any category, and was rated low in maintenance and crew requirements.

Table V-5 Forward Closure Attachment Selection Rating of Candidate Systems

PRI-ORITY	ITEM	WEIGHTING FACTOR	SNAP RING		DOUBLE BAYONET		BAYONET SCREW		SHEAR SPIN		BOLTED FLANGE	
			ACS	SPIN*	ACS	SPIN*	ACS	SPIN*	ACS	SPIN*	ACS	SPIN
1	Safety	Absolute	Yes		Yes		Yes		Yes	Yes	Yes	Yes
2	Technical Status in 1975	Absolute	Yes		Yes		Yes		Yes	Yes	Yes	Yes
3	Supply Requirements	20	20		15		15		20	20	20	20
4	Maintainability & Repair	15	14		13		12		14	14	9	9
5	Crew Requirements	15	15		14		12		15	15	8	8
6	Commonality	10	9		9		9		10	10	10	10
7	Onboard Equipment Requirements	10	9		5		9		10	10	8	8
8	Reliability	10	9		8		9		10	10	10	10
9	Space Station Interface Potential	N/A										
10	Performance/Reproducible Ignition	N/A										
11	Weight	5	5		3		4		5	5	5	5
12	Growth Potential	3	3		3		3		3	3	3	3
13	Cost	2	2		1		1		2	2	1	1
		90	86		71		74		89	89	74	74

*Not practical for use on 16-in.-diameter motor.

Selection: Snap Ring for ACS Motors;
Shear Pin for Spin/Despin Motors.

Table V-6 Selection of Motor Refurbishment Approach

PRIORITY	ITEM	WEIGHTING FACTOR	RATING OF CANDIDATE APPROACHES					
			MOVABLE TUBE		PARALLEL TRANSFER		NOZZLE CAP	
			ACS	SPIN	ACS	SPIN	ACS	SPIN
1	Safety	Absolute	Yes	Yes	Yes	N/A	Yes	Yes
2	Technical Status in 1975	Absolute	Yes	Yes	Yes	N/A	Yes	Yes
3	Supply Requirements	20	18	19	17		18	18
4	Maintainability & Repair	15	15	15	13		10	13
5	Crew Requirements	15	13	13	15		10	12
6	Commonality	10	10	10	10		10	10
7	Onboard Equipment Requirements	10	10	10	7		8	9
8	Reliability	10	10	10	9		7	8
9	Space Station Interface Potential	5	4	4	5		3	3
10	Performance	N/A	N/A	N/A	N/A	N/A	N/A	N/A
11	Weight	5	5	4	2		3	5
12	Growth Potential	3	2	2	1		3	3
13	Cost	2	2	2	1		0	1
		95	89	89	80		72	82

Selection: Movable Tube Approach for Both ACS and Spin/Despin Motors.

B. DESCRIPTION OF SELECTED TCA DESIGN

Table V-7 summarizes the design concepts and approaches that have been selected for the ACS and spin/despin motors and for the refurbishment equipment. The selected esign features a safe, reliable, easy-to-maintain system that provides optimum performance over the required operating life.

Table V-7 Selection Summary

CONCEPT	ACS MOTOR	SPIN/DESPIN MOTOR
Refurbishment	Movable Tube	Movable Tube
Forward Closure Attachment	Shear Pin	Shear Pin
Ignition System	Sparked Propane	Pyrogen Igniter
Fuel Grain	Monolithic (Cylindrical Port)	Segmented (Cylindrical Port)
Propellant Selection	PMM/PBD & GOX	PMM/PBD & LOX

1. ACS Motors

The ACS motors will use PMM/PBD fuel with GOX. The fuel grain will be a monolithic (one-piece) cartridge having a cylindrical port design. The igniture will use sparked gaseous propane mixed with GOX. A shear pin attachment design holds the forward closure to the motor case. The shear pin will facilitate removal and installation of the forward closure.

The movable tube motor refurbishment concept was selected for the ACS motors. During refurbishment, a tube assembly will be placed over the motor and attached to the motor mounting pad. This tube assembly will contain a sliding door with an external seal that closes off the motor port hole after the motor is retracted into the refurbishment tube. The tube will then be repressurized. The door will remain in position during motor removal and motor servicing. After refurbishment, the motor will be extended into its operational position and the tube assembly (including the environment door) will be removed and stored until needed for another motor refurbishment.

2. Spin/Despin Motors

The spin/despin motors will use PMM-PBD fuel with liquid oxygen (LOX). The fuel grain consists of segmented cartridges having a cylindrical port design. The segmented feature allows for ease of handling during motor refurbishment. A pyrogen igniter will provide ignition of the motor.

The forward closure is held to the motor case by 16 radial shear pins. A circumferential strap holds the pins in position during standby operation. The strap is locked in position with a suitcase-type latch and cotter keyed to prevent accidental unlatching. A special pin extracting tool will be used to remove the pins during motor servicing. Motor refurbishment will be accomplished using the movable tube approach in the same manner as the ACS motors.

C. OXIDIZER FEED ASSEMBLY SELECTION

1. Selection Procedure

A number of OFAs and resupply techniques were conceived, based on resupply/repair and performance considerations. Each candidate was evaluated against the selection criteria presented in Table V-1 to determine the optimum system and resupply/repair methods to fulfill the 10-year life requirement.

The evaluation of candidate methods for a given application generally is based on consideration of a number of selection criteria, $X_1, X_2, \ldots, X_n$. Furthermore, these criteria are weighted numerically. Two types of weighted criteria are employed: qualitative criteria of "go" or "no-go" character that candidate methods must satisfy to be acceptable, and quantitative factors that the methods can fulfill in varying degrees. Examples of the two categories are:

Qualitative Criteria	Quantitative Criteria
Safety	Performance
Stage-of-the-Art	Weight
	Size
	Cost
	Reliability

Some of the rating criteria can be both quantitative and qualitative, depending on the requirements of the application. For example, if a maximum weight of 100 kg (220 lb) were a requirement, all systems heavier than this would be eliminated. Systems lighter than this would be rated quantitatively.

The evaluation technique is considered an objective technique since the "figures of merit" that are used are independent of the system evaluation and are established before the evaluation. In the evaluation, an identical set of requirements and constraints is imposed on each method considered.

The figure of merit approach requires that each of the quantitative criteria be considered individually. This may be represented mathematically as:

$$\phi = \sum_{i=1}^{1} \phi_i, \qquad \text{[V-1]}$$

where:

ϕ = Overall figure of merit;

ϕ_i = Figure of merit for each quantitative criterion.

Furthermore, the number of individual figures of merit are reduced by placing the figures of merit in terms of certain common parameters. For example:

$$\phi_n = \frac{\left[(\phi_1)^a \; (\phi_2)^b\right]^y}{(\phi_3)^c \; (\phi_4)^d} \qquad \text{[V-2]}$$

The location of ϕ_i in the numerator or denominator depends on whether or not the particular ϕ_i improves or degrades ϕ_n.

The exponents a, b, c, d, and y represent the weight factors assigned to each criterion. Their values are determined in the following manner. For those common parameters making up the figure of merit, the lowest weighting factor is used as the base, and the exponents are determined accordingly. For example:

$$(WF_1)^a = (WF)_1$$

$$(WF_1)^b = (WF)_2$$

$$(WF_1)^c = (WF)_3 \qquad [V-3]$$

$$(WF_1)^d = (WF)_4$$

The same approach is used in determining the exponent y, etc.

Preliminary screening eliminated a number of candidate oxidizer feed assemblies due to safety and state-of-the-art considerations (Table V-8). Systems 3, 4, 5, 8 and 11 were eliminated because they involve combustion during the pressurization, which we believe presents a potential safety hazard. Systems 15 and 18 were eliminated because the elastomeric bladder materials are not compatible with cryogens. The jet pump, despite its simplicity, has never worked. The turbopump system was eliminated because turbopumps that small have never been developed and because the moving parts of the turbopump present reliability problems for a long-life manned system. Systems 6 and 7 were eliminated because, although they appear attractive, their feasibility has not been demonstrated

Table V-8 Candidate Systems Eliminated

SYSTEM	DESCRIPTION	REASON
3	Heater, Self-Pressurization	Safety
4	Heat Sink Material, Self-Pressurization	State-of-the-Art
5	Hydrazine Main Tank Injection	Safety
6	Electromechanical Bellows	State-of-the-Art
7	Mechanical Bellows	State-of-the-Art
8	Solid Gas Generator (Bellows)	Safety
9	Jet Pump	State-of-the-Art
10	Turbopump	State-of-the-Art
11	Solid Gas Generator (Capillary Screen)	Safety
18	Blowdown Stored Gas (Bladder)	State-of-the-Art

The feed systems were evaluated using the following figure-of-merit relation:

$$\phi = \phi_{ps} \left(\phi_R\right)^{1.86} \left(\phi_m\right)^{1.68} \qquad [V-4]$$

where:

ϕ = Overall figure of merit;

ϕ_{ps} = Figure of merit for the feed system;

ϕ_R = Figure of merit for the resupply requirements;

ϕ_m = Figure of merit for maintenance and repair.

The figures of merit for growth potential, Space Station integration potential, onboard servicing, etc, are assumed identical for all candidate systems. These assumptions are believed valid since all candidate systems are similar.

The figures of merit are evaluated in terms of reliability (R), cost (β), crew time (c), and weight (W) or mass fraction (λ). Thus

$$\phi_{ps} = \frac{R^{2.32}}{W^{2.32}\ \beta}, \qquad [V-5]$$

where the crew time is assumed equal for all systems;

$$\phi_R = \frac{R^{2.32}\ \lambda^{2.32}}{\beta\ c^{3.91}} \qquad [V-6]$$

and

$$\phi_m = \frac{1}{W^{2.32}\ \beta\ c^{3.91}}, \qquad [V-7]$$

where the reliability is assumed constant for all systems.

The exponents used in the figures of merit for all system calculations $\left(\phi_{ps}, \phi_R, \text{ and } \phi_m\right)$ were obtained from the following relations using the weighting factors in Table V-1.

$$2^a = 15 \qquad a = 3.91$$

$$2^b = 5 \qquad b = 2.32$$

The base 2 was used since it was the lowest weighting factor considered for these parameters.

For the overall figure of merit, the exponents were obtained as follows:

$$5^c = 20 \qquad c = 1.86$$

$$5^d = 15 \qquad d = 1.68$$

The base 5 represents the lowest weighting factor for this case.

The data used to determine these numbers were derived in the following manner. Each system was considered by parts, and the corresponding weights, costs, reliabilities, and crew times were determined. The values for these parts are presented in Tables V-9 thru V-12. Common numbers were used for all systems, which minimizes judgment errors because they are cancelled when one uses a relative comparison method.

Table V-9 Component Weights*

COMPONENT	WEIGHT UNITS	COMPONENT	WEIGHT UNITS
Bellows	7.2	Pressure Gage	1.2
Bellows Casing	12.8	Fill & Vent	0.2
Tubing	0.6	Three-Way Valve	0.8
Quad Check Valve	1.0	Electric Motor	5.0
Relief Valve	0.3	Spring	2.0
Burst Disc	0.5	Gas Tank	158.0
Shutoff Valve	0.4	LOX Tank	11.4
Filter	0.2	Capillary Screen	2.0
Regulator	1.2	Diaphragm	6.0
Pressurant Tank	6.2	Vaporizer	1.0

*Weight of attaching structure and remote instrumentation not included.

Table V-10 Component Cost*

COMPONENT	COST UNITS	COMPONENT	COST UNITS
Bellows Assembly	20,000	N_2 Tank	15,000
Quad Check Valve	160	Fill & Vent	820
Relief Valve	200	Three-Way Valve	800
Burst Disc	15	Spring	500
Shutoff Valve	500	LOX Tank	20,000
Filter	1,000	Diaphragm	2,000
Regulator	10,000	Vaporizer	2,000

*​*NASA Pressurization Design Guide.* Report No. 2736, July 1966.

Table V-11 System Cost*†

SYSTEM	LAUNCH COST	SYSTEM COST	TOTAL COST
13	875,000	245,380	1,120,380
14	877,000	245,380	1,122,380
16	878,000	229,100	1,107,100
17	880,000	235,380	1,115,380
1	902,000	245,380	1,147,380
2	908,000	250,580	1,158,580
12	1,420,000	177,180	1,597,180

*​*NASA Pressurization Design Guide.* Report No. 2736, July 1966.

†*Space Station Definition, Vol V - Subsystems.* MSFC-DRL-16, Line Item 8, Contract NAS8-25140.

Table V-12 Component Reliability (2.4 yr)

NAME	FAILURE RATE/ 10^6 HR OF OPERATION	FAILURE RATE/HR-NONOPERATE	RELIABILITY
Bellows	2.237	0.000002	0.958*
Diaphragm (Metal)	0.800		
Electric Motor	0.300		
Low-Pressure Tank	0.180		
Annular Screen	1.400		
Regulator	2.140		
Quad Check Valve	5.000		
Relief Valve	5.700		
Shutoff Valve	6.500		
Filter	0.300		
Fill & Vent Valve	5.700		
Three-Way Valve	4.000		
Spring	0.220	0.000002	0.958*

*Reliability = $\left(R_{\text{operate}}\right)\left(R_{\text{nonoperate}}\right)$.

$R_{\text{operate}} \approx 0.9999$ (for values of e to the n^{th} power <0.001, the reliability is approximately = 0.9999).

$R_{\text{nonoperate}} \approx 0.9589$.

The weight and cost of components for the calculation of the figure of merit for maintenance were obtained in the following manner. Using the results from the calculation of redundant reliability, we estimated that a half-system reliability of 0.61 would give a redundant reliability of 0.96. Thus, 0.61 was used in determining the times necessary for system replacement. The component failure rates were the same, so the time for replacement was a function of component number. The calculation resulted in the equation

$$t = 247{,}500/n$$

where t is the replacement time in hours and n is the number of components. Task times are presented in Table V-13.

Table V-13 Estimated Task Times

COMPONENT	PRESSURIZATION SUBSYSTEM (minutes)	PROPELLANT STORAGE & TRANSFER SUBSYSTEM (minutes)
Tank	81	255
Quick-Disconnect Valves	74	160
Three-Way Valve	85	211
Pressure Regulator	76	165
Check Valve	71	160
Relief Valve	78	167
Burst Disc	78	167
Filter	59	93
Lines & Fittings	144	213
Solenoid Valves	73	162
Motor	69	
Spring		153
Annular Screen		231
Diaphragm (Same as Tank)		255

The replacement weights and costs were obtained by dividing the system weight and cost by the number of years between replacement. The crew time was obtained from the unscheduled maintenance calculation. The reliability, weight, and cost of the system were obtained from previous calculations.

The results of the calculations for the feed systems are presented in Table V-14.

The resupply systems that were considered are listed in Table V-15. The results of the resupply analysis are presented in Table V-16.

Table V-14 Evaluation of OFA Systems

		ϕ_{ps}					ϕ_m				
NO.	NAME	R_{ps}	W_{ps} ($\times 10^2$)	β_{ps} (\$ in millions)	ϕ_{ps}	ϕ_R ($\times 10^2$)	W ($\times 10^2$)	β ($\times 10^5$ \$)	C	ϕ_m	ϕ ($\times 10^{-2}$)
1	Blowdown Gas, Bellows	0.8535	1.756	1.482	0.1265	3.32	0.999	1.39	1.19	0.366	1.04
2	Regulated Gas, Bellows	0.8585	1.804	1.6585	0.105	3.32	1.02	1.425	1.15	0.383	0.93
12	Gaseous Feed	0.9328	6.608	2.097	0.00507	9.35	0.31	0.63	0.395	8.48	0.784
13	Blowdown Gas, Capillary Screen	0.8535	1.384	2.1204	0.153	3.32	0.786	1.39	0.895	1.94	26.3
14	Regulated Gas, Screen	0.8238	1.40	2.1224	0.138	3.32	0.896	1.57	0.905	1.21	8.5
16	Blowdown Gas, Diaphragm	0.8535	1.584	1.8571	0.1275	3.32	0.90	1.30	2.32	0.0365	0.02
17	Regulated Gas, Diaphragm	0.8238	1.60	1.86538	0.115	3.32	1.02	1.495	2.34	0.0231	0.01

Table V-15 Resupply Techniques

OXYGEN RESUPPLY	PRESSURANT RESUPPLY
Bellows & Spring	Blowdown
Bellows & Motor	Bellows & Spring
Bellows & Manual Drive	Bellows & Motor
Bellows & Gas	Bellows & Manual Drive
Bladder & Gas	Modular Replacement
Diaphragm & Gas	
Screen & Gas	
Modular Replacement	
Paddle/Vortex	

Table V-16 Resupply Evaluation

a) LOX Resupply

NO.	APPROACH	R	λ	C (hr)	β ($\times 10^6$)	ϕ_R ($\times 10^{-3}$)
1	Bellows & Spring	0.9227	0.705	0.784	0.71616	1.33
2	Bellows & Motor	0.9235	0.685	0.815	0.69276	1.12
3	Bellows & Manual Drive	0.9259	0.710	1.2	0.68776	0.270
4	Bellows & Gas	0.9230	0.677	0.784	0.62876	1.38
5	Bladder & Gas	0.5563	0.748	0.784	0.60876	0.559
6	Diaphragm	0.9397	0.740	0.784	0.61036	1.80
7	Screen & Gas	0.9298	0.746	0.784	0.80716	1.38
8	Modular Replacement	0.9978	0.848	2.4	0.4807	0.0445
9	Paddle/Vortex	0.9396	0.710	0.815	0.89786	0.970

b) Pressurant Resupply

NO.	APPROACH	R	λ	C (hr)	β ($\times 10^6$)	ϕ_R ($\times 10^{-3}$)
1	Blowdown	0.9427	0.0498	0.75	0.24486	9.35
2	Bellows & Spring	0.9227	0.0437	0.75	0.36336	4.95
3	Bellows & Motor	0.9235	0.048	0.785	0.35676	5.95
4	Bellows & Manual Drive	0.9259	0.0462	1.17	0.35226	1.03
5	Modular Replacement	0.9981	0.0646	2.27	0.12872	0.548

2. Description of Selected OFA Design

The leading oxidizer feed system is the blowdown system with screens. This system is undergoing development as the propulsion system for the Grand Tour spacecraft, as well as for zero-g propulsion on the Shuttle. Thus, this system has been selected as the preferred oxidizer feed system.

The preferred resupply methods are:

1) Oxidizer -- Blowdown gas with screens;
2) Pressurant -- Blowdown.

The blowdown system with screens is rated equal to the bellows system for resupply of the oxidizer. However, to minimize development cost, the screen system is selected since this is also the preferred system for the oxidizer feed system. The bellows system presents materials problems if it is considered for reuse.

The blowdown system for the pressurant resupply is preferred since it minimizes crew time but is economical and possesses good reliability.

Note that in this analysis, crew time is of major importance. As a result, the preferred systems/methods are those that minimize crew time. Changing the weighting of the evaluation criteria would, of course, change the results.

The conceptual hybrid APS meets all APS performance requirements and has high safety and reliability, low maintenance and resupply requirements, and minimum weight. The design approaches presented in Chapter V were further optimized to minimize maintenance, repair, and resupply requirements. Propulsion operating conditions were optimized to ensure long nozzle life. Oxidizer flow components were optimized, based on the selection of LOX for the spin/despin motors and GOX for the ACS motors. Ignition system designs were optimized, and a fluidic propane injection system was selected for the ACS motors to reduce maintenance and increase reliability.

The APS was designed to operate safely and reliably for 10 years with a minimum of required inflight maintenance. Only state-of-the-art designs were considered, and off-the-shelf components were employed wherever possible. The spin/despin motors were optimized for the planned five artificial-g cycles during the first 18 months. In spite of their larger size, these motors were designed to be handled and refurbished by one man to reduce crew requirements. The integrated hybrid APS was designed with 16 ACS motors and three spin/despin motors; all associated lines and valves were located on two thruster pads. Mass requirements were evaluated for the ACS motors, the spin/despin motors, and the OFAs. Performance and exhaust products were evaluated for the hybrid APS, and ballistic data were presented for both motors. Reliability predictions were made for both motors and the complete system. The numerous safety features of the selected hybrid APS were compiled.

This task was composed of the following subtasks:

Subtask	Description
1	Long-Life Methods Design Guide
2	TCA Design Optimization
3	Attitude Control Motor Design
4	Spin/Despin Motor Design
5	Oxidizer Feed Assembly Design
6	Propulsion System Facilities
7	APS Mass and Performance
8	APS Safety and Reliability

A. LONG-LIFE METHODS DESIGN GUIDE

This section presents the design philosophy and design guidelines used to design the conceptual hybrid APS. This propulsion subsystem must have a long-life capability in space to satisfy the requirements of the Space Station. Long life is interpreted to mean:

1) Long exposure to the space environment ($\sim$10 yr);
2) Long total engine burntime ($\sim$2000 sec for the ACS motor and $\sim$10,000 sec for the spin/despin motors);
3) Many engine ignitions in space ($\sim$200 for the ACS motors);
4) Any combination of these requirements.

The life capability of the APS is a major consideration affecting the operating life of the Space Station. The long-life design methods presented below are tailored specifically for the hybrid APS although much of the data is applicable to other propulsion subsystems or similar types of subsystems.

The probability of successful hybrid APS operation for a specified period of time is basically a function of the wearout and rundown failure characteristics of the components that make up the hybrid APS. To determine what techniques are required to obtain the necessary reliability and safety for the 10-yr Space Station mission, it is necessary to ascertain whether wearout or rundown failures are dominant. Operating redundancy will not minimize wearout problems since redundant components are wearing simultaneously; redesign, standby redundancy, or replacement are the principal methods that can be employed to increase life. Decreasing the rundown failure rate will not solve the wearout problems.

Specific ground rules for establishing the most effective technique depend on the specific application. For our application (i.e., an APS for a Space Station for 10 yr), the operational requirements can be met only by employing inflight maintenance. A previous analysis had shown that the required reliability could not be obtained with a nonmaintainable ACPS. The total weight (or perhaps some other constraint) for the nonmaintainable APS is determined from the sum of the component weights for each time period. Similarly, another curve is determined for the maintainable case by determining the weight of the spares, isolation and detection equipment, etc, to achieve the same mission requirements. The following figure shows the general shape of the curves and the crossover point.

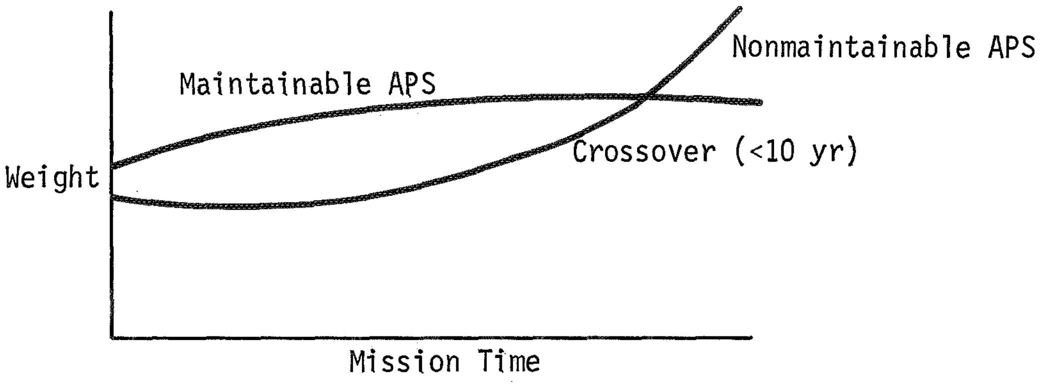

Fig. VI-1 Weight vs Mission Time for Maintainable and Nonmaintainable Propulsion Systems

1. Design Philosophy

Achieving long-life in the hybrid APS components requires the utmost attention to detail in adhering to a design philosophy designed to eliminate life-shortening factors in APS operations. This requires a complete familiarity with all of the APS design factors and as complete an understanding as possible of the elements involved in the installation, checkout, and operation of the APS on the Space Station.

One method of providing a long-life capability for the hybrid APS is to design all life-critical parts with large margins, i.e., the operating margins on the performance of the components. One area in which large margins can significantly contribute to long life in the hybrid APS involves the combustion chamber temperature margin. For example, decreasing the maximum chamber wall temperature from 3100°F to 2000°F* would increase chamber life from 30 minutes to more than 1000 hr. Similarly, the design margin for resisting internal pressures should also be large for the pressurant tanks, oxidizer tanks, combustion chambers, and associated plumbing.

Another means of achieving long life is to use self-healing characteristics in portions of the system that are subject to damage from long use or subject to unacceptable leaks.

A major problem in the past has been the thermal control of various subsystems. Therefore, the operating temperatures of the various components of the propulsion subsystem must be controlled within their design limits.

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*L. R. Bell: "Long-Life Reaction Control System Engines and Valves." AIAA Paper 70-603. AIAA 6th Propulsion Joint Specialist Conference, June 15-19, 1970.

The design of the hybrid APS has to enable proper operation in spite of failures. It is imperative that the failure of a critical component be eliminated if that failure could result in the loss of a single function or induce nonstandard operating conditions that would cause other components to be overstressed and enable failures to propagate, not only throughout the propulsion subsystem, but also throughout the Space Station. The only practical way of avoiding this problem is through the use of redundancy -- either by paralleling two or more physically identical systems, or by paralleling two or more functionally similar, but physically different systems. Functional redundancy in the paralleling of physically different, but operationally identical subsystems offers greater protection against casual failures, and in many cases can be designed into the system at relatively low cost in terms of power, weight, volume, and complexity.*

Another approach to long life is to use alternative operating methods to satisfy Space Station APS requirements. An example might be to use the environmental life support system to provide the oxygen.

Hardware commonality with other subsystems, when combined with inflight maintenance, provides another means of improving APS reliability.

It has long been recognized that reliability is enhanced by using the simplest possible design that will satisfy the required functions. This philosophy generally leads to designs in which the total number of parts is minimized. Obviously, for the design of long-life components, it is even more desirable to minimize the number of parts subjected to wear. This generally results in reducing the number of moving parts.

Another major consideration in the design of long-life propulsion subsystems is a thorough analysis of failure modes and effects. In addition, scrupulous attention must be devoted to developing adequate quality control techniques during all phases of fabrication, assembly, and testing.

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*R. Draper, T. Gavin, and E. Grogin: "Achieving a Long-Life, Reliable Spacecraft: An Overview." Jet Propulsion Laboratory, Pasadena, California, June 19, 1970.

Finally, a long-life propulsion system design can only be assured through subjecting the engine to a comprehensive test program during the development program. This program should initially cover, to the greatest extent possible, the full range of expected operational and environmental factors expected in the actual mission. To provide assurance of achieving a successful mission, ground tests should be structured to produce complete evaluation of the variables of engine functions, and environments expected during the life of the Space Station. Based on the experience of the Mariner program,* the overall test program should include:

1) Screening Tests - Before assembling type approval or flight propulsion systems, components are screened at extreme test levels to ensure that the components selected will be as free of infant mortality as possible, and as reliable as possible;
2) Developmental Test - Developmental tests are performed to confirm the analysis used to construct the selected design approach;
3) Type Approval Tests - Type approval tests are the formal environmental qualification tests of the engine design;
4) Flight Acceptance Tests - These tests verify that manufacturing and workmanship quality are acceptable for flight;
5) Life Tests - These tests provide information about the operating characteristics of the engines as a function of time, and are used to estimate the useful life of the engines and their components.

2. Design Guidelines

The design guidelines presented in Table VI-1 are based on general "do's" and "don't's" for long-life space components.† These general guidelines have been updated and modified for hybrid auxiliary propulsion subsystems.

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*R. Draper, T. Gavin, and E. Grogin: *Achieving a Long-Life, Reliable Spacecraft: An Overview.* Jet Propulsion Laboratory, Pasadena, California, June 19, 1970.

†*Handbook of Long-Life Space Vehicle Investigations.* M-68-21. Martin Marietta Corporation, Denver, Colorado, December 1968.

Table VI-1 Design Guidelines for a Long-Life Hybrid APS

DOs

1. Design to meet the environment.
2. Build the subsystem as designed.
3. Test to see that the design is met.
4. Subject electronics to temperature cycle tests.
5. Use margin tests on mechanical items.
6. Build the subsystem clean.
7. Incorporate rupture diaphragms into the ordnance valve body if possible.
8. Use spherical (ball-poppet) seals where possible.
9. Restrain Teflon on three sides to reduce cold flow.
10. Apply switch actuation and release forces directly to the contacts.
11. Exercise care in selecting pressure regulators because only a few are designed for use under the space environment.
12. Coat vacuum-exposed surfaces of polymer seals with an evaporation barrier.
13. Ensure that minimum seal stress is maintained under all environments.
14. Remember that some seal materials degrade in the space environment.
15. Use screen-type positive expulsion devices if possible.
16. Use nonconductive mountings for cryogenic storage tanks.
17. Insulate the spacecraft skin near the cryogenic storage tanks.
18. Minimize the need for controls in pressure-fed rocket propulsion systems because control valve failure rates are high.
19. Test for environmental compatibility and emphasize the possible interaction of the environments. For example, radiation affects some materials differently in a vacuum than in an oxygen atmosphere.
20. Evaluate the effect of mission duration on failure modes and failure mechanisms. For longer missions, different failure modes and failure mechanisms may become the major life-limiting factors.
21. Reduce the probability of cold welding by using contact materials that are dissimilar, and/or have hexagonal structure, and/or are mutually immiscible in the liquid state, and/or by maintaining a lubricant film between contact surfaces.
22. Provide adequate conductive heat removal, especially for polymer lubricants that require special heat-dissipation consideration.
23. Prevent outgassing contaminants from condensing on optical surfaces.
24. Use conservative opening and closing valve force margins (a margin of 300% is suggested). Verify these margins by test.
25. Use redundant seats and solenoids in valves when practical, and prove force margins with one and both solenoids operating.
26. For vacuum exposures, design valves so that all moving, mating parts are on the pressure side of the valve.
27. Design cryogenic storage tanks so that welded or brazed joints can be thoroughly inspected.
28. Hold welded or brazed joints in cryogenic storage tanks to a minimum.

DON'Ts

1. Don't ignore the obvious.
2. Don't forget that metal seals may cold weld.
3. Don't expect long life from rubber O-rings.
4. Don't forget that leaks due to contamination are a major cause of valve failure.
5. Don't use Teflon seats at temperatures above 300°F because they are easily damaged by large particles and vibration.
6. Don't forget that Teflon will cold flow.
7. Don't plate internal valve parts exposed to fluid.
8. Don't forget that some solders melt at relatively low temperatures.
9. Don't forget that some seal materials may vulcanize to the seal gland.
10. Don't expect convoluted metal diaphragms to recycle.
11. Don't forget that machining may expose subsurface inclusions in metals that have been rolled or extruded.
12. Don't allow a malfunction to release toxic gases that might harm men or equipment.
13. Don't depend solely on redundancy to provide reliability.

B. TCA DESIGN OPTIMIZATION

1. Motor Operating Point

Selecting the optimum motor operating conditions involves trading off maintenance, repair, and resupply requirements. Since fuel grain replacement is the primary maintenance function for a hybrid TCA, minimizing maintenance means maximizing the total impulse between grain changes. For a given thrust level based on the parametric motor analysis performed in Chapter III, maximizing the total impulse means using higher O/F ratios and higher chamber pressures to increase the maximum port area and expansion ratio.

A hybrid APS will have minimal repair requirements unless the motor operating conditions are severe enough to require frequent replacement of the motor case and nozzle assembly. A molybdenum disilicide-coated, radiation-cooled molybdenum motor case and nozzle assembly has been selected as the optimum design approach. The silicide coating on molybdenum has a long history of established fabrication techniques. During tests* with an NTO/(85% N_2H_4/15% H_2O) propellant system, a $MoSi_2$-coated molybdenum throat survived firings of over 1000 sec at 862 kN/m^2 (125 psia) at a wall temperature of 1783°K (2750°F) without being damaged. In a final test, the throat temperature exceeded the melting point of the $MoSi_2$ coating and failure occurred at a throat temperature of 2033°K (3200°F). These and other tests indicate that $MoSi_2$ coatings can provide nearly unlimited protection for molybdenum cases as long as the temperature is held below 1922°K (3000°F) and the boundary layer is not oxidizer-rich.

Because both the ACS and spin/despin motors operate for an extended period of time during their required lifetimes, the maximum steady-state throat temperature must be under 1922°K (3000°F) and the maximum short-term temperature for pulsed operation should be substantially less than this. Based on current impulse requirements, the average 222-N $\left(50\text{-lb}_f\right)$ ACS motor will be fired in hundreds of pulses for a total of about 2000 sec during its 10-year life, and the three baseline 1114-N $\left(250\text{-lb}_f\right)$ spin/despin motors will be fired 10 times for a total of about 9300 sec during

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*N. R. Balling and R. I. Batista: "Rocket Engine Evaluation of Protective Coatings." AIAA Paper 68-597.

18 months. By holding the maximum throat temperature below 1922°K (3000°F) and by providing a fuel-rich boundary layer, the spin/despin motor cases can be expected to complete their mission without being replaced. Similarly, by holding the ACS motor throat temperature after a 10-sec firing to between 1367°K (2000°F) and 1478°K (2200°F), the ACS motor cases can be expected to survive 10 years without replacement.

The nozzle thermal analysis performed in Chapter III showed that oxidizer-rich operation was incompatible with long nozzle life. But hybrid combustion is fuel-rich, and the flame zone O/F ratio is only approximately 75% of the motor O/F. The boundary-layer cooling effect in the aft closure and nozzle is strongly affected by the nozzle contour. The unsubmerged nozzle contour chosen for the APS motors will maintain a cool, fuel-rich boundary layer to protect the aft closure and nozzle. The O/F ratio in this boundary layer should be equivalent to about 67% of the motor O/F ratio, or slightly cooler than the temperature in the flame zone.

Oxidizer rich operation dramatically increases the boundary-layer temperature and shortens nozzle life. A boundary layer O/F = 1.33 and a chamber pressure of 552 kN/m^2 (80 psia) is required to limit the steady-state maximum throat temperature to less than 1922°K (3000°F). This allows for time variations or special variations in throat temperature without damaging the $MoSi_2$ protective coating.

The regression characteristics of PMM/PBD fuel with oxygen favor a slight shift to fuel-rich operation during motor firing. When the oxidizer mass flux, G_o is above about 7.037 kg/m^2-sec $\left(0.01\ lb_m/in.^2\text{-sec}\right)$, the fuel regression rate is roughly proportional to G_o. However, at lower values of G_o, radiation effects flatten the regression rate curve and tend to make a motor with a central part grain operate fuel-rich. Fuel-rich operation can be corrected by shortening the grain length to maintain a constant fuel flow. However, decreasing the grain length extends the boundary layer distance from the end of the fuel grain to the nozzle throat, and a longer boundary layer reduces the film cooling effects at the throat. Therefore, to maintain an effective boundary layer O/F of 1.33 at the throat, the motor must be allowed to operate more fuel-rich as the grain length decreases. Initially, motor operation at O/F = 2.0 or slightly higher should be sufficient to maintain an effective boundary layer O/F = 1.33 at the throat. However, as the grain length shortens during firing, a lower motor O/F (e.g., 1.80) would be advisable to ensure continued film cooling at the throat.

Motor operation at an O/F = 2.0 is near peak performance and only results in a 5 to 10% loss in total impulse. A lower O/F ratio reduces the oxidizer flowrate and reduces the maximum motor diameter to satisfy minimum G_o constraints. In the present design, this also limits the exit diameter and expansion ratio. Fortunately, the minimum regression rate of the PMM/PBD fuel system is so low that the maximum expansion ratio still exceeds 100 (the maximum considered). Therefore, operation at O/F = 2.0 will not result in any loss in I_{sp} due to a reduced expansion ratio. The effect of a reduced c* at 552 kN/m^2 (80 psia) and at slightly fuel-rich (O/F = 2.0) performance will only reduce I_{sp} by 3 to 4 sec over the original design conditions $\left[O/F = 2.4, P_c = 689\ kN/m^2\ (100\ psia)\right]$. Operation at O/F = 2.0 and P_c = 552 kN/m^2 (80 psia) will reduce the total impulse by approximately 8.1%.

Under normal operation, the ACS motors would optimize at a higher O/F than the spin/despin motors, but efforts to achieve commonality and maximum reliability led to the selection of identical operating conditions for both motors. The 10-sec maximum throat temperature is only 1173°K (1650°F) for motor operation at O/F = 2.0 and P_c = 552 kN/m^2 (80 psia). If the spin/despin motors were not present and a 10 to 15-sec firing limitation would not restrict the operation of the ACS motors, the ACS motors would probably be designed to operate closer to the O/F = 2.4, P_c = 689 kN/m^2 (100 psia) conditions originally selected. However, in developing the APS, maintaining complete ballistic similarity between the ACS and spin/despin motors allowed direct scaling and eliminated a two-motor development program. In addition, a common chamber pressure should simplify oxidizer feed system and instrumentation requirements by allowing use of common components. Furthermore, the small savings in maintenance from increased total impulse probably does not justify a 10 to 15-sec burntime limitation on the ACS motors. Based on these considerations, the 222-N $(50\text{-}lb_f)$ ACS motors will also be designed to operate at a motor O/F ratio of 2.0 and a chamber pressure of 552 kN/m^2 (80 psia).

2. Oxidizer Flow Component Optimization

Although three candidate oxidizer control valve concepts were considered in Task I, the oxidizer flow components were not evaluated until the oxidizer had been selected. The chosen GOX and LOX systems present different requirements for value, line, and coupling selection. Therefore, these two systems were evaluated separately, with an eye toward commonality wherever possible.

a. ACS Motor Oxidizer Flow Components - In addition to the valve candidates presented in Task I (solenoid, ball, and spool valves), other basic types are gate, rotary, and butterfly valves. However, the leakage associated with these last three types precluded their consideration. The advantages and disadvantages of the solenoid, ball, and spool valves are listed in Table VI-2. The primary design considerations of these types of valves are as follows for the GOX system:

1) Solenoid Valve - The primary seal should be made of Teflon, KEL-F, or silicon and there should be a secondary metal-to-metal seal downstream. This is considered optimum to avoid hard vacuum (10^{-8} torr) primary seal exposure. The metal-to-metal seal also serves to prevent continual cold flow or compression setting of the primary shaft seal, and prevents impact deformation during turn off.

   A normally closed solenoid valve has an inherent mechanical fail-closed position due to spring force bias. With a slight redesign (additional coil), an additional closing force could be induced in case the spring force was insufficient due to poppet seizure or sticking. However, the additional value of the second coil could only be considered marginal in affecting a closure.

   With an inline poppet, it is difficult to have mechanical or electrical position indication. A right-angle poppet not only enables electrical and mechanical position indication (with one external leakage path), but it also provides mechanical assistance for closing the valve by hand, if necessary.

   An inline valve has a lower pressure drop than a right-angle unit and has a smaller physical envelope. Designs in which pinning and/or swaging is employed should be avoided if inflight maintenance or refurbishment is applicable.

Table VI-2 Comparison of Solenoid, Ball, and Spool Valves for the ACS Motors

VALVE	ADVANTAGES	DISADVANTAGES
Solenoid Valve	High Response (2 to 20 msec) Low Wear Zero External Leakage (to cabin) Dual Hard & Soft-Seal Integration Smallest Physical Size Powered Open & Optionally Powered Closed, in Addition to Spring Force Designed to Fail Closed via Spring Bias No Lubrication Required Relatively Low Pressure Drop, Depending on Activation Power Level	No Easily Implemented Mechanical or Electrical Position Indicator on Inline Design No Self-Cleaning of Poppet Seat Seals Abrupt Flow Termination due to Poppet Acceleration
Ball Valve	Mechanical &/or Electrical Position Indication Easily Implemented Lowest Pressure Drop No Lubricant Self-Cleaning of Seat Seals Capability to Fail Closed Achievable by Addition of Torque-Return Spring Mechanical Operation by Hand, if Desired Smoother Flow Termination	Minimum of One External Leak Path Relatively Slow Response (100+ msec) Primary Seal Exposed to Hard Vacuum Greatest Power Requirement Largest Physical Envelope with Actuation Mechanism & On/Off Valve
Spool Valve	High Response (10 to 50 msec) Low Wear Zero External Leakage No Lubrication Required Other than Dry Film Lubrication (i.e., Microseal) Low Power Requirements Position Controllable if Staged (Possible Application during Ignition)	Relatively High Internal Leakage Greater Sensitivity to Thermal Transients Highly Sensitive to Contamination No Easily Implemented Mechanical or Electrical Position Indication Adversely Affected by Hard Downstream Vacuum Larger Physical Envelope than Solenoid Valve; Also Requires On/Off Valve

Physical envelope dimensions of an inline and a right-angle solenoid valve are approximated 7.6x5.1x5.1 cm (3x2x2 in.) and 7.6x7.6x5.1 cm (3x3x2 in.), respectively. The weight can be as low as 0.453 kg (1 lb) depending on whether the body is constructed of aluminum or steel.

The calculated pressure drop through a 12.7-mm (1/2 in.) right-angle valve is approximately 165 kN/m^2 (24 psid) at a system pressure of 689 kN/m^2 (100 psig), an oxygen flowrate of 0.05 kg/sec (0.1102 lb/sec), and a temperature of 278°K (80°F).

2) Ball Valve - The ball can be either fixed or floating. If fixed, one seal is required; if floating, two seals are used. The simplest and least expensive is the full floating ball. In this design, the backup seal is the upstream one. This seal will not, by itself, provide zero internal leakage; rather, it is a safety feature that allows a limited, relatively small amount of leakage (but not enough to sustain combustion) and allows safe replacement.

3) Spool Valve - Spool valves are typically designed for hydraulic applications on an individual basis. Their primary drawback is the excessive internal leakage inherent in designing spool clearances to accommodate temperature changes. The actuation torque force is lower for this type of valve than for the other valves being considered because of pressure balancing of the spool and because its shutoff bias spring has a low preload and low actuation rate. The response of a spool valve is equivalent to that of a solenoid valve. The pressure drop is greater than in a ball valve, but less than or equal to that in a solenoid valve.

Based on an evaluation of these kinds of oxidizer valves for the GOX system, the inline solenoid valve was chosen for the ACS motors. This valve had the lowest internal/external leakage, the fastest response time, the smallest physical envelope and weight, the highest reliability, and was the easiest to refurbish. The parameters of position indication, pressure drop, and seal cleaning were traded off in favor of the advantages listed above.

For quick response, the oxidizer control valve will have to be close coupled with the ACS motors. The valve will be mounted on the forward closure, downstream of the motor disconnect. Although the baseline design featured a quick disconnect, an upstream disconnect failure would vent GOX into the Space Station and make the GOX line difficult to reconnect.

Since speed of coupling is not important, a double-poppet, screw-together coupling is recommended for the ACS motors. Such a coupling provides an engagement length before the poppet can move. This engagement stroke can be vented to physically determine whether excessive leakage is present -- before the halves of the coupling are finally disengaged -- without posing a safety hazard to the operator. Standard aluminum seamless tubing, 12.7 mm (0.500 in.) O.D. and 11.3 mm (0.444 in.) I.D., can be used to supply GOX to the motor pad through a short length of flexible steel/braided Teflon hose connected to each motor via a screw disconnect.

b. Spin/Despin Motor Oxidizer Flow Components - The spin/despin motors use LOX. Being a cryogenic liquid, LOX introduces thermal shock and water hammer effects not present in the ACS motors. The oxidizer flow valves will be mounted on pads upstream of the motor disconnect. This will automatically purge the lines during motor shutdown. The initial flow will be boiling liquid. Although this reduces the severity of the thermal shock, the transient flow conditions prolong the ignition transient. The duration of nucleate boiling will depend primarily on component material and size. To reduce the rate of heat transfer in the valve, the unit should be made of a 300-series stainless steel. In addition, the valve should be vacuum-jacketed to avoid external icing and to protect the crew from low-temperature burns which could result from accidental contact.

Increased pressure caused by sudden flowrate changes can be minimized by lowering fluid velocity or limiting control valve response to less than two time constants of the fluid system. Based on a 6-m (20-ft) line length, the time constant of the LOX system would be 0.0074 sec. If a -8 line size is used [11.3 mm (0.444 in.) I.D.], the peak pressure oscillation about the system operating pressure is theoretically +2206 kN/m (+320 psia) when the required flowrate of LOX is stopped in 0.0148 sec or less. The compression wave does not present a design stress problem, but the rarefaction wave could cause partial flashing (liquid-to-gas transformation) of the LOX in the lines. At this time, no definite information was obtainable to determine the severity of this problem, but it would seem good engineering practice to avoid any rarefaction wave that would cause the static pressure to fall below the vapor pressure of the flowing fluid.

The options available to avoid water hammer are to increase the line size (and thereby reduce the fluid velocity) or to damp the closing action of the valve (thereby establishing a minimum closing time). Assuming the LOX will be supplied at a pressure of 1034 kN/m^2 (150 psia) and at a temperature no warmer than 103°K (-275°F),* a minimum closing time of 0.0947 sec would limit the pressure oscillation to ±344 kN/m^2 (±50 psia). This provides a safety factor of two against flashing.

The two candidate spin/despin motor oxidizer valves are the solenoid valve and the ball valve; the spool valve was eliminated due to its high internal leakage rate with LOX. The slow relative response (100 msec) of the ball valve is an advantage for the LOX system; however, a solenoid valve could easily be designed with a closing damper to limit the minimum closing time to 0.100 sec. The other advantages and disadvantages of the solenoid and ball valves as given for the GOX system remain as listed for the LOX system.

When the actuator mechanism is sized for the LOX ball valve, an extra force margin must be used because of the icing condition at the actuating rod/valve housing interface. This implies that the piston diameter becomes larger for a pneumatic system, or that more power is required for an electric actuator. This also implies that, because of the cold flow/preload effect that thermal cycling has on Teflon or Kel-F, a ball seal has less inherent reliability than the seal in a poppet valve, where a constant preload is achieved regardless of thermal shifts. However, the reliability is associated with the seal leakage rate, rather than with failure of the valve to operate. Therefore, the temperature/time cycle-related leakage is what would have to be determined to rate the acceptability of the particular ball valve.

In short, neither type of valve has a clear cut advantage in the LOX system. However, the solenoid valve is being recommended because it has inherently better sealing characteristics, is not subject to icing in the actuator, is smaller, and is more often used in LOX systems.

Vacuum jackets are recommended for the LOX feedlines. These will prevent excessive boiling of the LOX and facilitate handling the lines during refurbishment. The LOX control valves will be mounted to the thruster pad and connected to the two spin/despin motors via flexible, vacuum-jacketed lines. A vacuum-jacketed quick disconnect coupling will mount directly on the

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*P_{vapor} = 310 kN/m^2 (45 psia).

forward closure. This will allow sufficient thermal soakback during postfire nozzle cooldown to prevent the formation of ice in the coupling during refurbishment.

3. Ignition Systems Optimization

Based on their vastly different operational requirements, different ignition systems have been selected for the spin/despin motors and the ACS motors. The spin/despin motors will use a pyrogen igniter. This was selected because of the size of these motors, their relatively few starts, and their use of LOX. A sparked butane ignition system has been selected for the ACS motors to provide the large number of starts required for attitude control. Sparked butane systems have been used successfully for years.

a. Pyrogen Ignition System for Spin/Despin Motors - Hybrid ignition is fundamentally different from ignition in a solid propellant motor. Since solid propellant combustion is highly pressure-sensitive, the ignition delay depends on the heat flux on the propellant grain and the motor pressure provided by the igniter. In a hybrid motor, a pyrogen igniter supplies warm, fuel-rich gases that vaporize and combust with the oxidizer. The resulting hot oxidizer vaporizes the fuel and initiates hybrid combustion. A chemical interaction between the oxidizer and the fuel also contributes to the ignition process. Test results have shown that an average oxidizer temperature close to the fuel surface temperature [600°K (620°F) for PMM/PBD] is adequate for ignition.

Since hybrid combustion is insensitive to pressure, the design of the igniter is more flexible in a hybrid propulsion system than in a solid propellant motor. Also, the igniter only supplies about 5% of the total flow. Therefore, the igniter can continue burning after full pressure has been achieved, since this will not cause overpressurization of the motor.

Figure VI-2 shows the oxidizer flame temperature vs the ratio of the weight of igniter flow to the rate of liquid oxidizer flow for IRFNA and LOX. Based on these curves, a 5% igniter flow would heat the LOX to 800°K (980°F), which should be more than sufficient for ignition, based on test experience. A 5% flowrate will provide an igniter with a 3-sec duration. This is more than an order of magnitude longer than the required ignition time. Although the igniter's burntime could be substantially reduced, durations of 1 to 2 sec are beneficial with liquid oxidizers to help vaporize the oxidizer and promote smooth ignition. This is more important at a high initial G_o, where the possibility of flooding is higher.

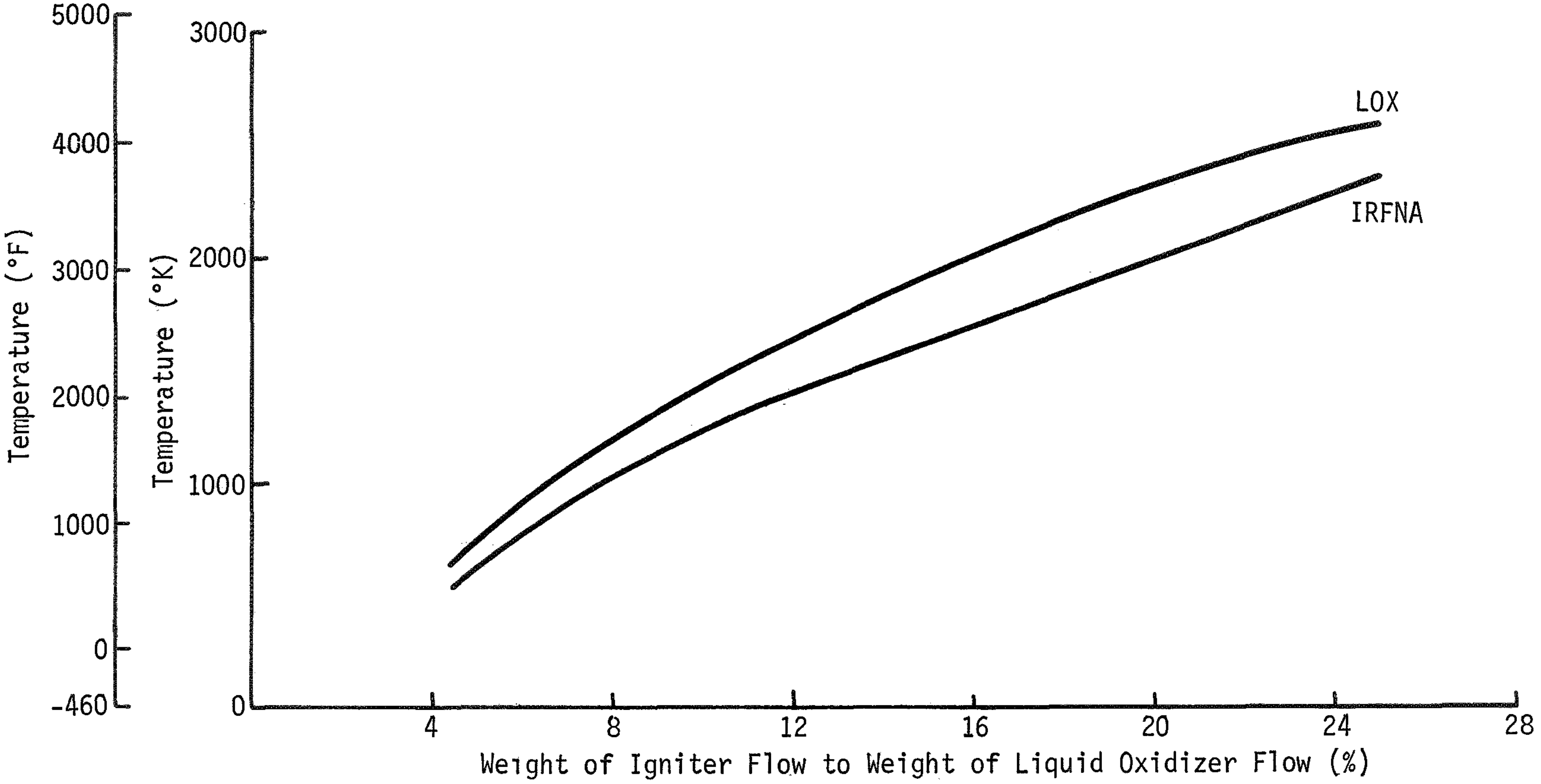


Fig. VI-2 Oxidizer Temperature vs the Ratio of the Weight of Igniter Flow to the Weight of Liquid Oxidizer Flow

A pyrogen igniter supplying 5% of the oxidizer flowrate for 2 sec will provide a smooth, reliable ignition for the spin/despin motors. For a spin/despin motor using LOX/(PMM/PBD) with a thrust of 1112 N (250 lb) and an O/F ratio of 2.0, the required igniter flowrate will be about 0.115 kg/sec $\left(0.026\ \text{lb}_m/\text{sec}\right)$. The total weight of the igniter propellant will be about 0.23 kg $\left(0.052\ \text{lb}_m\right)$, which corresponds to a volume of about 0.000016 m^3 (1 in.^3).

b. <u>Sparked Propane Ignition System for ACS Motor</u> - Several versions of the sparked propane system have been used successfully for years. The system is safe, reliable, and simple to operate. A measured pulse of a light hydrocarbon (butane, propane, etc) is injected into a precombustor and mixed with GOX. The mixture is ignited with a spark and is then injected into the motor. The hot, oxidizer-rich gases heat the fuel and initiate hybrid combustion. Successful operation requires a dependable spark source and a reliable injection system.

The ignition fuel depends on motor operating conditions. The ignition fuel, which will be stored in a replaceable canister on the forward closure (inside the cabin) should vaporize readily at the ignition temperature to ensure thorough mixing with the GOX. However, the vapor pressure at normal cabin temperatures should not present a storage problem. Figure VI-3 shows the vapor pressure of two candidate ignition fuels, propane and butane, as a function of temperature. Propane, which has a vapor pressure above 202.7 kN/m^2 (29.4 psia) at temperatures down to 248°K (-13°F), and a vapor pressure below 2027 kN/m^2 (294 psia) up to a temperature of 330°K (134°F), is much more ignitable at low temperatures than butane and presents no storage problems at cabin temperatures. Therefore, propane was selected as the ignition fuel for the ACS motors.

The fluidic sparked-propane ignition system is based on a fluidic propane injection system recently designed for UTC's GOX/PMM hybrid cutting torch. The system schematic is shown in Fig. VI-4.

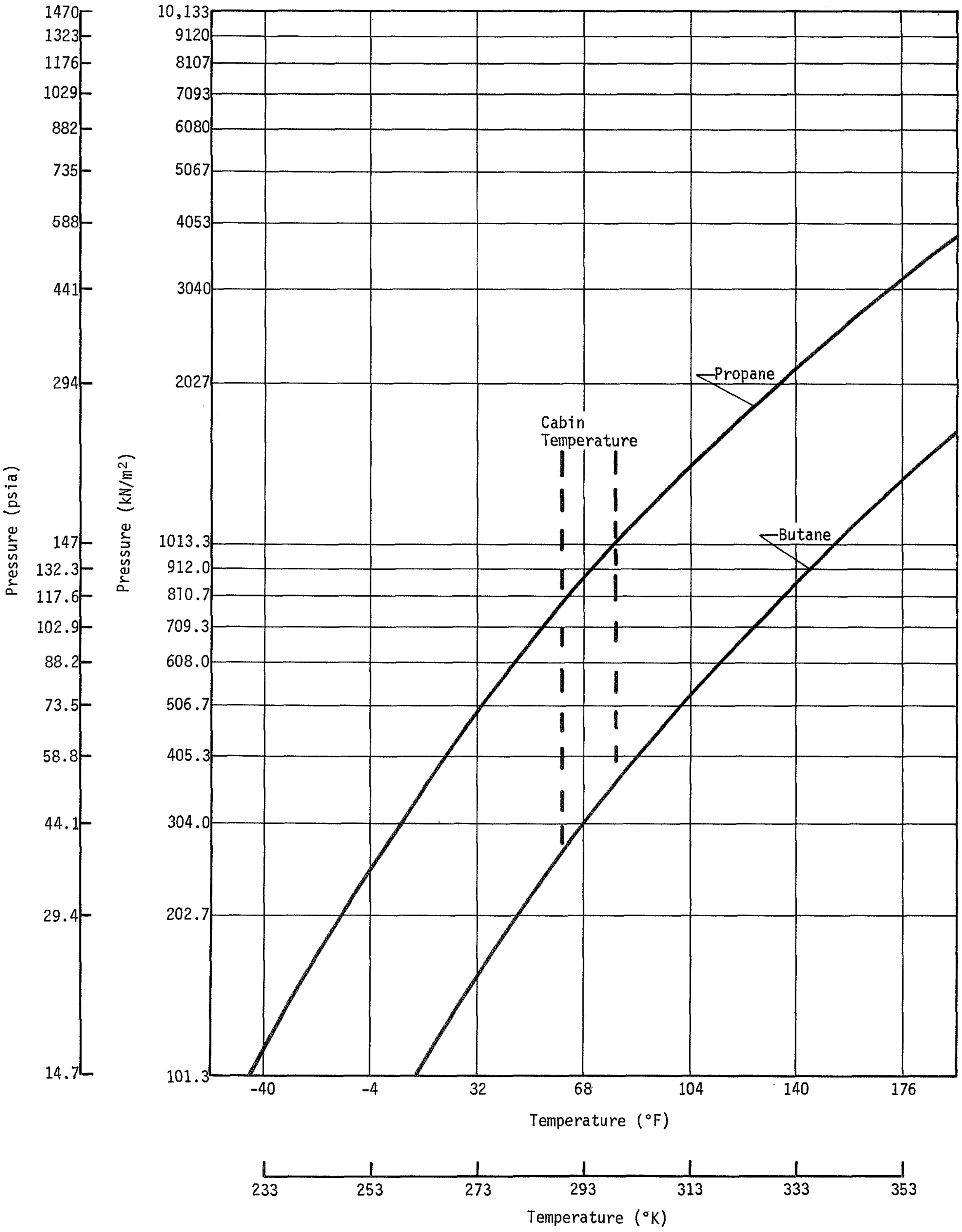


Fig. VI-3 Vapor Pressure vs Temperature for Candidate Ignition Fuels

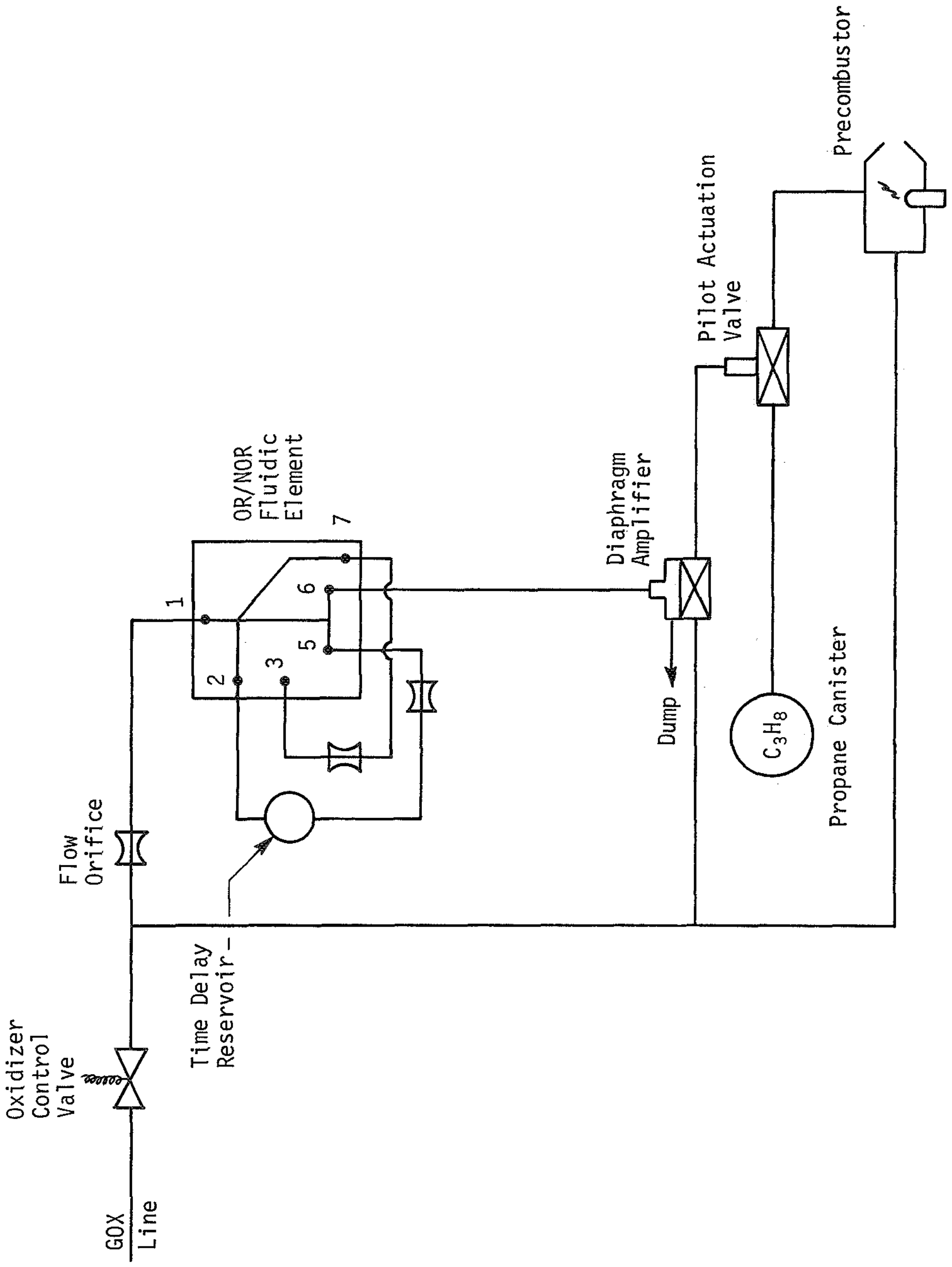


Fig. VI-4 Fluidic Sparked-Propane Ignition System

Opening the oxidizer control valve allows GOX to flow both into the precombustor and through an orifice to the supply port on an OR/NOR fluidic module. This generates a signal at outlet ports 5 and 6. The low-pressure signal at port 6 opens a diaphragm amplifier. This allows the higher pressure GOX to open a single 2-way (NC) pilot actuation valve and allows propane to flow into the precombustor, where the propane/GOX mixture is ignited with a spark. The signal at port 5 passes through a second control orifice and into a reservoir that acts as a time delay. As soon as this reservoir has become sufficiently pressurized, a signal is generated at inlet port 2. This signal switches the flow to outlet port 7, where it passes through a flow-limiting orifice and is dumped after passing through port 3. The oxidizer bleed required to energize the fluidic logic represents about 0.1% of the main oxidizer flow. When the fluidic output shifts to port 7, the diaphragm amplifier closes. This closes the pilot actuation valve and shuts off the propane.

The propane spark-initiated ignition system has been used successfully for years on a number of small hybrid motors. Typically, these ignition systems operate at a mixture ratio of about four. Propane pulses of 0.050 to 0.100 sec can be used with a properly timed spark. Therefore, a 222-kg $\left(50\text{-lb}_f\right)$ motor with a GOX flowrate of about 0.045 kg/sec $\left(0.10\ \text{lb}_m/\text{sec}\right)$ would require 0.0006 to 0.0012 kg $\left(0.0013 \text{ to } 0.0026\ \text{lb}_m\right)$ of propane per start. One hundred restarts would require about 0.09 kg $\left(0.2\ \text{lb}_m\right)$ of propane, corresponding to a volume of about 0.00009 m^3 (9.5 in.^{3}).

C. ATTITUDE CONTROL MOTOR DESIGN

1. Design Objective

Although the ACS motors supply less than 20% of the total impulse for the APS, they were the prime focus of the present study. These 16 motors must safely and reliably meet all ACS requirements for the 10-year life of the Space Station and still have minimum maintenance, repair, and resupply requirements. The long mission time and high utilization rate of the ACS motors required innovative approaches to motor design and to maintenance, repair, and resupply procedures in order to produce minimum impact on the operation of the Space Station. Although these requirements were also very important for the spin/despin motors, they were less critical due to the relatively short required life (18 months) and relatively few number of firings required for the spin/despin system.

2. Attitude Control Motor Description

The ACS motors meet all ACS performance and maintainability requirements while maximizing safety and reliability. They deliver an average thrust of 225 N $\left(50.5\ \mathrm{lb}_f\right)$ at an average specific impulse of 323 sec for a duration of 386 sec before fuel replenishment is required. Their total impulse is 86,630 N-sec $\left(19{,}480\ \mathrm{lb}_f\text{-sec}\right)$. The ACS motor propellants -- GOX and a rubber-based fuel grain composed of 20% PMM and 80% PBD -- were selected because of their complete safety and high performance. Similarly, the low average chamber pressure of 558 $\mathrm{kN/m^2}$ (81 psia) promotes safe operation.

The attitude control motor TCA (Fig. VI-5 and Table VI-3) was designed for safety, minimum maintenance, and simplified repair and resupply procedures. The TCA can be conveniently handled by one man in either a weightless or 0.7-g condition. It has an overall length of 939.8 mm (37.0 in.) and a motor case O.D. of 164.64 mm (6.50 in.). The TCA has a loaded mass of 20.6 kg $\left(45.3\ \mathrm{lb}_m\right)$ and an empty mass of 10.1 kg $\left(22.2\ \mathrm{lb}_m\right)$. The single-piece case and nozzle assembly is constructed of molybdenum disilicide-coated molybdenum and is designed to operate without replacement for the 10-yr life of the Space Station. The PMM/PBD fuel grain is cast into a tripwire-lined phenolic cartridge. The trip wires provide a fail-safe indication of fuel depletion and initiate motor shutdown after the fuel has been consumed.

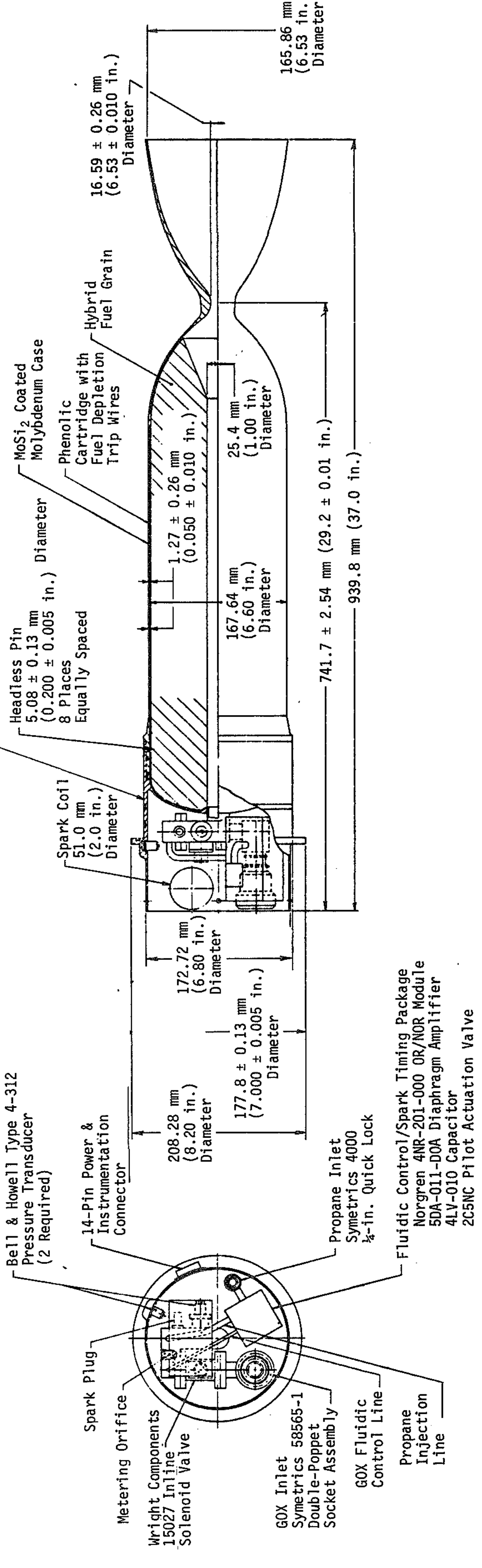


Fig. VI-5 ACS Thrust Chamber Assembly

Table VI-3 Conceptual Attitude Control Motor TCA

PERFORMANCE SUMMARY	
Propellants	GOX/(20% PMM/80% PBD)
Average O/F Ratio	1.815
Average Chamber Pressure, kN/m^2 (psia)	558 (81)
Nozzle Expansion Ratio	100
Average Specific Impulse (sec)	323
Average Thrust, N $\left(lb_f\right)$	225 (50.5)
Total Impulse, N-sec $\left(lb_f\text{-sec}\right)$	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 to the Motor Case with Eight Shear Pins
Motor Case & 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
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)
Motor Refurbishment	Movable Tube Approach

The motor case attaches to the forward closure assembly at a shear pin flange that is located outside the Space Station when the motor is in the operating position. This unique design approach eliminates the only possible hot gas path from the motor into the Space Station: if the motor case seal fails during a motor firing, the chamber gases will vent to space. Another design feature is that the 304 stainless steel forward closure assembly serves as the housing for the Space Station's redundant O-ring pressure seal, protects the oxidizer control system, and also provides the structural attach points for all motor refurbishment operations.

As shown in Fig. VI-6, the oxidizer control system regulates the flow of GOX and controls the ignition sequence. The GOX line attaches to the TCA via a double-poppet screw disconnect. An inline solenoid valve downstream of the disconnect controls the flow of GOX to the motor. Gaseous propane is mixed with GOX in a precombustor and sparked during the ignition sequence. The propane line attaches to the TCA via a quick disconnect. The flow of propane is controlled by a fluidic circuit that injects a measured amount of propane into the precombustor whenever the oxidizer control valve is opened. A simple solid-state circuit sparks the GOX/propane mixture 0.075 sec after the oxidizer control valve is commanded open. The hot GOX/propane combustion products enter the combustion chamber through a low-velocity injector and initiate the hybrid combustion process.

3. ACS Motor Component Description

All ACS motor component designs are based on demonstrated technology and can satisfy the 1975 technology requirement. Wherever possible, qualified off-the-shelf components have been selected to reduce the complexity and expense of a hybrid ACS development program. All components were selected on the basis of absolute safety, high reliability, and minimum maintenance.

a. Motor Case and Nozzle Assembly - The single-piece, radiation-cooled motor case and nozzle assembly is constructed of molybdenum and coated with molybdenum disilicide to resist oxidation at high temperature. The contour of the aft closure, the fuel grain, and the operating conditions for the motor have been selected to hold the steady-state throat temperature below 1922°K (3000°F) by providing a cool, fuel-rich boundary layer and by maximizing the amount of heat radiated to space from the nozzle and aft closure. The nozzle is purposely thick in the throat region to conduct heat away from the throat into the expansion cone, thereby increasing radiation. Tests have shown that a

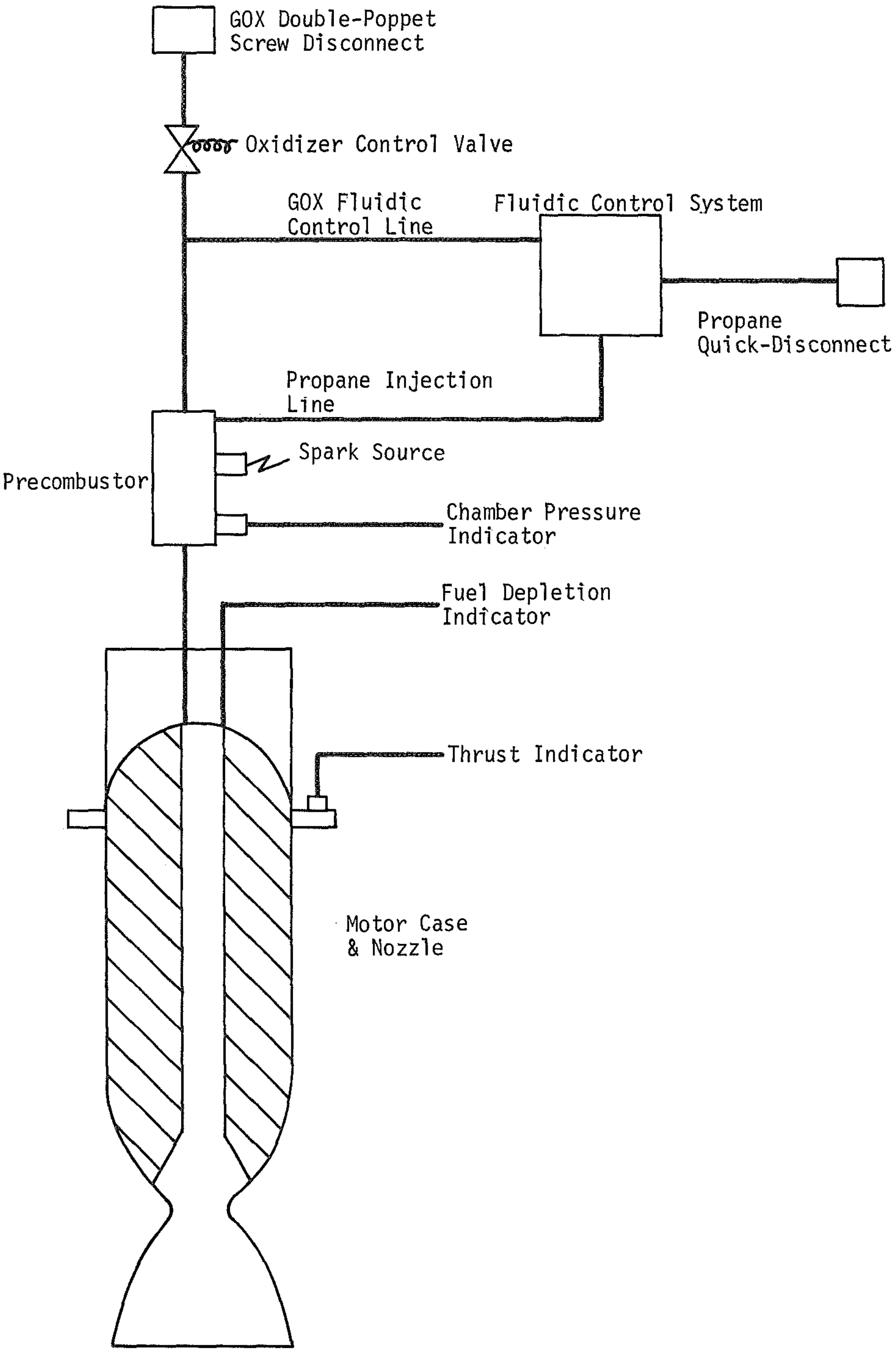


Fig. VI-6 ACS Motor Schematic

$MoSi_2$-protected molybdenum throat can operate almost indefinitely without damage to the coating as long as the surface temperature is held below 1922°K (3000°F). Furthermore, the heat capacity of the nozzle holds the maximum throat temperature during a nominal 10-sec firing to under 1478°K (2200°F); for shorter firings, the maximum temperature is much lower.

The nozzle and aft closure are contoured to achieve desired motor performance and ballistic characteristics. The nozzle has a throat diameter of 16.6 mm (0.653 in.) to obtain the desired average chamber pressure of 558 kN/m^2 (81 psia). Because of the low minimum regression rate of PMM/PBD, the nozzle expansion ratio can exceed 100 before the exit diameter exceeds the maximum motor diameter and presents handling problems. However, a maximum expansion ratio of 100 was selected in view of the small performance gains for larger expansion ratios. A bell-contoured nozzle was selected to reduce nozzle length, nozzle weight, and nozzle heat transfer. The extended aft closure contour was chosen to satisfy the desired motor ballistic characteristics and maximize radiation. At low values of oxidizer flux $\left(G_o\right)$, the slope of the fuel regression rate decreases, causing the motor to operate fuel-rich. The contoured aft closure reduces the effective grain length and helps maintain the proper O/F ratio.

b. Fuel Grain Assembly - The fuel grain is designed for relatively long burntimes to minimize required maintenance. The PMM/PBD fuel system selected for the ACS motors has a very low critical regression rate. Therefore, a relatively large fuel grain diameter can be used. This results in a small $G_o \left(\max\Big/\frac{\pi}{4} D^2_{port}\right)$ at burnout without charring or melting the fuel. Naturally, increasing the allowable fuel grain diameter increases the fuel web, which increases the motor burntime and reduces the fuel grain replacement rate. The single-port fuel grain provides the longest motor burntime for a given thrust, while maintaining a grain length consistent with good handling characteristics.

The longest motor burntime does not necessarily provide the lowest maintenance, repair, and resupply requirements. For a short burntime, motor refurbishment will be required to replenish the fuel long before other components need inspection or replacement. Conversely, exceptionally long burntimes will increase unscheduled maintenance to replace components that fail before fuel depletion occurs. Furthermore, exceptionally high total-impulse ACS fuel grains would increase system weight and increase resupply requirements. The selected grain design delivers 86,630 N-sec $\left(19{,}480\ \text{lb}_f\text{-sec}\right)$ of total impulse. Based on the current 10-yr ACS total impulse requirements (not including spin/despin) of 7,110,500 N-sec $\left(1{,}598{,}890\ \text{lb}_f\text{-sec}\right)$, the 16 ACS motors will need fuel replenishment every 2.16 yr, assuming a 50% fuel reserve at the end of 10 yr. This refurbishment interval provides high reliability along with minimum overall maintenance (scheduled and unscheduled), repair, and resupply.

The ACS motor fuel grains have been designed to provide film cooling for the nozzle while achieving high delivered performance. The ACS motors use film cooling and a low chamber pressure to reduce the convective heat flux to the radiatively cooled motor case and nozzle assembly. Hybrid combustion is primarily a turbulent-boundary-layer, convective heat transfer phenomenon. In a hybrid motor, at the aft end of the fuel grain there is a thick, fuel-rich boundary layer. The gradual diffuser section at the aft end of the ACS fuel grain allows the boundary layer to attach to the aft closure without breaking up. This relatively cool boundary layer significantly reduces the convective heat transfer to the nozzle while imposing only a 2 to 4% performance penalty.

The contour of the fuel grain at the aft closure allows the grain length to decrease during motor operation to maintain the desired O/F ratio. The regression rate of PMM/PBD tends to flatten out at low values of oxidizer mass flux. Therefore, for a constant grain length, fuel flow would increase as the motor burns, causing the motor to operate excessively fuel-rich and degrading performance. By contouring the aft end of the fuel grain, the grain length can decrease with web burnback to maintain the desired motor O/F ratio. An O/F ratio of 2.0, which is slightly fuel-rich, was selected for the ACS motor to improve nozzle cooling characteristics. As the grain length decreases during firing, the distance from the end of the fuel grain to the nozzle throat increases. To ensure adequate film cooling for the throat, the fuel grain design allows the motor O/F ratio to decrease to about 1.7 at web burnout. This reduces the average specific impulse by about 7 sec, to 323 sec.

The fuel grain is cast in a trip wire-lined phenolic cartridge. The phenolic cartridge supports the fuel grain (especially near web burnout), protects the grain from damage during storage, and facilitates the removal of depleted fuel grains. The phenolic cartridge is lined with helically wound trip wires before the fuel is cast. These trip wires provide a fail-safe indication of fuel depletion via a continuity check and also signal motor shutdown. Fuel depletion will occur over a period of several seconds, due to small nonuniformities in the regression rate. Although rapid shutdown is not essential to protect the motor, continued operation with a depleted fuel grain dramatically reduces performance and could lead to overheating of the throat. Since hybrid fuel regression requires convective heat transfer, fuel forward of the injector normally does not burn. However, to ensure absolute safety, the lined phenolic cartridge covers the entire forward closure.

c. Forward Closure Assembly - The single-piece forward closure assembly is constructed of 304 stainless steel to simplify fabrication and reduce weight, and is designed for maximum safety and hih reliability. The forward closure assembly is attached to the motor case by eight equally spaced shear pins. These shear pins provide a nearly failure-free attachment design that has proven its reliability in UTC's 120-in. motor program. A metal strap holds the pins in place. The only hot gas seal is in a motor case flange that is outside the Space Station when the motor is in the operating position. Therefore, failure of this seal will vent combustion gas to space, not into the Space Station. The forward closure has redundant seals to prevent cabin air from leaking to space. The face seal on the forward closure flange is a thin-walled rubber tube, filled with a hydraulic fluid and connected to a Bell and Howell Type 4-312 pressure transducer. A normal cabin pressure of 101.3 kN/m^2 (14.7 psia) produces a load of 2380 N $\left(534\ lb_f\right)$ on the motor; during operation, motor thrust reduces this load to 2165 N $\left(483\ lb_f\right)$. The type 4-312 pressure transducer can be calibrated to measure thrust within ±4%. This is accurate enough for the malfunction detection system. The forward closure skirt protects the oxidizer control system and provides the structural attach points for motor refurbishment. The motor refurbishment container attach flange is connected to the forward closure skirt by four shear pins that are identical to the eight pins used for the motor case/forward closure attachment. The oxidizer control assembly is mounted on the oxidizer injector, which is brazed to the forward closure.

d. Oxidizer Control Assembly - The oxidizer control assembly (Fig. VI-7) is designed for minimum maintenance and maximum reliability. Gaseous oxygen is supplied to the ACS thrust chamber assembly at 1033.5 kN/m^2 (150 psia) via a braided Teflon flexline. The flexline is connected to the motor with a Symetrics 58565-1 double-poppet screw disconnect for maximum safety. During refurbishment, the screw disconnect allows the operator to detect

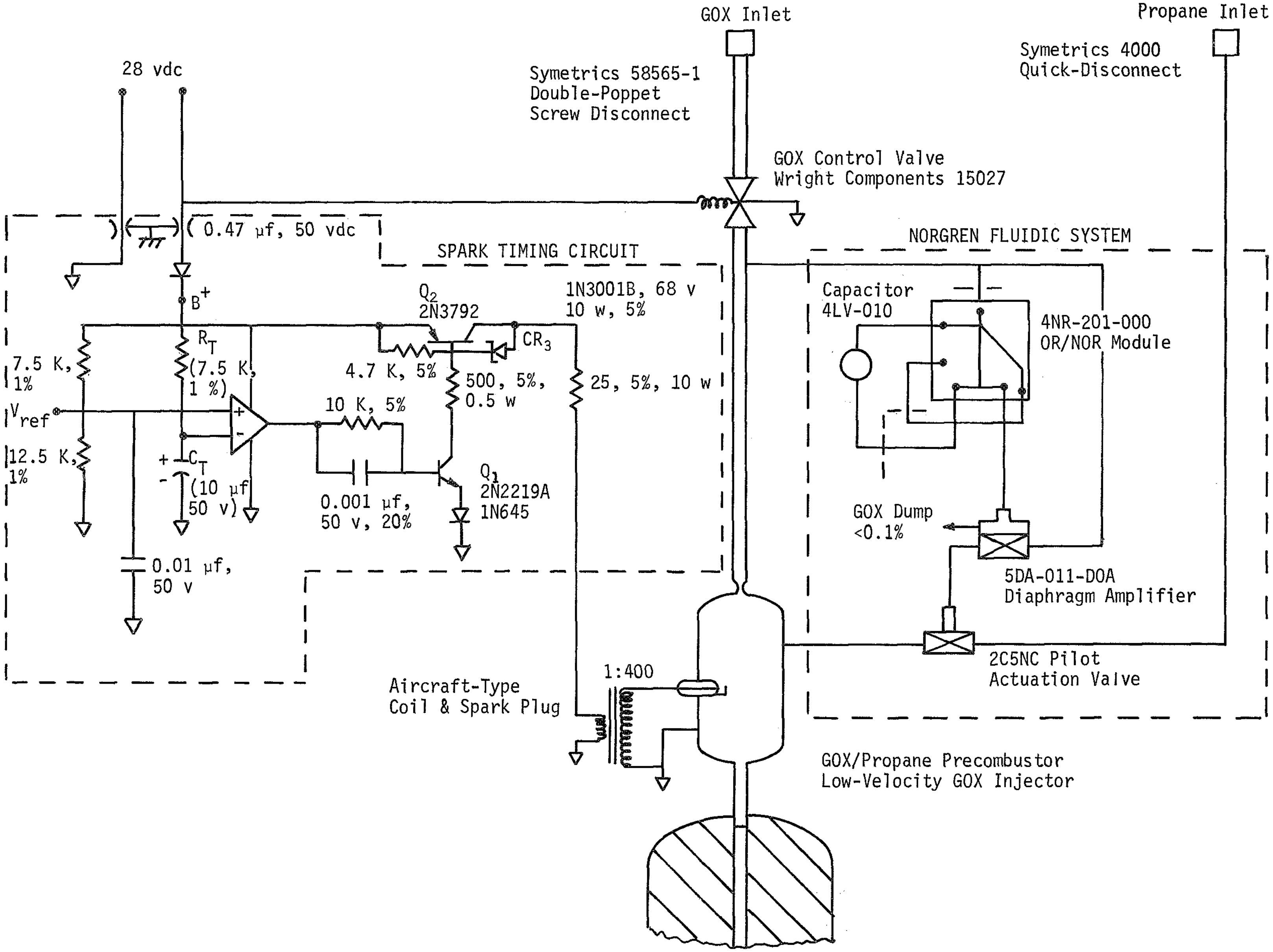


Fig. VI-7 Oxidizer Control System Schematic an upstream poppet failure before he disengages the last few threads [a simple quick-disconnect would be difficult to reconnect with a jammed upstream poppet, and would allow GOX at 1034 kN/m^2 (150 psia) to vent into the Space Station]. The oxidizer control valve (Wright Components 15027) is immediately downstream of the screw disconnect. This inline solenoid valve was selected for its fast response, high reliability, and near-zero leakage. The 28-vdc signal that commands the oxidizer control valve open also activates the fluidic propane injection system and the spark ignition system. All the components selected were successfully demonstrated on UTC's hybrid cutting torch.

After the oxidizer control valve opens, GOX flows through a metering orifice and then through a Norgren 4NR-201-000 OR/NOR fluidic module. The relatively low-pressure signal from the OR/NOR module opens a 5DA-011-DOA diaphragm amplifier that allows high-pressure GOX to flow to a 2C5NC pilot actuation valve. Gaseous propane entering the oxidizer control assembly via a Symetric 4000 quick-disconnect flows through the pilot actuation valve and into the precombustor. A fluidic propane injection system was selected for its simplicity and inherent high reliability. GOX from the control valve passes through a metering orifice and enters the precombustor, where the propane and GOX are mixed to create a combustible mixture.

The same 28-vdc signal that opens the oxidizer control valve also energizes the spark ignition circuit. The start command is received by the spark generator via two feedthrough capacitors and a diode (CR_1). The capacitors minimize the influence of externally generated electromagnetic interference (EMI) on the operation of the spark generator; the diode provides reverse voltage polarity protection for the timing circuit and powers all the remaining circuit elements.

The ignition spark is generated by the inductive kick of a high-turn-ratio, high-voltage transformer similar to an automobile ignition coil. After receiving the start command, a current of about 1 amp is allowed to flow through the low-impedance primary of the transformer for a nominal period of 75 msec. At this time the current is switched off, causing the stored magnetic energy in the transformer to generate a pulse of sufficiently high voltage to arc across the spark gap in the ignition cavity and ignite the GOX/propane mixture.

The current flowing through the primary winding of the transformer is controlled by a solid-state timing circuit. On receipt of the start command, the input circuits of comparator amplifier OA_1 force the amplifier output high, which turns on Q_1. The on state of Q_1 allows base current to flow through Q_2, switching Q_2 on and allowing current to flow via a 25-ohm resistor to the primary winding of the transformer. The timing of the switch off point is established by the $R_T C_T$ product at the input of OA_1. The increasing voltage across the timing capacitor C_T is compared against V_{ref} by OA_1. When the timing capacitor voltage exceeds the reference voltage, OA_1 switches its output from high to low. This switching action, speeded up by the 0.001-μf lead capacitor, turns off Q_1 (and therefore Q_2), thereby initiating the spark transient.

While the spark timing circuit is operating, low-pressure GOX flowing through the OR/NOR fluidic module pressurizes a 4LV-010 fluid capacitor in 0.100 sec and switches the output to node 7. This cuts off the flow of propane by closing both the diaphragm amplifier and the pilot actuation valve. The burning GOX/propane mixture flows from the precombustor through a low-velocity injector into the motor, where it heats the fuel grain and initiates the hybrid combustion process. The low-velocity injector was selected primarily to ensure uniform axial regression. This type of injector is also ideally suited to a sparked-propane ignition system.

D. SPIN/DESPIN MOTOR DESIGN

The spin/despin motor has been designed to minimize the maintenance, repair and resupply requirements for the five artificial-gravity maneuvers. Several factors favored using a separate motor for spin/despin despite the decrease in system commonality. These factors were:

1) The ACS and spin/despin systems have vastly different impulse/time requirements (the spin/despin motors use nearly half the 10-yr total impulse for the entire attitude control system in 4 hr during each spinup or despin maneuver);
2) The two systems have significantly different operating lives (the spin/despin motors are only used for the first 18 months, but the ACS motors must operate reliably for 10 yr);
3) The spin/despin motors operate with single burns at predictable intervals, but the ACS motors operate for hundreds of burns at random intervals.

The maintenance analysis performed in Task 2 revealed that using the ACS motors to perform the spin/despin maneuvers or designing a compromise motor to perform both tasks would increase the maintenance requirements of the APS. On the other hand, the spin/despin motor delivers 12 times the total impulse of an ACS motor for only a 60% increase in refurbishment time (45 man-minutes to refurbish one ACS motor vs 75 man-minutes for one spin/despin motor).

Although the spin/despin motors have 12 times the total impulse of the ACS motors, the two motors have nearly identical ballistic characteristics. The spin/despin motor is an exact scale-up of the ACS motor: every dimension has been increased by a factor of 2.29. Both the chamber pressure and oxidizer mass flux vs percent web are identical for the two motors. Since both motors are in the small motor category, no scale-up problems are expected and the two motors could be qualified in one development program.

1. Design Objective

The spin/despin motors provide the Space Station with a rotational velocity of 4 rpm to produce an internal 0.7-g environment. An impulse of 3110 kN-sec $\left(698{,}050\ lb_f\text{-sec}\right)$ is needed to accomplish a spin or despin maneuver. A three-motor system will be used in which each motor provides 1039 kN-sec $\left(233{,}675\ lb_f\text{-sec}\right)$ of impulse. These three motors exceed spin/despin impulse requirements by 13.3 kN-sec $\left(2975\ lb_f\text{-sec}\right)$ to ensure successful completion of the spin/despin maneuvers.

The use of three motors provides a system whereby each motor is of sufficient size and weight to allow ease of handling during refurbishment, while providing a system requiring the least amount of storage space. Five complete spin/despin maneuvers are planned during the first 18 months of space station operation. Thus, each set of three motors will be used 10 times.

Table VI-4 summarizes the design and performance of the proposed hybrid spin/despin motor.

2. Motor Description

Each spin/despin motor (Fig. VI-8) has an overall length of 2032 mm (80 in.) and has fully loaded mass of 206 kg (454 lb), of which 117 kg (257 lb) is the useful weight of the fuel grains. Each motor contains the following subassemblies:

1) Nozzle and motor case;
2) Segmented fuel grain assembly;
3) Forward closure and skirt assembly;
4) Igniter assembly;
5) Oxidizer line and injector assembly;
6) Instrumentation.

Table VI-4 Conceptual Spin/Despin Motor

	PERFORMANCE SUMMARY
Propellants	LOX/(20% PMM-80% PBD)
Average O/F Ratio	1.850
Average Chamber Pressure, kN/m^2 (psia)	558 (81)
Nozzle Expansion Ratio	100
Average Specific Impulse (sec)	326.2
Average Thrust, N $\left(lb_f\right)$	1170 (263)
Total Impulse, N-sec $\left(lb_f\text{-sec}\right)$	1,039,180 (233,675)
Duration (sec)	888
	DESIGN SUMMARY
Motor Design	
Ignition	Pyrogen igniter using UTC Propellant UTX 9423
Oxidizer Flow Control	
Forward Closure	304 Stainless Steel Forward Closure Attached to the Motor Case with 16 Shear Pins
Motor Case & Nozzle	Radiation-Cooled, $MoSi_2$-Coated Molybdenum
Grain Design	Segmented Single-Port Fuel Grain Cast into Phenolic Cartridges. Trip Wires Imbedded in the Cartridge Signal Fuel Deplection
Grain Diameter, mm (in.)	366 (14.4)
Grain Length (7-Segments), mm (in.)	1298 (51.1)
Throat Diameter, mm (in.)	38 (1.49)
Overall Length, mm (in.)	2032 (80.0)
Motor Refurbishment	Movable Tube Approach

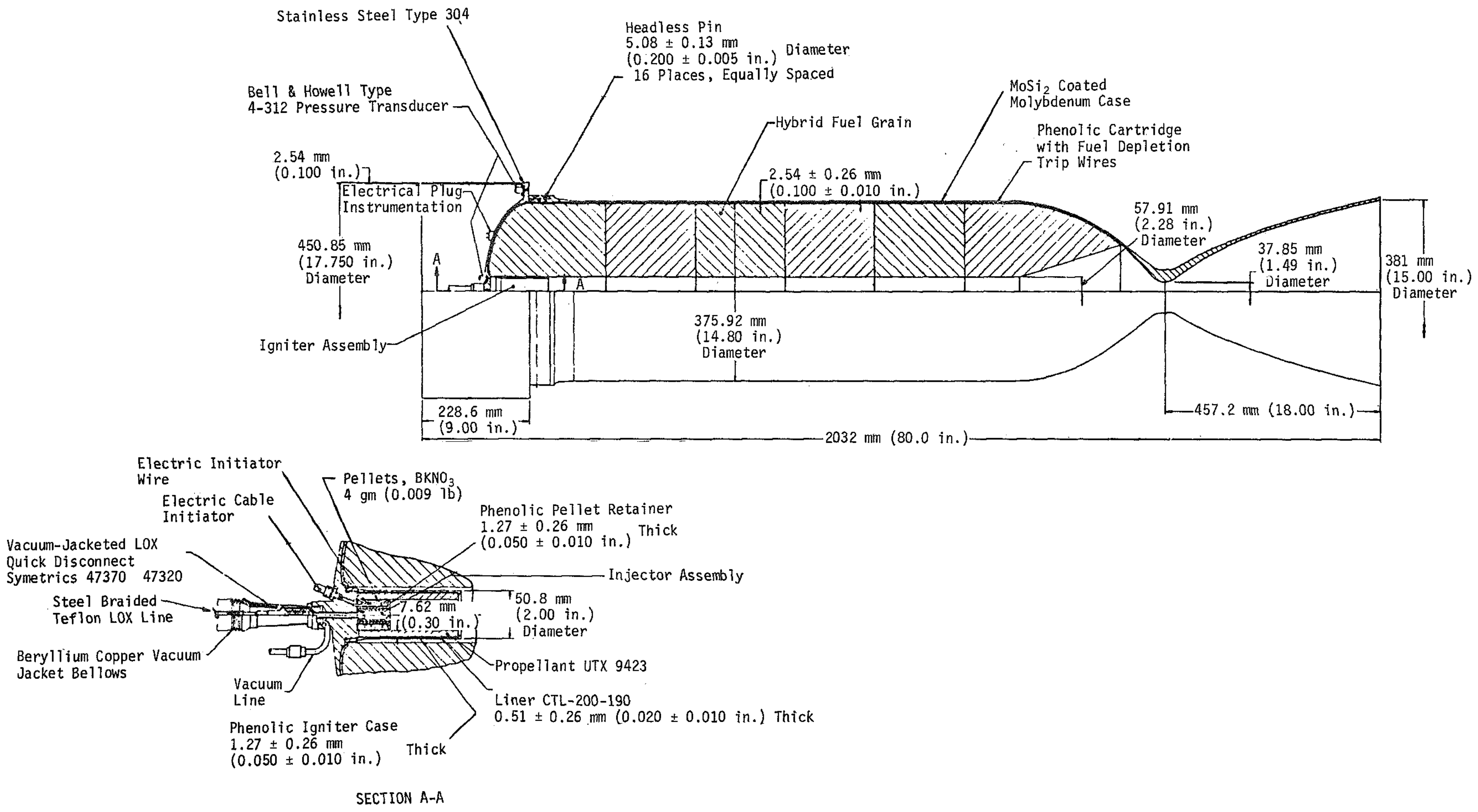


Fig. VI-8 Spin/Despin Thrust Chamber Assembly

a. Nozzle and Motor Case Assembly - A single-piece motor case and nozzle eliminates an aft closure joint. The molybdenum case is coated with $MoSi_2$ to provide a heat resistant surface and allow radiation cooling for long nozzle life. The case has an overall diameter of 376 mm (14.8 in.) and a wall thickness of 2.54 mm (0.100 in.). The case and nozzle assembly has an overall length of 1643 mm (64.7 in.) long and a mass of 54 kg (120 lb). An optimum expansion ratio of 100 is provided by the nozzle's 38-mm (1.49-in.) throat diameter and the 381-mm (15-in.) exit diameter. The exit contour is a 70% bell, which provides a savings in overall length and the same efficiency as a 15-deg half-angle conical nozzle.

b. Segmented Fuel Grain Assembly - The fuel grain is segmented into six sections to facilitate fuel grain handling during refurbishment. Each segment has a mass of not more than 22.7 kg (50 lb). The segments are as follows:

Segment	Quantity	Length	Mass*
Forward Head	1	254 mm (10 in.)	22.7 kg (50 lb)
Cylindrical	4	191 mm (7.5 in.)	20 kg (45 lb)
Aft Section	1	330 mm (13 in.)	22 kg (49 lb)

*Total mass per segment includes phenolic cartridges and residual fuel.

A total of 180 segments are required to accomplish the five complete spin/despin maneuvers during the 10-yr flight mission. These segments are listed below:

Segment	Quantity
Forward Head Segments	30
Cylindrical Segments	120
Aft Section Segments	30
Total	180

The fuel is a rubberized compound consisting of 20% PMM and 80% PBD. This nontoxic material can be stored and handled aboard the Space Station in complete safety. The fuel is cast into phenolic cartridges with a 2.54-mm (0.100-in.) wall thickness and a 366.8-mm (14.4-in.) diameter. The six cartridges used for each motor weigh a total of 5 kg (11 lb). Electrical continuity wire is cast around the 366-mm (14.4-in.) O.D. of the fuel grain to determine when the grain is depleted. At web burnout, the electrical continuity is destroyed. This condition is indicated on the motor firing control panel, and motor operation is automatically shut down. Continuity between segments is maintained through male and female jack/pin connectors (two per segment) that are connected during motor fuel grain assembly.

The fuel grain has a constant, 58-mm (2.28-in.) port diameter through five segments. In the aft segment, the port tapers open to 94 mm (3.7 in.) to facilitate boundary layer cooling behind the nozzle. The port-to-throat area ratio is 2.3. This fuel grain design provides a total impulse of 1,039,180 N-sec $\left(233{,}675\ \mathrm{lb_f\text{-}sec}\right)$. The 154-mm (6.06-in.) thick web allows 888 sec of motor operation at an average chamber pressure of 558 kN/m^2 (81 psia) and an average thrust of 1170 N $\left(263\ \mathrm{lb_f}\right)$.

c. Forward Closure - The forward closure and attachment skirt is a one-piece stainless steel assembly that provides for an igniter assembly, oxidizer injector, and flight instrumentation. The closure assembly is attached to the case by 16 shear pins and has a mass of 24 kg (53 lb). The pins are held in place during motor assembly and handling by an elastic strap (similar to a watch band) that fits around the motor and over the head of the pins. The pins are recessed so that the strap, when seated, is flush with the motor surface. The skirt portion of the closure is used to attach to the refurbishment tube assembly. Holes are provided for pinning the skirt to the retracting assembly of the refurbishment tube. During retraction and refurbishment, the motor is supported by the forward skirt. The motor case flange is located outside the Space Station when the motor is in the firing position; failure of this hot gas seal will vent the chamber gases to space, not into the Space Station.

d. Igniter Assembly - The igniter assembly consists of an electrical initiator wire, 4 gm of $BKNO_3$ pellets, a pellet retainer, a 0.14-kg (0.3-lb) solid propellant charge, and an igniter housing.

The igniter assembly is a self-contained unit that mounts inside the forward closure around the LOX injector (Fig. VI-8). This eliminates the possibility of damage to the forward closure and provides complete safety to the crew inside the Space Station in case of an igniter malfunction.

The igniter is 102 mm (4 in.) long, 51 mm (2 in.) in diameter, and has a mass of 0.3 kg (0.7 lb). The propellant charge weighs 0.14 kg (0.3 lb).

Ignition is initiated by providing an electric signal to an electric match mounted inside the igniter chamber. The electrical signal cable connects to the outside of the forward closure, and the electric match is attached to the inside of the closure. The plug connection provides for easy refurbishment. The match ignites 4 gm of $BKNO_3$ pellets that are retained in the igniter chamber by a phenolic ring. The phenolic ring also provides a chamber compartment where pressure can build up to 689 kN/m^2 (100 psia). The propellant charge extends into this compartment, where it is ignited by the $BKNO_3$ pellets. The propellant grain is designed to burn for 2 sec.

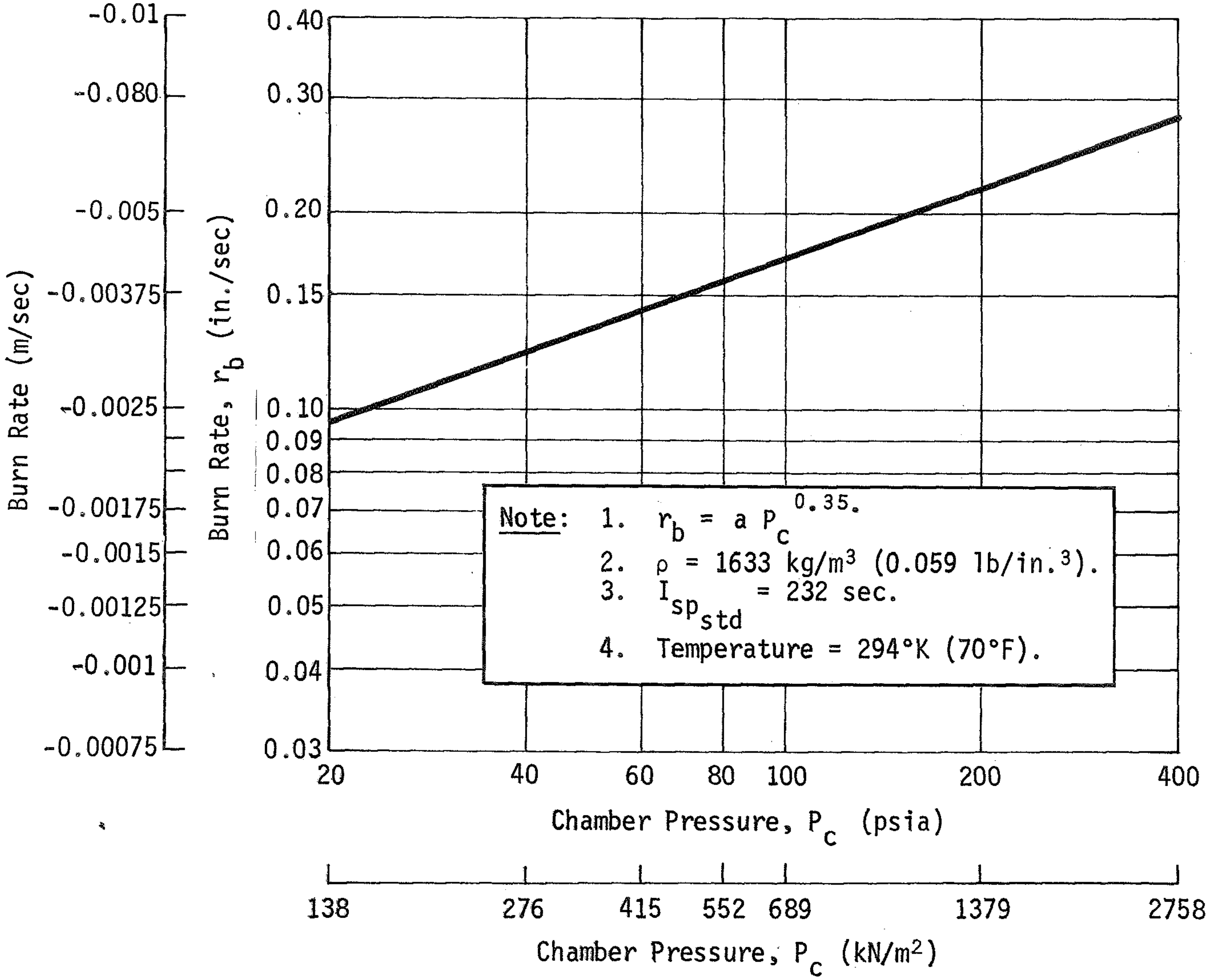
Just before the igniter is fired, the LOX is injected into the aft igniter chamber, where it burns with the igniter propellant in a liquid-augmented solid mode. The hot, oxidizer-rich gases flow from the unchoked igniter into the fuel port, where they initiate the hybrid combustion process. The phenolic igniter chamber is designed to ablate away after ignition, allowing full impingement of the LOX on the hybrid fuel grain.

The igniter design provides various safety features. Since the igniter cartridge is open at both ends, the loaded cartridge can be stored with no possibility of explosion or ignition. Once installed in the motor, the forward closure protects the Space Station from any malfunction of the igniter. Since LOX is required to ignite the main motor, a premature firing of the igniter would be a harmless malfunction requiring only an igniter refurbishment.

The solid propellant used in the igniter is a UTC CTBP type, designated UTX 9423, which is smokeless and contains no aluminum oxidizer. Figure VI-9 shows its burn rate as a function of chamber pressure.

e. Oxidizer Line and Injector Assembly - The oxidizer system consists of a LOX control valve, a LOX line quick-disconnect, a vacuum line quick-disconnect, and an injector nozzle.

During motor operation, LOX flows at a rate of 0.23 kg/sec (0.5 lb/sec), which means that 213 kg (470 lb) of LOX are required per motor firing. An electrically operated oxidizer control valve stops the oxidizer flow to terminate motor operation. A quick disconnect consisting of a mating socket assembly and a nipple assembly provides an easy, quick, and safe method of disassembling the oxidizer line.



<u>Note</u>: 1. $r_b = a\ P_c^{0.35}$.
2. ρ = 1633 kg/m^3 (0.059 lb/in.^{3}).
3. $I_{sp_{std}}$ = 232 sec.
4. Temperature = 294°K (70°F).

Fig. VI-9 Burn Rate vs Chamber Pressure for UTX 9423 Propellant

After being connected, the socket assembly opens after the nipple assembly; when disassembled, the socket assembly closes before the nipple assembly. The socket assembly will be mounted on the LOX line to ensure that there is no leakage of LOX during quick-disconnect operations. The downstream side of the control valve will be free of LOX, due to the vacuum downstream of the control valve, after the oxidizer flow is terminated. The disconnect assembly described provides an important feature to prevent ice formations due to the flow of LOX. The internal flow path of the LOX is vacuum-jacketed. A vacuum line is provided on the nipple assembly that is mounted on the motor side of the disconnect. The vacuum line has a quick disconnect of its own, providing for easy disassembly during refurbishment.

The oxidizer line is 10 mm (0.4 in.) in diameter up to the injector orifice. The injector orifice is 3.89 mm (0.153 in.) in diameter. Oxidizer injection pressure is maintained at 767 kN/m^2 (110 psia), providing a 0.23 kg/sec (0.5 lb/sec) flow during motor operation. A total of 213 kg (469 lb) of LOX is required during one motor operation.

E. OXIDIZER FEED ASSEMBLY DESIGN

1. Design Objectives

The OFA onboard the Space Station supplies oxidizer for the attitude control motors only, and provides less than 20% of the total oxidizer required over the 10-yr period during which APS impulse is required. However, this feed assembly is of major interest to the present study. It must operate safely and reliably and meet the ACS requirements during the 10-yr life of the Space Station, while minimizing repair, maintenance, and resupply requirements. The long life and high utilization rate of the OFA dictate that novel design concepts and resupply, maintenance, and repair methods be considered to reduce its impact on the operation of the Space Station.

These requirements are also important for the OFA for the spin/despin motors. However, because this latter system uses LOX instead of GOX, it requires such large quantities of oxidizer that the LOX will be supplied directly from the cargo module of the logistics vehicle. We propose that the feed assembly for the spin/despin motors be a scaled-up version of the conceptual design described below. The design of the feed system in the cargo module is beyond the scope of this study.

2. Oxidizer Feed System Description

The OFA satisfies all the ACS performance, safety, and reliability requirements and minimizes crew commitments and inflight maintenance. It also combines commonality, growth potential, and Space Station integration potential with minimum development risk.

The OFA is basically a pressurized feed system that uses a cold gas in a blowdown manner to force oxidizer contained by surface tension out of a positive expulsion tank. Gaseous oxygen was chosen as the oxidizer due to the desired start transients dictated by the hybrid TCA for the ACS. However, the oxidizer is stored in liquid form to minimize weight and volume. Helium was selected as the pressurant. The storage capability of the OFA is 293 kg $\left(645 \text{ lb}_m\right)$ of LOX and 17.1 kg $\left(37.68 \text{ lb}_m\right)$ of helium pressurant gas.

The OFA is shown in Fig. VI-10 and described in Table VI-5. Each of the two subassemblies fits in an aluminum cabinet 2032 mm (80 in.) by 1219 mm (48 in.) by 610 mm (24 in.), which requires a volume of 1.51 m^3 (53.3 ft^3). This cabinet is shown in Fig. VI-11.

The 10-yr life requirement dictates that the OFA 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 OFAs for each module are interconnected, and each system has redundant components and an assembly of "quad" check valves to eliminate single-point failures. A potential failure on one side of the quad valve is eliminated by redirecting the flow through the redundant side. This also permits replacing the "failed" side of the quad valve without hindering the operation of the propulsion system. A two-stage pressure and flow regulation assembly is used to obtain coarse regulation, followed by fine regulation. Use is also made of interconnections (crossover valves) between the two systems making up a propulsion module. These interconnections have been provided downstream of the pressurant tank, downstream of the oxidizer tank, and just upstream of the TCA units to enable interaction between the two systems of the propulsion module, if required. Each system also contains relief valves and burst discs at locations where an 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 OFA may become defective, modularization is used when possible to facilitate replacement.

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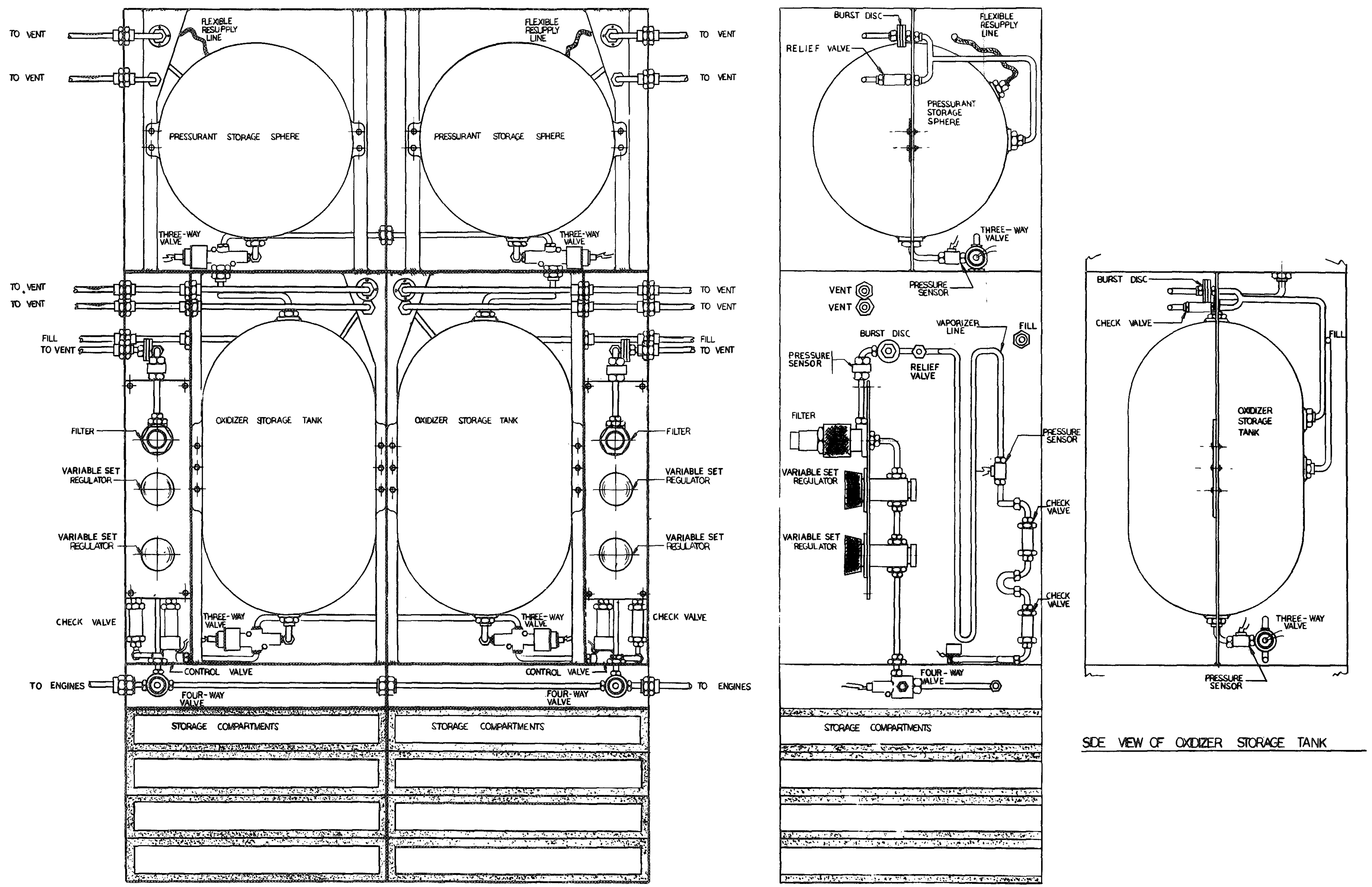

Fig. VI-10 Conceptual Oxidizer Feed Assembly

Table VI-5 Conceptual Oxidizer Feed Assembly

PROPELLANT TANKAGE ASSEMBLIES	
Minimum Total Oxidizer Capacity, kg (lb_m)	293 (645)
Total Oxidizer Volume, m^3 (ft^3)	0.27 (9.22)
Typical Size of Capillary Screen Tank Assembly, m (in.)	4.19 (16.5) diameter by 0.699 (27.50) long
Total Weight, kg (lb_m)	38.8 (85.72)
HIGH PRESSURE STORAGE ASSEMBLIES & PRESSURE CONTROL ASSEMBLY	
Pressurant	Helium at 3445 kN/m^2 (500 psia)
Total Pressurant Capacity, kg (lb_m)	7.4 (16.32)
Total Pressurant Volume, m^3 (ft^3)	0.20 (7.08)
Number of Titanium Spheres	4
Typical Size of Titanium Spheres, m (in.)	0.457 (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 System/ Manifolds/Umbilicals, kg (lb_m)	31.7 (85)

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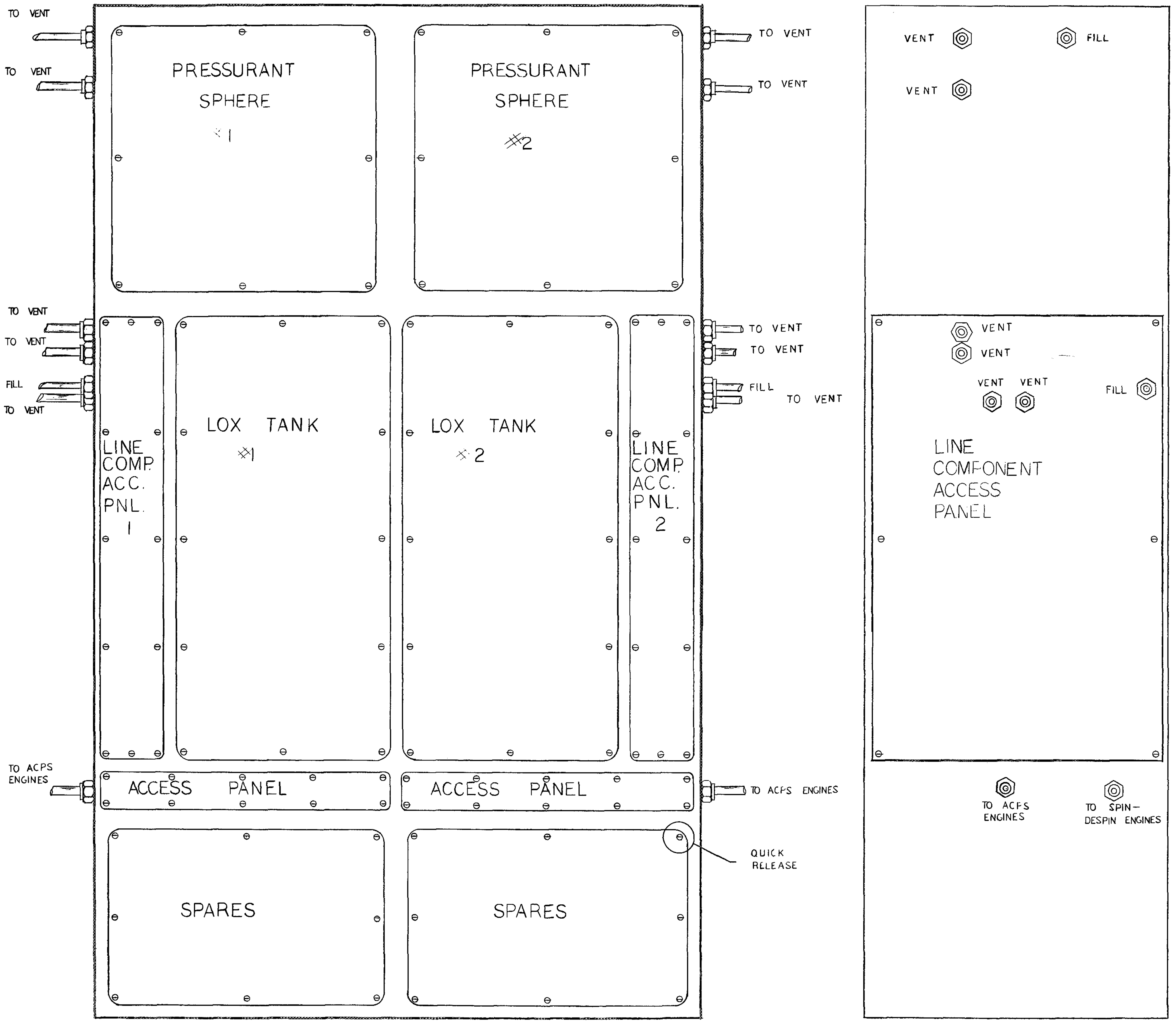

Fig. VI-11 OFA Cabinet

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

The OFA will be resupplied using a blowdown screen arrangement; a blowdown system will be used to resupply pressurant. The pressurant bottle onboard the logistics craft will be sized so that the residual pressurant resupply gas can be used as the pressurant for oxidizer resupply.

Self-sealing disconnects will be used to prevent spills. The pressurant level will be determined by pressure gages on the Space Station storage tank. The oxidizer level will be predetermined on the logistics craft, and all the fluid will be transferred.

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

The LOX lines and tanks are covered with aluminized Mylar, a super insulation, to minimize heat transfer effects.

3. Oxidizer Feed Assembly Component Description

All components of the OFA are based on demonstrated technology and can satisfy the 1975 technology requirement. Where possible, qualified off-the-shelf components have been selected to reduce the complexity and expense of the oxidizer feed development program. All components were selected on the basis of absolute safety, high reliability, and minimum maintenance.

a. Technical Status Description - An assessment of the technology of the components and subsystems that compose the OFA and resupply subsystems must begin with the question "What is the status of the technology today?" Today's state-of-the-art is defined as that technology that has been demonstrated. The technological status of the components and methods proposed for the OFA is presented below.

Capillary Screen Tank - Screen tanks have been developed and used on propulsion systems to control liquid propellant, but tanks for cryogenic storage are still under development. Capillary screen tanks are noted for their high reliability and efficiency due to their lack of moving parts.*

Pressurant Tank - Pressurant tanks are standard commercial items in any size and material. Their generic failure rate is given at 0.044 ppm/hr.†

The pressurant tanks are titanium spheres that have a diameter of 457.2 mm (18 in.) and a wall thickness of 0.7366 mm (0.029 in.). Each of the four spheres is connected to a burst disc and a relief valve. The tanks are mounted to permit easy access and replacement (Fig. VI-12).

Oxidizer Tank - Four oxidizer tanks are required. The tanks are made of titanium and are 698.50 mm (27.5 in.) long, 419.10 mm (16.50 in.) in diameter, and have a wall thickness of 0.6731 mm (0.0265 in.) (Fig. VI-13). The distance between the wall and the capillary screen liner is 6.35 mm (0.25 in.). The screen material is stainless steel dutch twill. The screen weighs 0.4536 kg $\left(1.0\ \text{lb}_m\right)$ and the tank weighs 1.3245 kg (2.92 lb/in.^{2}). The maximum tank pressure is 4135 kN/m^2 (600 psia).

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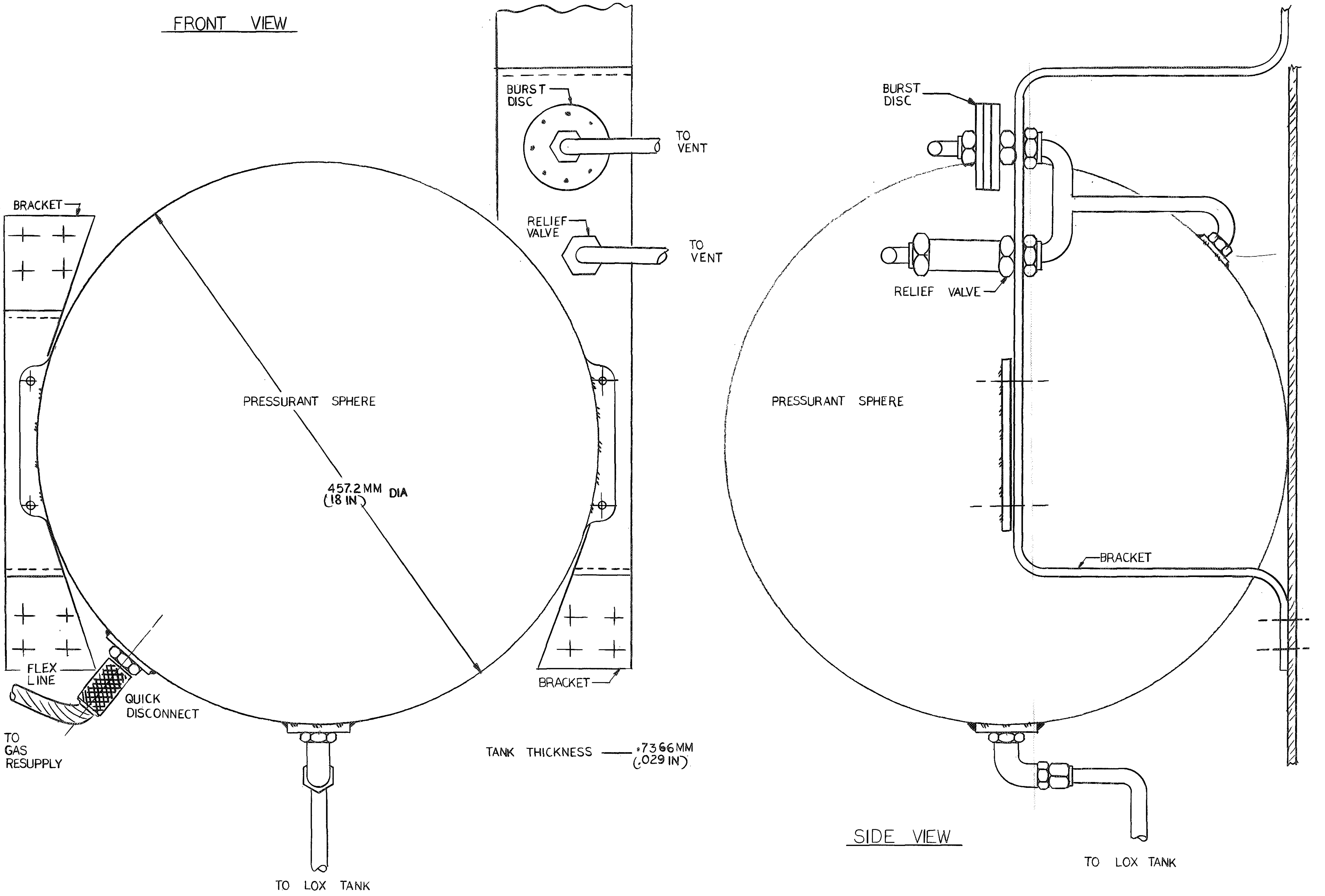
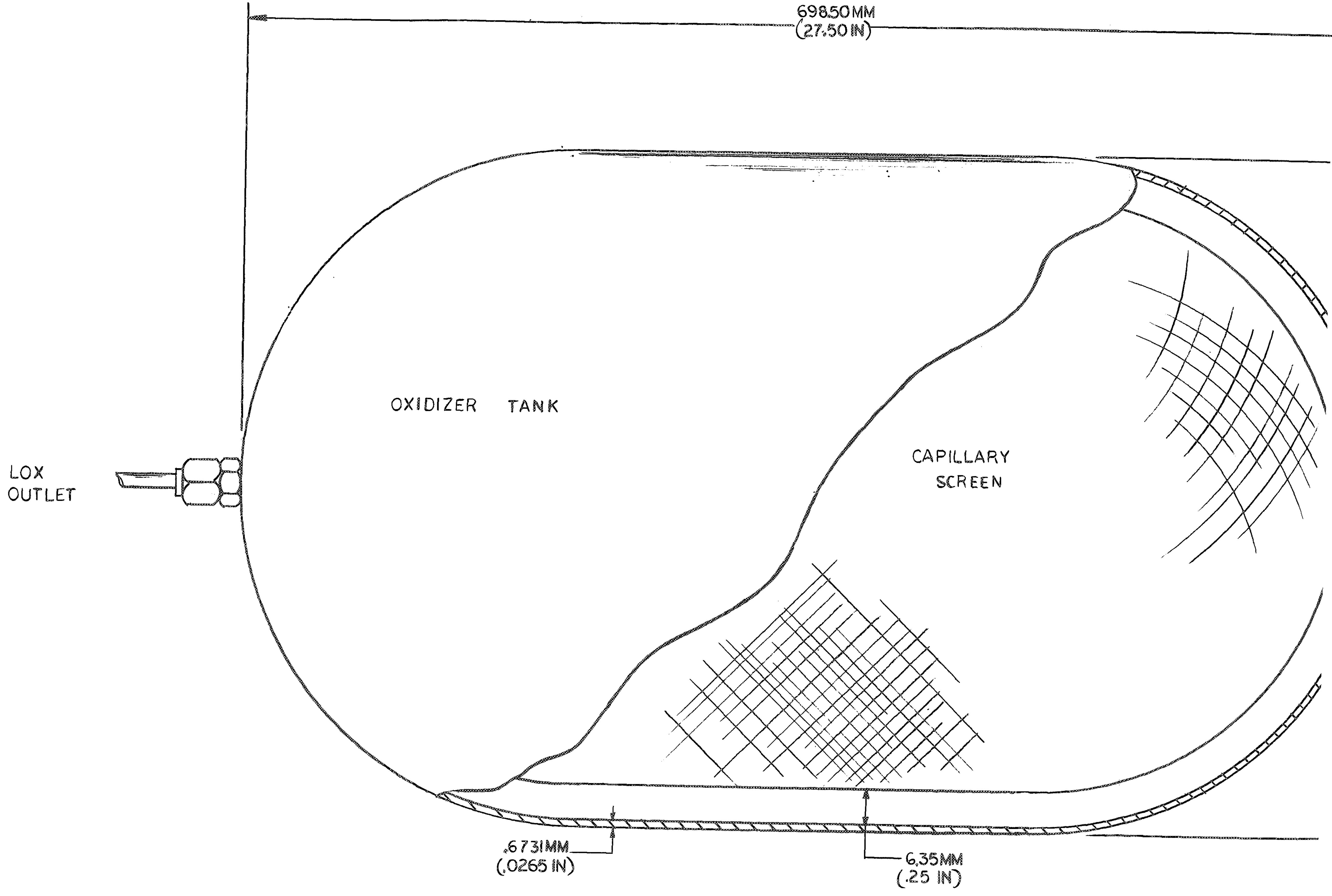
†*Handbook of Piece-Part Failure Rates.* Martin Marietta Corporation, Denver, Colorado, June 22, 1970.



FRONT VIEW

SIDE VIEW

Fig. VI-12 Pressurant Tank


698.50MM
(27.50 IN)
OXIDIZER TANK
CAPILLARY SCREEN
LOX OUTLET
.6731MM
(.0265 IN)
6.35MM
(.25 IN)

1

2

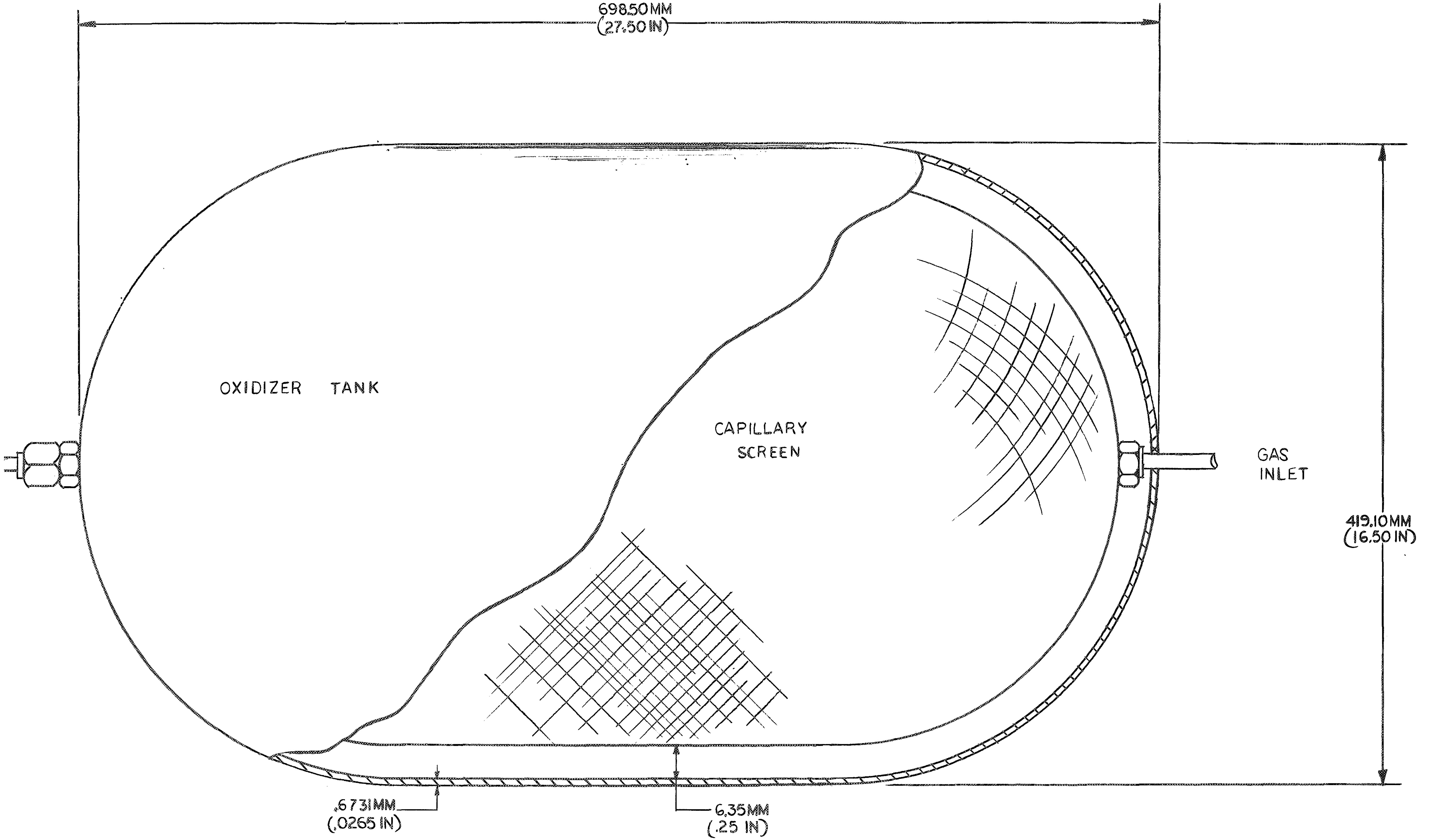


Fig. VI-13 Oxidizer Tank

2

3

Pressure Transducer - Pressure transducers are standard commercial items available from several vendors. Their generic failure rate is 23.2 ppm/hr.*

Regulator - The life of off-the-shelf regulators is in excess of 100,000 cycles; this can be extended to 250,000 cycles if required. For long missions, the compatibility of the valve material with either the fluid medium or the environment may be the life-limiting parameter, rather than the cyclic life. Internal leakage due to contamination is the major life-limiting failure mode. The generic failure rate is 1.2 ppm/hr of operation.*

The pressure regulators (Fig. VI-14) are made by Victor Controls, Model BLR 10A 1/2 1/2 1/2 TTI. They are made out of 2024-T4 aluminum and have a maximum inlet pressure of 41,800 kN/m^2 (6000 psig) and an outlet pressure range of 384 to 41,800 kN/m^2 (50 to 6000 psig). They weigh 24.4948 kg $\left(5.5\ lb_m\right)$, are rated at a maximum airflow of 42.65 m^3/minute (1500 scfm), and operate between 219°K (-65°F) and 344°K (160°F). These pressure regulators are 161.798 mm (6.37 in.) long and have a maximum diameter of 101.6 mm (4.00 in.).

Relief Valve - Relief valves are fairly reliable. Their generic failure rate is only 0.224 ppm/hr. If a failure does occur, it will probably be due to premature leakage, valve chatter, inability to cope with transient pressure surges, or poor regulation.*

Burst Disc - The response time or actual opening time is extremely fast (2.5 msec). Based on tests of the Titan II first stage engine, their reliability is 0.9997.*

Check Valve - Check valves are common standard commercial items available from several vendors. The check valve is the simplest of all valves, which accounts for their low generic failure rate of 0.16 ppm/hr.*

The check valve arrangement (Fig. VI-15) is based on 303 stainless steel valves (Model K2120T-4TT-8) by James, Pond and Clark, Inc. These valves require special assembly and LOX cleaning for cryogenic service. They weigh 0.1701 kg $\left(0.375\ lb_m\right)$ each, and operate at pressures between 0 and 6890 kN/m^2 (0 and 1000 psia) and temperatures between 78°K (-319°F) and 344°K (160°F). The valve spring is made from 17-7PH, and the seal, from Teflon. The cracking pressure is 55 kN/m^2 (8 psia).

**Handbook of Piece-Part Failure Rates*. Martin Marietta Corporation, Denver, Colorado, June 22, 1970.

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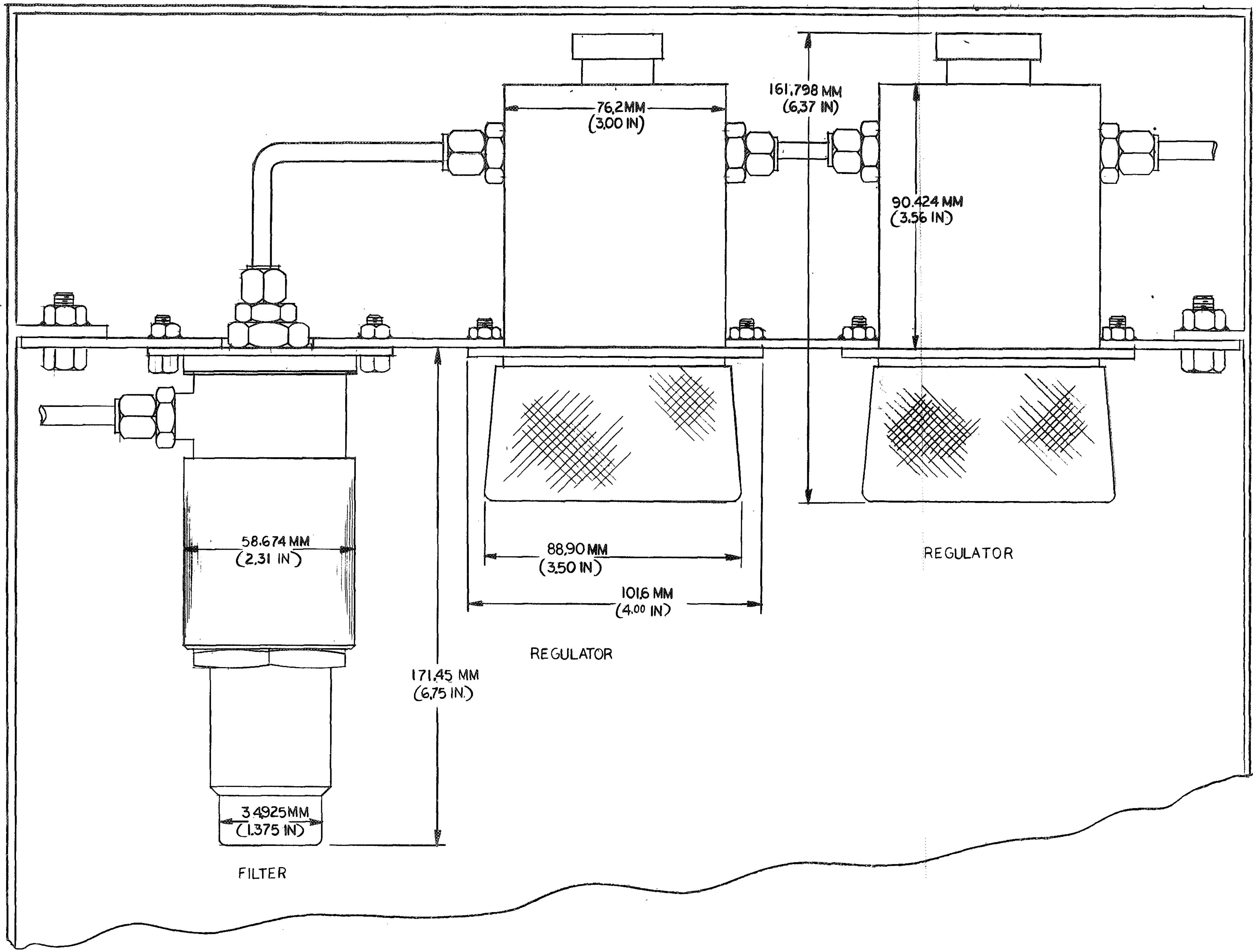

Fig. VI-14 Schematic of Pressure Regulators and Inflight Maintenance Filter

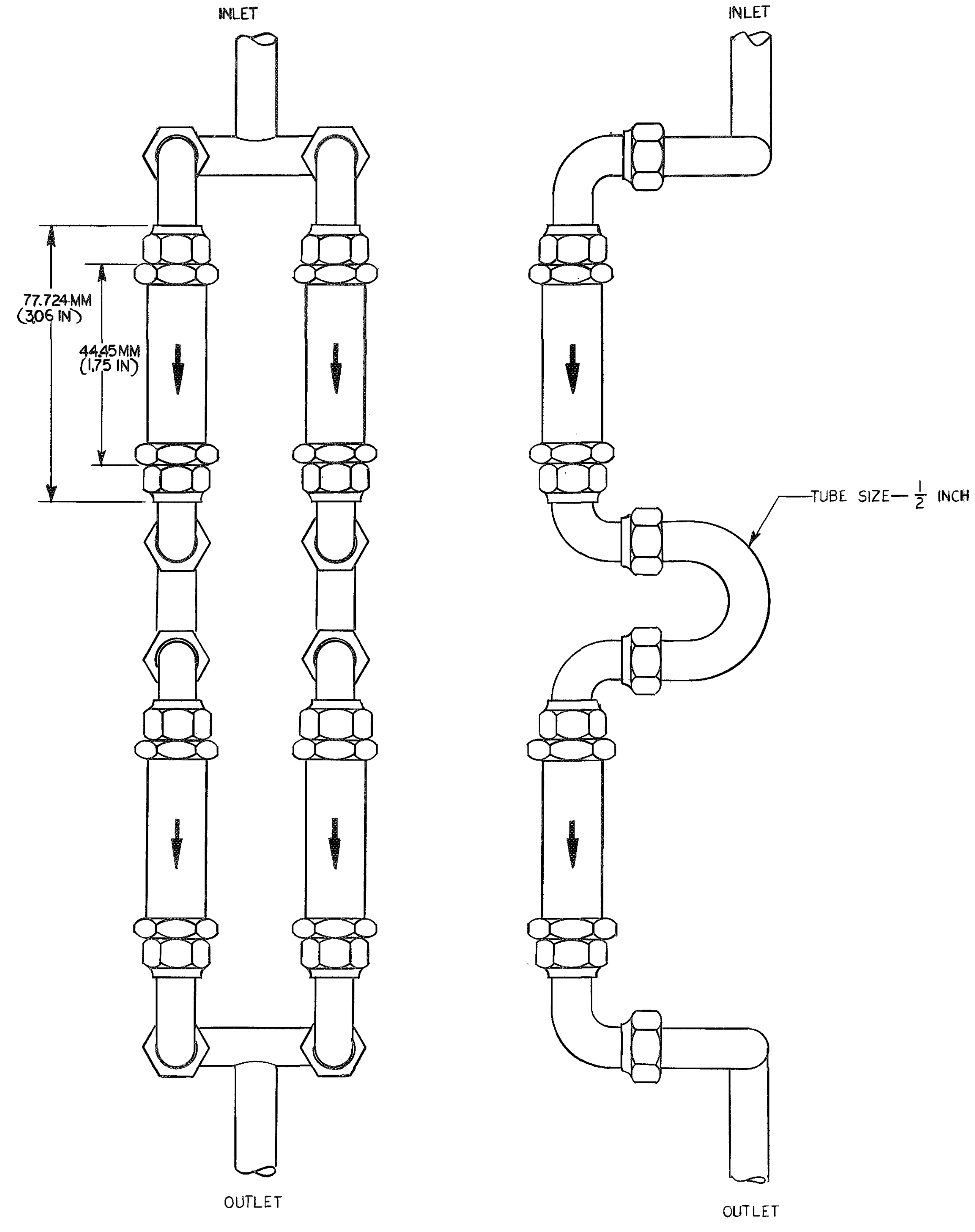

Fig. VI-15 Check Valve Arrangement

Solenoid Valves - A valve life of 100,000 cycles is possible, but may be limited by compatibility with the fluid medium and the space environment. Internal leakage caused by contamination is the major life-limiting failure mode. Such contamination may be either from the fluid medium or due to wearing out of the valve material. Solenoid valves have a generic failure rate of 0.51 ppm/hr.

The selected solenoid valve (Fig. VI-16) is manufactured by James, Pond, and Clark, Inc. (Model V4077T) and has a pressure range of from 0 to 6890 kN/m^2 (0 to 1000 psia). It is made out of 303 stainless steel and weighs 0.6804 kg $\left(1.50\ \text{lb}_m\right)$. It has a voltage of 28 vdc and a nominal power rating of 18 w. Its maximum rated leakage rate is 1 cc/hr for liquids and 5 cc/hr for air. These valves operate between 219°K (-65°F) and 344°K (160°F).

Three-Way Valves - The operational requirements for the three-way valves, as used in the OFA, are different than those for normal operation. This prevented locating suitable valves and may indicate the need to design special valves for the OFA.

The three-way valve must be capable of interconnecting any two of the three parts. Martin Marietta has a prototype three-way valve that could be modified to perform the required three-way functions.

A conceptual design of a three-way solenoid valve is shown in Fig. VI-17. These valves will be made of stainless steel and weigh 0.680 kg $\left(1.5\ \text{lb}_m\right)$. They will have an operating pressure range of 0 to 6890 kN/m^2 (0 to 1000 psia) and a temperature range of 219°K (-65°F) to 344°K (160°F). Their voltage rating will be 28 vdc, and their nominal power rating will be 20 w. They will have a leakage rate comparable to that obtained with the solenoid valve.

Filter Assembly - A maintainable filter is currently under development at Martin Marietta. A prototype model has been built and is ready for testing. Commercially available filters have a generic failure rate of 0.045 ppm/hr.*

**Handbook of Piece-Part Failure Rates*. Martin Marietta Corporation, Denver, Colorado, June 22, 1970.

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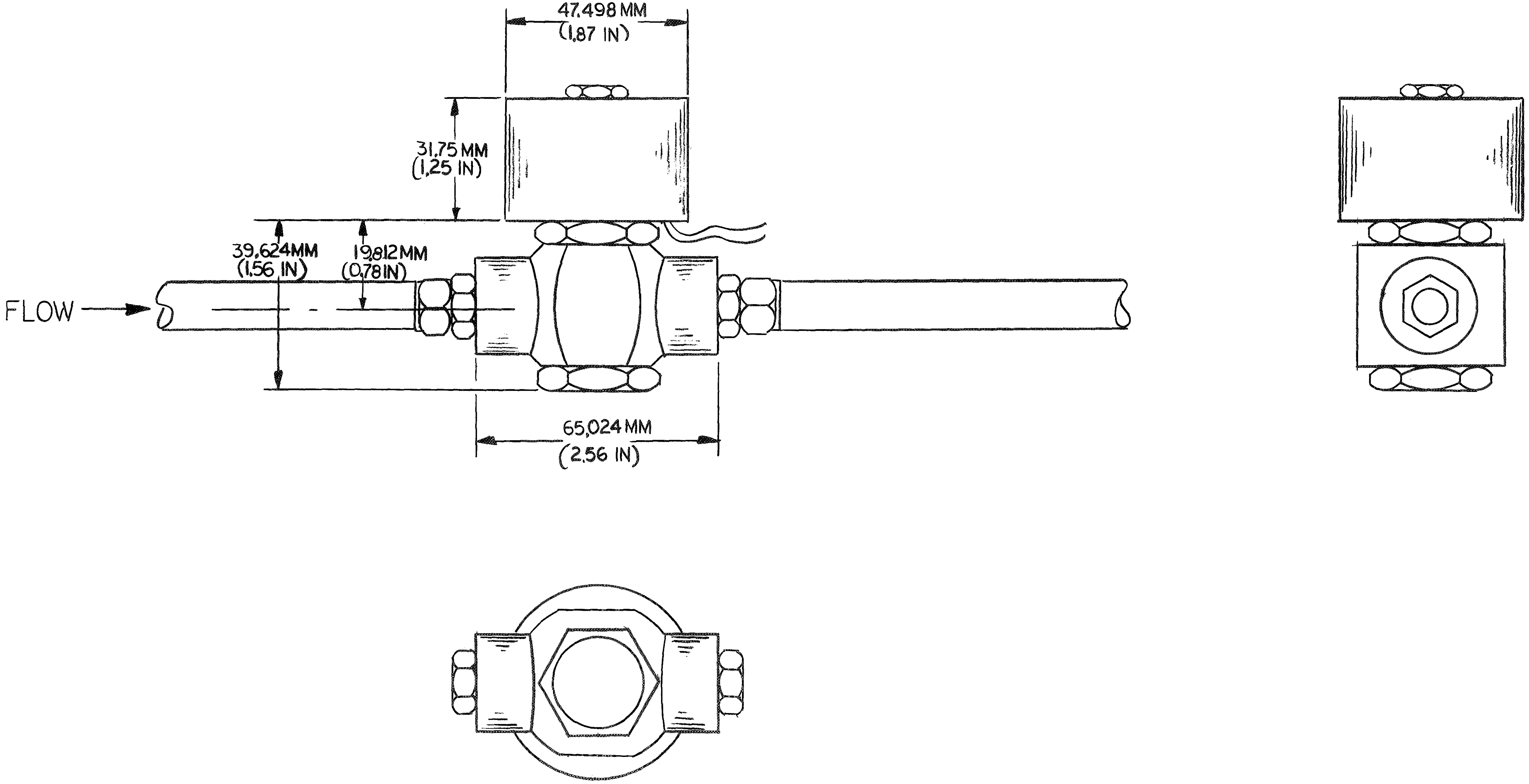

Fig. VI-16 Solenoid Shutoff Valve

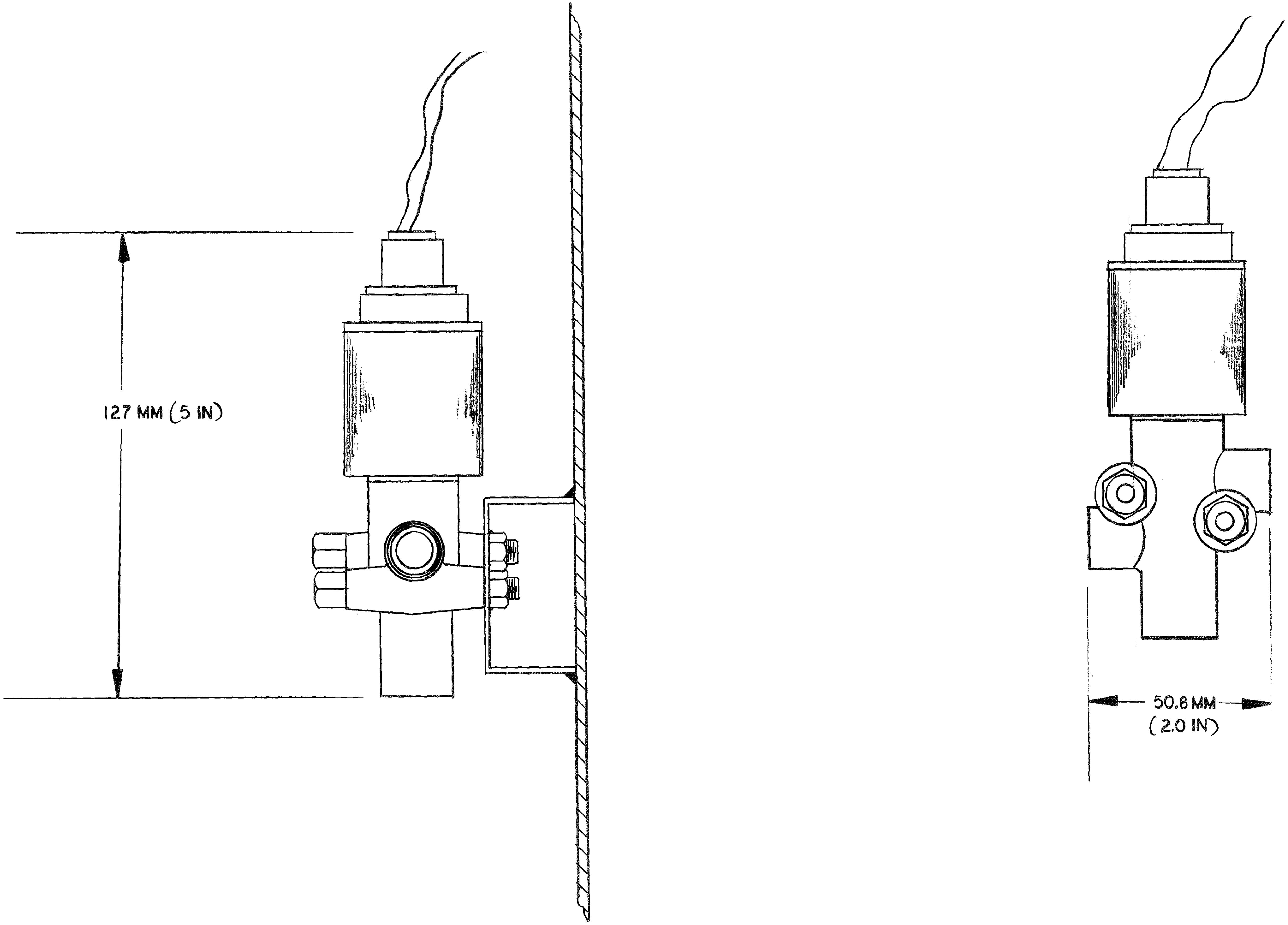

Fig. VI-17 Three-Way Solenoid Valve

The inflight maintenance filter, shown in Fig. VI-14, is designed for easy replacement. The case material is 303 CRES; the filter element is available from Aircraft Porous Media. The filter housing is made from 7075-T6 aluminum. The filter has a weight of 0.9526 kg $\left(2.1 \text{ lb}_m\right)$, a length of 171.45 mm (6.75 in.), and a diameter of 58.674 mm (2.31 in.).

Vaporizer - The vaporizer uses the 309,560 Btu/hr (90.6 kw) of heat rejected by the Space Station. This heat is more than sufficient to satisfy the required heat input, 10 kw per vaporizer or 40 kw total required for the ACS. The details of the heat rejection approach are not adequately defined. Thus, the design of this vaporizer and its interface with the Space Station is not possible at this time.

Tubing and Fittings - Stainless steel and aluminum are the most extensively used materials for tubing; 300-series stainless steels provide the best properties and are most readily drawn into tubing form.*

The tubing connection most extensively used in aerospace vehicles conform to national aerospace standards, military standards, and Air Force/Navy aeronautical standards. For long-term storage of fluids, brazed or welded joints are used to preclude leakage. The generic failure rate for tubing and fittings is 0.05 ppm/hr.†

**Handbook of Long-Life Space Vehicle Investigations.* M-68-21. Martin Marietta Corporation, Denver Colorado, December 1968.

†*Handbook of Piece-Part Failure Rates.* Martin Marietta Corporation, Denver, Colorado, June 22, 1970.

b. Resupply Methods

Gas Pressurant Blowdown with Capillary Screen Feed System - The blowdown technique has been used for some time, and the capillary screen is beginning to appear more often in propulsion systems. The combination of these two items assures a successful mission. Further development is required when LOX is used to check heat loss from adjacent hardware.*

Blowdown Pressurant-Resupply - Pressurant is resupplied by equalizing the pressure between a high-pressure storage bottle onboard the logistics craft and the expended storage tank onboard the Space Station. Although this system may be heavier, it requires a minimum of new technology and is well suited for immediate design and development.†

Oxidizer Resupply (Capillary Screen) - The same principle to be used in the feed system is applied to resupply. Further development is required to solve heat transfer problems in the transfer line and venting problems when LOX is used.§

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*J. A. Stark: *Study of Low-Gravity Propellant Transfer, First Quarterly Progress Report.* GDC 584-4-549. General Dynamics/Convair, San Diego, California, September 28, 1970.

Study of Low-Gravity Propellant Transfer. P-70-25. Martin Marietta Corporation, Denver, Colorado, March 1970.

Capillary Screen Device Technology Summary. M-70-18. Martin Marietta Corporation, Denver, Colorado, July 1970.

†V. A. DesCamp *et al.: Study of Space Station Propulsion System Resupply and Repair, Final Report.* MCR-70-150, Contract NAS8-25067. Martin Marietta Corporation, Denver, Colorado, June 1970.

§C. A. Armontrout: *Design Guide for Surface-Tension Positive Expulsion Tankage.* 8500-927018 (Rev A). Bell Aerosystems Company, Buffalo, New York, September 1970.

4. Operating Procedures

The Space Station OFA 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. The condition of the system will be indicated on the control panel (Fig. II-9). This panel will consist of a system schematic and have warning lights for all major portions or modules of the system. Three lights will be provided for each module: green for the operating path, white for standby, and red for a failed module.

If the crew wishes to perform experiments or emergency attitude corrections, they can move the toggle switch on the control panel from automatic to manual operation. Once 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 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.

F. INTEGRATED HYBRID APS FACILITIES

The integrated APS has been designed to verify that a hybrid propulsion system can meet high safety and maintainability standards while satisfying all APS performance requirements. The high level of safety achieved in the OFA and the individual ACS and spin/despin TCA motor designs has been maintained in the overall system. The system design considered all aspects of human engineering per MIL-STD-1472 to achieve high system maintainability. Auxiliary propulsion facilities and space requirements were minimized to minimize the impact of the APS on the operation of the Space Station.

The APS shown in Fig. VI-18 provides all the equipment and facilities required to satisfy performance objectives and to perform all maintenance, repair, and spares storage functions. As shown, the APS is located on the bottom deck of the proposed Space Station. The Space Station has an outer diameter of 10.1 m (33.0 ft), a central transit and utility core with an inner diameter of 3 m (5.0 ft), and a floor-to-ceiling height of 2.03 m (80.0 in). The APS motors are located on two raised thruster pads on opposite sides of the Space Station. These thruster pads are positioned inside a motor refurbishment room that has maintenance, repair, and storage facilities. The OFAs are located next to the thruster pads.

G. APS THRUSTERS

The two APS thruster pads are shown schematically in Fig. VI-19. Each pad has eight ACS motors and two spin/despin motors, as well as all their required oxidizer, instrumentation, power, ignition, and refurbishment lines. The thruster pads are in the shape of raised pillboxes 2.03 m (80.0 in) on a side, and extend 45.7 cm (18.0 in) above the surface of the Space Station. The eight ACS motors each have GOX lines, propane lines, and power/instrumentation lines. The two spin/despin motors require only LOX lines and power/instrumentation lines. The instrumentation lines from each motor are connected to the MDS/automatic monitoring and control system (AMCS). The MDS/AMCS interfaces with the manual or automatic fire control system to effect motor shutdown in the event of a serious malfunction and to alert the operator to minor malfunctions. Along with the 10 APS motors, each pad contains a three-way valve and a vacuum refurbishment line.

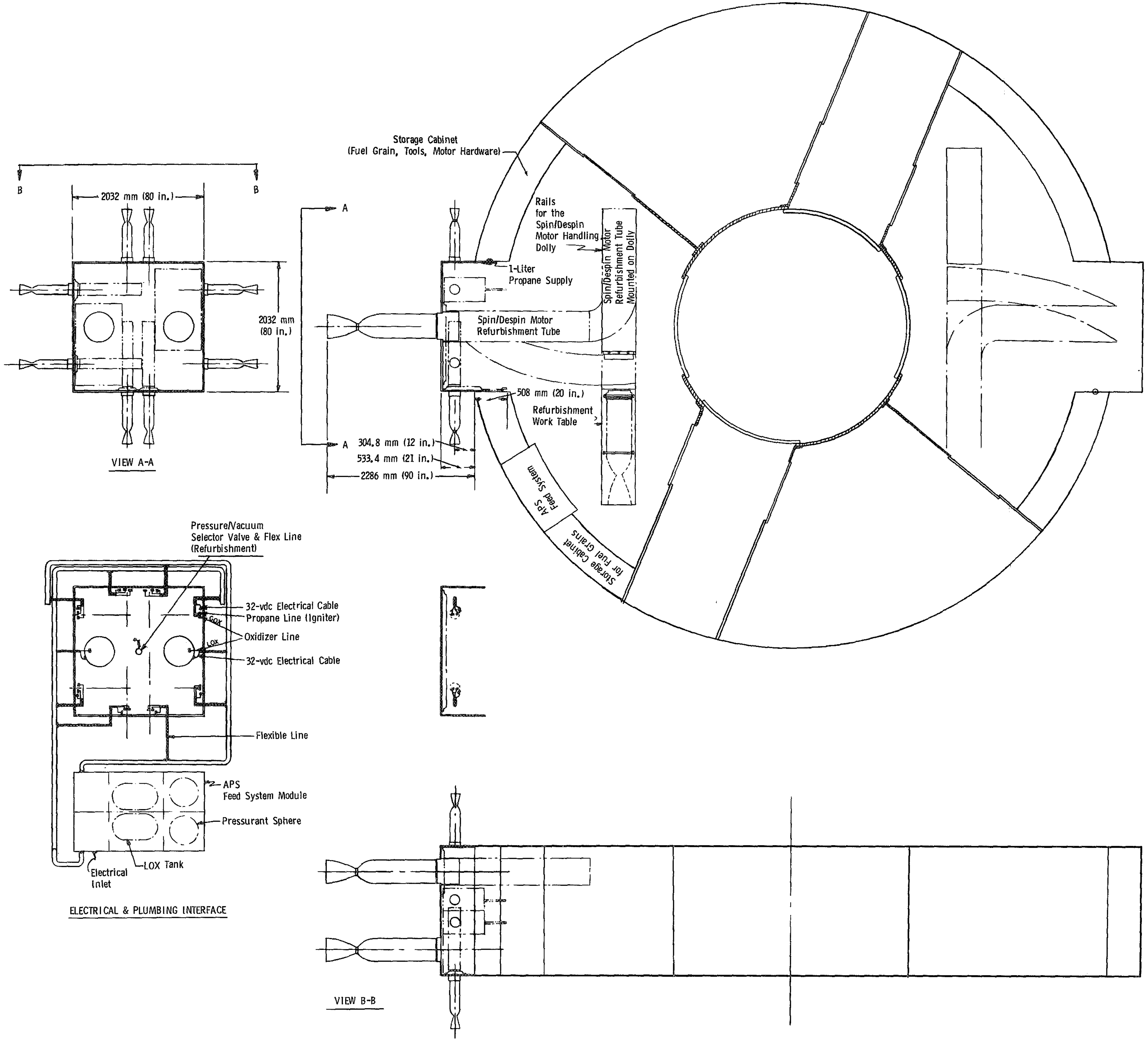

Fig. VI-18 APS Pads and Refurbishment Compartment

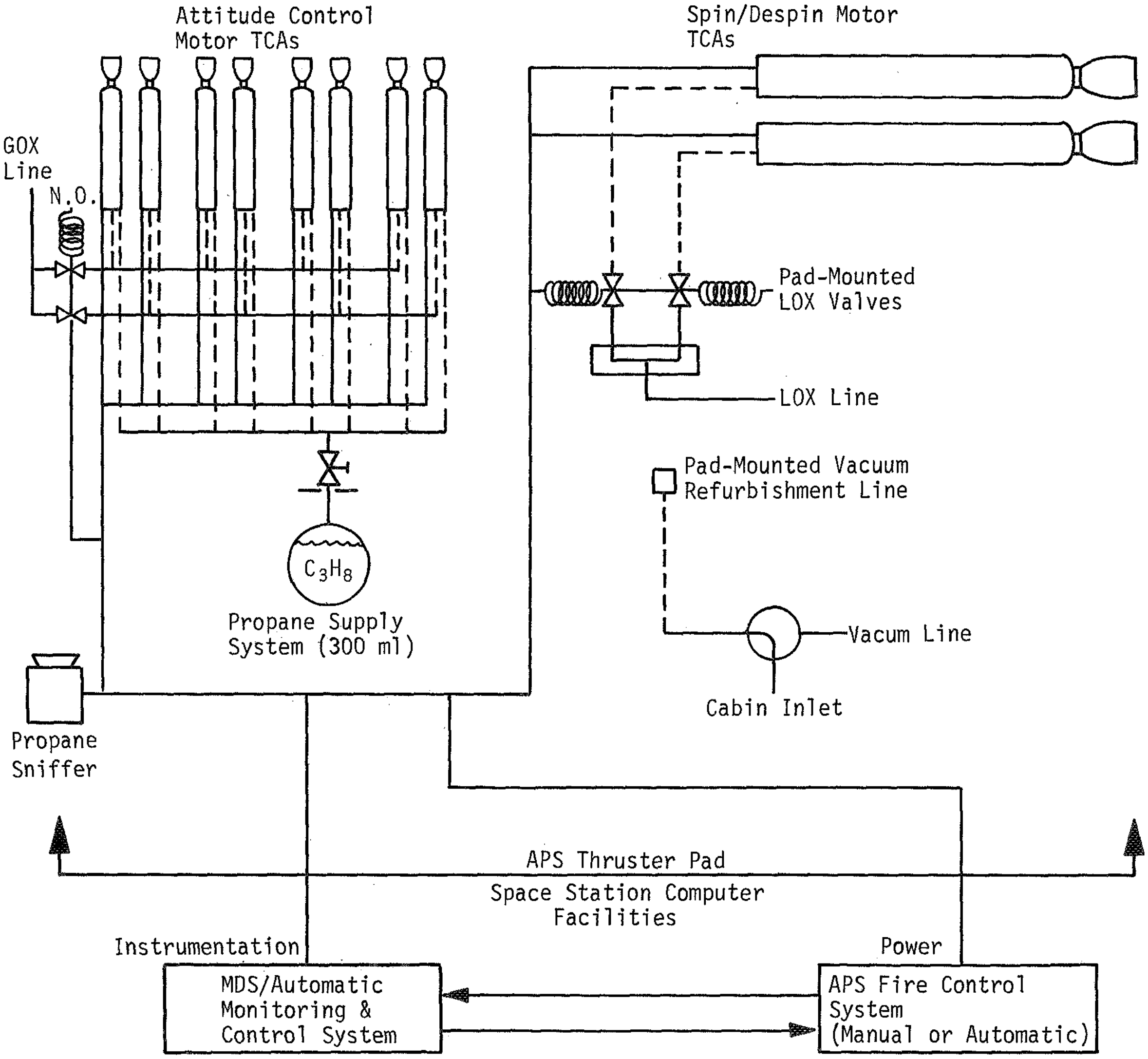

Fig. VI-19 APS Thruster Pad Schematic

A raised pad allows the eight ACS motors to be oriented in their proper directions and still be retracted axially for simplified refurbishment. During launch, all motors would be stored inside the Space Station and the thruster pad would be protected with an aerodynamic shroud. The eight ACS motors are arranged into four redundant pairs to provide a roll, pitch, and yaw capability. One pair is located on each side of the thruster pad. Redundancy improves reliability and always keeps one motor ready while its twin is being refurbished. Each ACS motor receives GOX via a braided Teflon flexline (Aeroquip 666) that is attached to a common, pad-mounted GOX hard line. The hard line is constructed of seamless aluminum tubing with a 127-mm (0.5-in.) O.D. and a 113-mm (0.444-in.) I.D. The GOX flexline attaches to the TCA with a Symetrics 58560 double-poppet screw disconnect socket assembly. A power and instrumentation cable is attached to each motor. Pressure, thrust, and fuel depletion signals are fed to the MDS/AMCS, which directs the fire control system to terminate motor operation in the event of a serious malfunction. The fire control system supplies 28 vdc to operate the oxidizer control valve and the spark ignition circuit.

The propane ignition system has been designed to maximize safety, ensure reliable motor operation, and minimize maintenance. The light hydrocarbon gases evaluated for ACS ignition are 100 to 1000 times less toxic than typical bipropellants evaluated for Space Station attitude control. More important, however, the ignition gas makes up less than 0.2% of the ACS propellants (assuming a nominal 10-sec burn). A 0.100-msec ACS motor ignition pulse requires only 1.14 gm $\left(0.0025\ \mathrm{lb_m}\right)$ of propane. The selected propane supply system uses a single 300-ml $\left[176\text{-gm}\ \left(0.39\ \mathrm{lb_m}\right)\right]$ bottle located adjacent to each thruster pad. Based on an average yearly total impulse of 356.188 kN-sec $\left(79{,}945\ \mathrm{lb_f\text{-}sec}\right)$ per pad and an estimated average burntime of 10 sec, 300 ml of propane would provide ignition capability for an entire thruster pad (eight motors) for 1 yr.

The low-pressure propane $\left[P_{vapor} \sim 10.33 \text{ kg/cm}^2 \text{ (147 psia) at 299°K (72°F)}\right]$ will be stored in sealed replaceable tanks. A flexline will supply propane to each TCA using a Symetrics 4000 1/4-in. quick disconnect. A propane sniffer will be provided in each APS room to monitor the concentration of propane and alert the crew to any serious leak. The propane bottle has a flow-limiting orifice that allows the crew time to shut the propane hand valve in case a propane quick disconnect jams during refurbishment. Although no anticipated leakage rate of propane could pose a safety hazard, the absolute safety requirement dictates that no single accident can cause serious injury to the crew or damage to the Space Station. Therefore, the situation of a full propane tank rupturing was investigated. Since each APS room occupies about 25% of the lower deck of the Space Station (or 5% of the entire Space Station), a ruptured propane bottle would suddenly dump 175 gm of propane into an APS room [volume = 42.3 m^3 (1490 ft^3)]. This would raise the concentration of propane to about 0.33% by volume. But the lower limit of flammability of propane in air is 2.4%, so the 300 ml in the propane ignition bottle is insufficient to pose an explosion hazard. Furthermore, the concentration of 0.33% is within short-term tolerance limits and would not prevent anyone in the room from leaving. Even if the propane were inadvertently allowed to diffuse throughout the Space Station, its concentration would still be within the 8-hr tolerance limit and allow sufficient time for decontamination.

Each thruster pad can handle two spin/despin motors. A spin-up or despin maneuver requires three spin/despin motor firings to produce the required 3.110 MN-sec $\left(698{,}050 \text{ lb}_f\text{-sec}\right)$ of total impulse. Therefore, a minimum of one motor replacement is required to complete a spin/despin maneuver. The three spin/despin motors provided may be manipulated in various ways as discussed in Section II-E, based on motor refurbishment scheduling requirements. These motors are located vertically in line and extend perpendicularly through the outer face of the thruster pad. All three spin/despin motors would be stored inside the Space Station during launch and be extended after the Space Station was in orbit.

Each spin/despin motor requires a vacuum-jacketed LOX line and an instrumentation line. The two vacuum-jacketed LOX control valves (Vacco Valve Co, Model SDL-01P-403-2C) are pad-mounted to avoid handling during motor refurbishment. The two LOX control valves are connected to a distribution block by vacuum-jacketed hard lines, and by a common vacuum-jacketed hard line to a 1033-kN/m^2 (150-psia), pressure-regulated oxidizer supply system. The LOX lines from the valves to the spin/despin motors will be vacuum-jacketed lines consisting of Aeroquip 666 braided Teflon hose and beryllium copper bellows. The LOX lines will terminate in Symetrics 47325 vacuum-jacketed socket assembly; this mates with a Symetrics 47320 nipple assembly that is hard-mounted to the forward closure of the spin/despin motors. The vacuum flexlines from the socket assembly to the forward closure use a Symetrics 4000-1/4-in. quick disconnect. These vacuum lines are connected to the motor-mounted nipple assembly to prevent the formation of ice during motor operation.

The spin/despin motors may be fed by either LOX line. This feature provides redundancy and operational flexibility. Since the LOX valves are located upstream of the disconnect, the LOX line will be purged of LOX after motor shutdown. This removes the hazard of LOX spills during refurbishment.

Each spin/despin motor is connected to the fire control system by a power and instrumentation cable. Outputs from the pressure transducer, thrust transducer, and fuel depletion wires are sent to the MDS/AMCS. Firing commands are sent to the pyrogen igniter and the proper oxidizer control valve. The MDS/AMCS signals the fire control system to close the oxidizer control valve or in the event of a motor malfunction at the first indication of fuel depletion.

H. APS MASS AND PERFORMANCE

Although the hybrid APS was primarily designed for maximum safety, high reliability, and minimum maintenance, it also achieves a low total mass, along with excellent performance. Fuel replenishment makes the system less sensitive to the inert mass of the motor. Furthermore, the oxygen/(PMM/PBD) propellant system offers outstanding performance, even allowing for a lower efficiency to provide nozzle film cooling.

1. APS Mass Requirements

All APS components were designed with high factors of safety to ensure high reliability and minimum maintenance. The mass requirements for an attitude control motor TCA are shown in Table VI-6. With recommended maintenance, the motor case/nozzle, forward closure, and oxidizer flow control components [total mass = 10.6 kg (23.2 lb)] are capable of operating without replacement for the required 10-yr life of the Space Station. The cartridge-loaded fuel grain [10.5 kg (23.1 lb)] provides 9.71 kg (21.4 lb) of usable fuel. The remaining mass is divided almost equally between residual fuel and the tripwire-lined phenolic cartridge. The total loaded mass of spares and resupply items is 21.0 kg (46.3 lb), which in a 0.7-g environment weighs 144 kg $\left(32.4\ \text{lb}_m\right)$, and can therefore be easily handled by one man, even under artificial gravity. At an average O/F ratio of 1.815, the ACS motors burn 17.6 kg $\left(38.9\ \text{lb}_m\right)$ of GOX with each fuel grain.

Although the spin/despin motors are scaled-up (2.29:1) versions of the ACS motors, their size removes some of the minimum wall criteria placed on the ACS motors. This allows the spin/despin motors (Table VI-4) to have a mass less than 12.0 (2.29^3) times the mass of the ACS motors contrary to what would be expected on the basis of a direct scaleup. The motor case/nozzle assembly, forward closure assembly, oxidizer flow control (vacuum-jacketed LOX disconnect and injector assembly), and instrumentation have a total mass of 79.0 kg $\left(174\ \text{lb}_m\right)$. The cartridge-loaded fuel grain, which is divided into six segments, has a total mass of 126.4 kg $\left(278.7\ \text{lb}_m\right)$. Since no single segment has a mass larger than 22.7 kg $\left(50\ \text{lb}_m\right)$, which corresponds to 156 N $\left(35\ \text{lb}_f\right)$ in a 0.7-g environment, the fuel segments can be handled by one man. The igniter assembly is installed around the injector during refurbishment and has a mass of 0.23 kg $\left(0.5\ \text{lb}_m\right)$. The loaded motor has a mass of 205.7 kg $\left(453.5\ \text{lb}_m\right.$. The refurbishment dolly is used to transport the spin/despin motor between the thruster pad and the work table. Each spin/despin motor burns 213.7 kg $\left(468.9\ \text{lb}_m\right)$ of LOX with 116.5 kg $\left(256.\ \text{lb}_m\right)$ of useful fuel, for a total propellant mass of 329.2 kg $\left(725.8\ \text{lb}_m\right)$.

Table VI-6 Attitude Control Motor TCA Mass Summary

COMPONENT	MASS kg	MASS 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

A hybrid APS can satisfy all APS mission objectives with a low total system mass. The total mass required for the ACS motors was combined with that required for the spin/despin motors to show total APS mass required (Table VI-7). Since the design of the Space Station shell was not available, there was no way to calculate the mass increment attributable to the raised APS thruster pads. Furthermore, these raised pads reduce the APS space requirements, and therefore reduce the effective mass attributable to the APS. The mass of the APS refurbishment table, administrative work area, and storage cabinets was not included since these facilities could be used for other Space Station activities; the portion of their mass attributable to the APS would be determined later.

The ACS (Table VI-7) requires a total mass (including propellant) of 2643 kg $\left(5844\ lb_m\right)$ to deliver 7.12 MN-sec $\left(1,598,890\ lb_f\text{-sec}\right)$ of total impulse. The primary ACS, consisting of 16 TCAs, oxygen and ignition lines, and two complete refurbishment assemblies, has a mass of 232 kg $\left(510\ lb_m\right)$. Spares and scheduled resupply adds another 21 kg $\left(45\ lb_m\right)$, for a total ACS inert mass of 253 kg $\left(555\ lb_m\right)$. Ninety fuel grains have been provided, allowing for a 50% fuel reserve at the end of 10 yr. The total expended mass of the ACS, including fuel, GOX, and propane bottles, is 2390 kg $\left(5289\ lb_m\right)$.

Table VI-7 APS Mass Summary

COMPONENT	QUANTITY	MASS	
		kg	lb_m
ATTITUDE CONTROL SYSTEM			
Inert Mass			
Primary System			
Thrust Chamber Assemblies	16	168	371
Motor Refurbishment Tubes	2	17	38
Sliding Door Assemblies	2	13	28
Motor Replacement Caps (Used for Launch)	16	22	48
GOX Lines & Disconnects	16	7	15
Propane Supply Systems	2	5	10
Spares & Scheduled Resupply			
Motor Case/Nozzle Assemblies	2	10	23
Forward Closure Assembly	1	4	8
Oxidizer Control Valves	2	1	2
Spark Ignition & Fluidic Circuits	2	1	2
Miscellaneous (Spark Plugs, Seals, Pins Electrical Plugs, etc)		5	10
Total ACS Inert Mass		253	555
Expended Mass for 10-yr Requirements			
Fuel Grain Assemblies*	90	943	2,080
Propane Ignition Bottles (1 Spare)	21	9	19
GOX		1,448	3,190
Total Expended Mass		2,390	5,289
TOTAL ACS MASS		2,643	5,844
SPIN/DESPIN SYSTEM			
Inert Mass			
Thrust Chamber Assemblies	3	237	522
Motor Refurbishment Tube & Dolly	1	118	260
Sliding Door Assemblies	4	181	400
Motor Replacement Caps (Used for Launch & after 18 Months)	4	23	50
Vacuum-Jacketed LOX Lines & Valves	4	9	20
Miscellaneous Spares (Seals, Pins, Plugs)		7	15
Total Spin/Despin Inert Mass		575	1,267
Oxidizer Feed Assembly			
Propellant Tankage Assemblies		38.8	85.72
Pressure Control Assembly		17.1	37.68
Resupply		31.7	70
Total OFA Inert Mass		87.6	193.40
Expended Mass for 18-Month Spin/Despin Requirements			
Fuel Grain Assemblies (1 Spare)	31	3,920	8,640
Igniter Assemblies (2 Spare)	32	7	16
LOX		6,382	14,067
Total Expended Mass		10,309	22,723
TOTAL SPIN/DESPIN SYSTEM MASS		10,884	23,990
Total APS Inert Mass		914.6	2,015
Total APS Expended Mass		12,700	28,812
Total APS Mass		14,441.6	30,827.4

*Includes allowance for 50% fuel reserve at the end of 10 years.

†Does not include inert mass of oxidizer feed system or thruster pad structure.

The spin/despin system (Table VI-8) requires a total mass (including propellant) of 10,884 kg $\left(23,990 \text{ lb}_m\right)$ to deliver 31.1 MN-sec $\left(6,980,000 \text{ lb}_f\text{-sec}\right)$ of total impulse. The spin/despin system includes three TCAs, four door assemblies, and one refurbishment tube and dolly assembly, along with lines, valves, motor caps, and miscellaneous spares. Its total inert mass is 575 kg $\left(1267 \text{ lb}_m\right)$. This can be returned to earth after 18 months when the spin/despin system is no longer needed. Thirty-one fuel grains have been provided to accomplish the 30 spin/despin motor firings. The total expended mass of the spin/despin system, including fuel, LOX, and igniters, is 10,309 kg $\left(22,723 \text{ lb}_m\right)$.

The combined ACS-spin/despin APS has a mass of 14,442 kg $\left(30,827 \text{ lb}_m\right)$ and provides a total impulse of 38.0 MN-sec $\left(8,509,590 \text{ lb}_f\text{-sec}\right)$. As a figure of merit, the equivalent specific impulse (total impulse/total system mass) for the system is 278 sec. The total expended mass is 12,700 kg $\left(28,812 \text{ lb}_m\right)$ and the total inert mass is 915 kg $\left(2015 \text{ lb}_m\right)$.

Table VI-8 Spin/Despin TCA Mass Summary

COMPONENT	MASS	
	kg	lb_m
Motor Case/Nozzle	45.4	100
Forward Closure	24.0	53
Oxidizer Flow Control & Instrumentation	0.6	1.3
Reusable TCA Mass	79.0	174
Phenolic Fuel Cartridge	5.0	11
Igniter (Cartridge & Propellant)	0.2	0.5
Useful Hybrid Fuel	116.5	256.9
Residual Hybrid Fuel	4.9	10.8
Expended TCA Mass	126.6	279.2
Loaded Motor Mass	206	454
Useful Propellant Mass		
Oxidizer	212.7	468.9
Fuel	116.5	256.9
TOTAL PROPELLANT MASS	329.2	725.8

2. APS Performance

The selection of an oxygen/(PMM/PBD) propellant system allows the hybrid APS to achieve exceptionally high performance. The theoretical propellant performance at a chamber pressure of 551 kN/m^2 (80 psia) and a nozzle expansion ratio of 100 is shown in Fig. VI-20; the maximum theoretical specific impulse is 369 sec at an O/F ratio of 2.2. To achieve long nozzle life, an O/F ratio of 2.0 was selected for nominal motor operation. Table VI-9 shows the computer-calculated theoretical propellant performance at an O/F ratio of 2.0; the theoretical vacuum specific impulse is 367.5 sec at an expansion ratio of 100. Table VI-9 also shows the thermochemical analysis of the propellant combustion products. The combustion products are entirely gaseous both in the chamber and in the exhaust. The four primary exhaust species (99.9$^+$%) are, in moles/100 gm (0.22 lb): CO, 1.343; CO_2, 0.962; H_2, 0.711; and H_2O, 1.034.

The ACS and spin/despin motor designs used conservative efficiencies and the results of motor tests to establish predicted performance and motor ballistic characteristics. A specific impulse efficiency of 90% was used for both the ACS and spin/despin motors to allow for nozzle film cooling. Performance summaries for the ACS and spin/despin motors are shown in Table VI-10. Since the spin/despin motor is a scaled-up version of the ACS motor, the two systems only differ with respect to thrust, duration, and total impulse.

The ACS motor-delivered vacuum specific impulse and oxidizer/fuel ratio are shown as functions of time in Fig. VI-21. The motor O/F ratio -- initially 2.08 -- is allowed to decrease during motor operation to insure adequate film cooling as the aft end of the fuel grain moves forward. Although this reduces the motor O/F ratio to a minimum value of 1.68 at 350 sec, the propellant flow increases by less than 8%. The delivered specific impulse is reduced from an initial value of 332 sec to 320 sec near web burnout. The slight variations in propellant flow and specific impulse tend to compensate to produce a nearly neutral thrust trace. As shown in Fig. VI-22, the thrust increases from 220 N $\left(49.4\ lb_f\right)$ to a minimum of 229 N $\left(51.3\ lb_f\right)$ at 350 sec. The chamber pressure varies slightly more than the thrust due to an increase in the characteristic exhaust velocity at lower O/F ratios (maximum c* occurs at an O/F ratio of 1.70); the chamber pressure varies from an initial value of 530 kN/m^2 (77 psia) to 576 kN/m^2 (84 psia) at 350 sec.

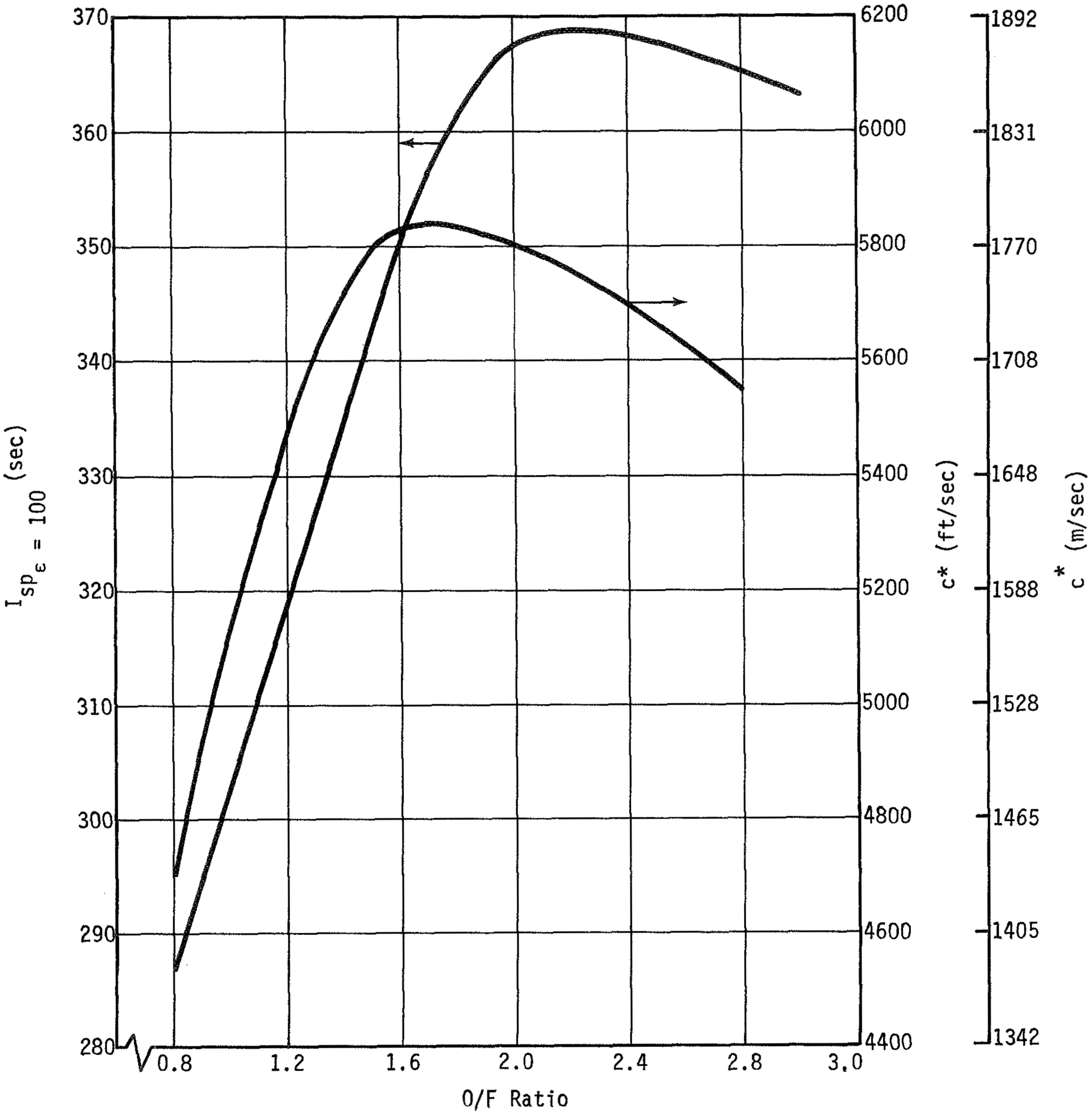

Fig. VI-20 Theoretical APS Propellant Performance of GOX/ (20% PMM-80% PBD) at P_c = 551 kN/m^2 (80 psia)

Table VI-9 GOX/(PMM/PBD) Propellant Performance at O/F = 2.0, P_c = 551 kN/m^2 (80 psia)

PARAMETER	CHAMBER	THROAT	ε = 60 EXHAUST [1]	ε = 80 EXHAUST [2]	ε = 100 EXHAUST [3]	EXHAUST [0]
Area Ratio		1.00000000@+00	6.00000000@+01	8.00000000@+01	1.00000000@+02	0.00000000@+00
Optimum I_{sp} (sec)		1.17611470@+02	3.44391034@+02	3.49970002@+02	3.53973127@+02	0.00000000@+00
Vacuum I_{sp} (sec)		2.22004099@+02	3.60066775@+02	3.64396581@+02	3.67517954@+02	0.00000000@+00
C* (m/sec)		1.76701809@+03				
C* (ft/sec)		5.79729203@+03				
Velocity (m/sec)		1.15337505@+03	3.37732388@+03	3.43203488@+03	3.47129216@+03	0.00000000@+00
Velocity (ft/sec)		3.78403144@+03	1.10804371@+04	1.12599348@+04	1.13887314@+04	0.00000000@+00
Density (gm/cc)		2.70643906@-04	1.54021773@-06	1.13691252@-06	8.99243775@-07	0.00000000@+00
Density (lb/in.^{3})		9.77836432@-06	5.56480666@-08	4.10766493@-08	3.24896776@-08	0.00000000@+00
Pressure (kN/m^2)	5.51576000@+02	3.19561959@+02	7.99764378@-01	5.52024820@-01	4.14528086@-01	0.00000000@+00
Pressure (psia)	8.00000000@+01	4.63489287@+01	1.15996980@-01	8.00650964@-02	6.01372193@-02	0.00000000@+00
Temperature (°K)	3.37568633@+03	3.22309381@+03	1.54198664@+03	1.44195274@+03	1.36932567@+03	0.00000000@+00
Temperature (°F)	5.61654739@+03	5.34188086@+03	2.31588795@+03	2.13582693@+03	2.00509821@+03	0.00000000@+00
Heat Capacity (cal/°K/gm)	4.64677565@-01	4.62960551@-01	4.17307364@-01	4.13103508@-01	4.10008238@-01	0.00000000@+00
Heat Capacity (Btu/°F/lb)	2.65191486@-02	2.64211586@-02	2.38157313@-02	2.35758172@-02	2.33991701@-02	0.00000000@+00
Enthalpy (kcal/gm)	-2.38965449@-02	-1.82790772@-01	-1.38632101@+00	-1.43081978@+00	-1.46318998@+00	0.00000000@+00
Enthalpy (Btu/lb)	-2.45477257@+00	-1.87771821@+01	-1.42409826@+02	-1.46980962@+02	-1.50306191@+02	0.00000000@+00
Entropy (cal/°K/gm)	2.90602093@+00	2.90602093@+00	2.90602092@+00	2.90602093@+00	2.90602093@+00	0.00000000@+00
Entropy (Btu/°F/lb)	1.65846614@-01	1.65846614@-01	1.65846614@-01	1.65846614@-01	1.65846614@-01	0.00000000@+00
Moles of Gas/100 gm (0.44 lb)	4.47612498@+00	4.40611357@+00	4.05015030@+00	4.04997497@+00	4.04991900@+00	0.00000000@+00

COMBUSTION PRODUCTS [Moles/100 gm (0.22 lb)]

C	G	5.37814321@-09	1.83156584@-09	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
CH	G	1.16406715@-09	3.62144464@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
CH_2	G	2.13738181@-10	5.57459138@-11	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
CH_2O	G	5.74511924@-07	3.25454671@-07	1.40594397@-09	1.06645991@-09	8.63745857@-10	0.00000000@+00
CH_3	G	7.04177318@-10	2.69365435@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
CH_4	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1,00000000@-10	1.00000000@-10	0.00000000@+00
CO	G	1.80980846@+00	1.77132578@+00	1.41422122@+00	1.37584567@+00	1.34314573@+00	0.00000000@+00
CO_2	G	4.94672105@-01	5.33234121@-01	8.90474650@-01	9.28850284@-01	9.61550262@-01	0.00000000@+00
C_2	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
C_2H	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
C_2H_2	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
C_2H_4	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
C_2O	G	4.41583797@-10	1.28621760@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
C_3	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
C_3O_2	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
C_4	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
C_5	G	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
H	G	2.73599243@-01	2.39184958@-01	5.19216338@-04	1.90680329@-04	8.34840627@-05	0.00000000@+00
HCO	G	2.14722531@-04	1.35648852@-04	1.37368887@-07	6.83444396@-08	3.88746064@-08	0.00000000@+00
HO_2	G	7.12479814@-05	4.36075341@-05	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
H_2	G	4.71671705@-01	4.61591265@-01	6.39963996@-01	6.78492820@-01	7.11244026@-01	0.00000000@+00
H_2O	G	1.00909299@+00	1.05592073@+00	1.10494200@+00	1.06658855@+00	1.03389335@+00	0.00000000@+00
H_2O_2	G	9.58708528@-06	5.66004600@-06	1.00000000@-10	1.00000000@-10	1.00000000@-10	0.00000000@+00
O	G	8.75241491@-02	6.71902917@-02	2.01520965@-08	1.73210395@-09	2.15604595@-10	0.00000000@+00
OH	G	2.54925419@-01	2.15960173@-01	2.90400958@-05	6.89253798@-06	2.10670881@-06	0.00000000@+00
O_2	G	7.45347715@-02	6.15210051@-02	1.61207634@-08	1.28732298@-09	1.43014514@-10	0.00000000@+00
C	S	0.00000000@+00	0.00000000@+00	0.00000000@+00	0.00000000@+00	0.00000000@+00	0.00000000@+00

	Ingredients	Weight Percentage	Elements	gm-Atoms	lb-Atoms
0090	Polymethyl Methacrylate	6.67	C	2.30469577@+00	5.08093229@-03
0096	Polybutadiene	26.66	H	3.49036033@+00	7.69484838@-03
0189	Oxygen, Gas	66.67	O	4.30014173@+00	9.48009246@-03
	Propellant Density (gm/cc)	1.49913914@-03			
	Propellant Density (lb/in.^{3})	5.41638971@-05			

Table VI-10 APS Motor Performance Summary

PARAMETER	ACS MOTORS	SPIN/DESPIN MOTORS
Propellants	GOX/(20%PMM-80%PBD)	LOX/(20% PMM-80% PBD)
Average Motor O/F Ratio	1.815	1.815
Average Motor Chamber Pressure, $kN/_m{}^2$ (psia)	558 (81)	558 (81)
Nozzle Expansion Ratio	100	100
Average Thrust, N $\left(lb_f\right)$	225 (50.5)	1170 (263)
Total Impulse, kN-sec $\left(lb_f\text{-sec}\right)$	86.63 (19,480)	1039 (233,675)
Duration (sec)	386	888

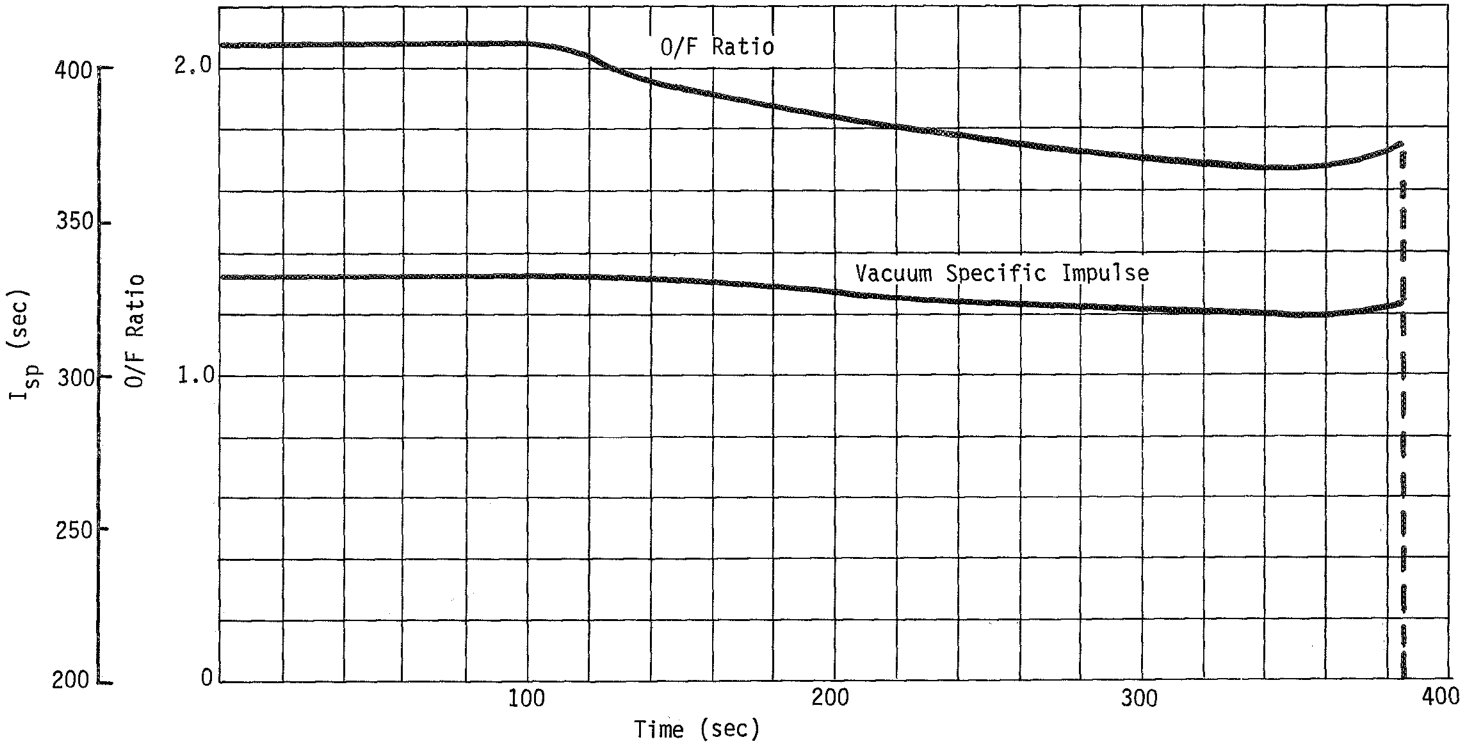

Fig. VI-21 Hybrid ACS Motor O/F Ratio and Specific Impulse vs Time

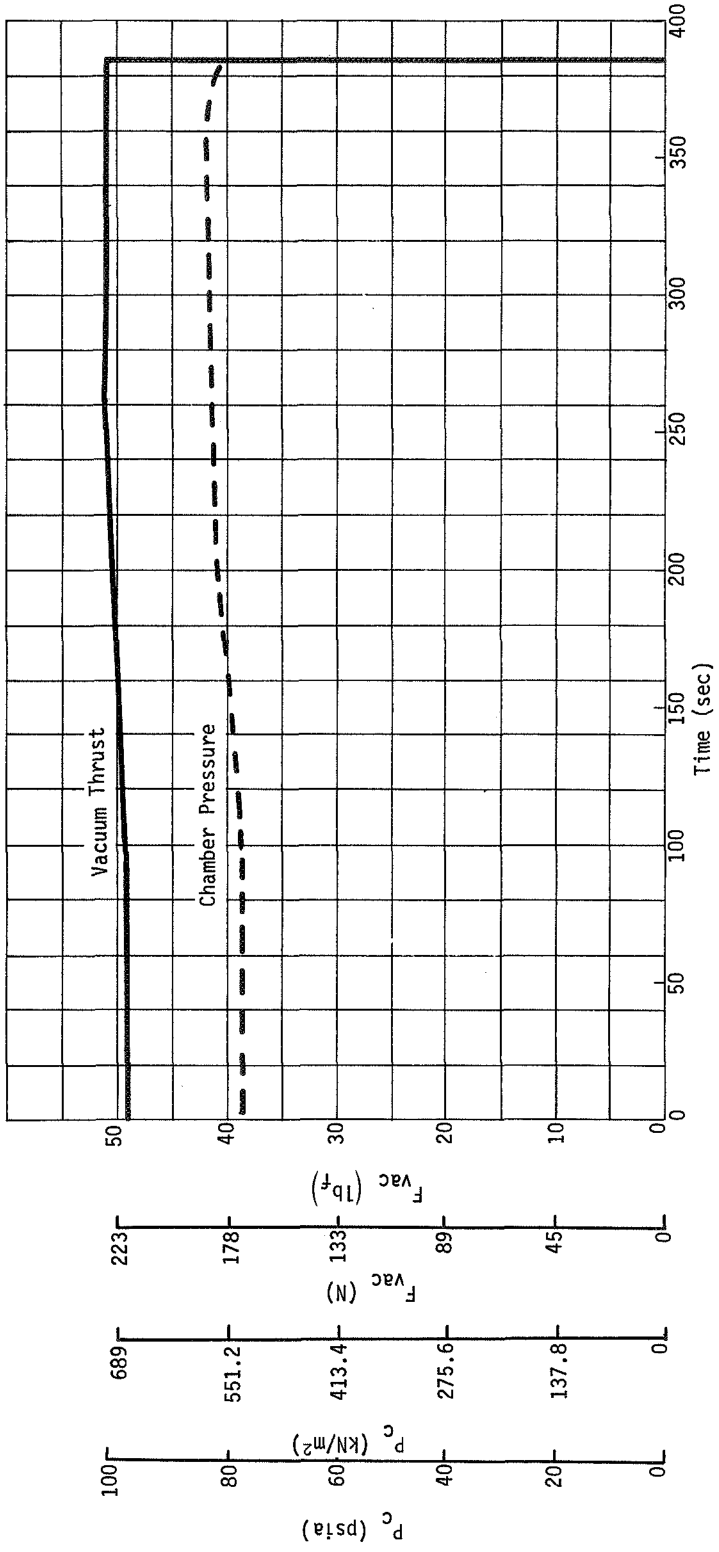

Fig. VI-22 Hybrid Attitude Control Motor Performance

Since the spin/despin motors use the same fuel geometry, have the same oxidizer mass flux vs percent web, and operate at the same pressure as the ACS motors, both motors have nearly identical ballistic characteristics.

The spin/despin motor O/F ratio and specific impulse curves shown in Fig. VI-23 and VI-24 follow the same pattern as those for the ACS motors, except the burntime of the spin/despin motors (888 sec) is 2.29 times (scaleup factor) longer than that for the ACS motors. The spin/despin motor propellant flowrate is 5.24 times (scaleup factor squared) the flowrate of the ACS motors; therefore, the spin/despin thrust is 5.24 times the ACS motor thrust at the same web fraction. Since the throat area of the spin/despin motor is 5.24 times the throat area of the ACS motor, the values of chamber pressure for the two motors are identical at the same percent web (Fig. VI-25).

I. APS SAFETY AND RELIABILITY

Throughout the system design phase, a concentrated effort was directed at improving the reliability of the hybrid APS. However, the highest reliability system is not *a priori* the safest system. The failure mode analysis performed in Task II was reviewed and primary emphasis was placed on removing any failure modes that posed a safety hazard to the crew. Concurrently, an effort was made to achieve the highest reliability through maintenance and design redundancy.

1. APS Reliability

Inflight maintenance is required for a hybrid ACS to achieve high reliability for a 10-yr operating life. Component redundancy and improved component reliability will not be sufficient to ensure successful operation without periodic maintenance. The ACS have been sized to provide 86,790 N-sec $\left(19{,}480\ \text{lb}_f\text{-sec}\right)$ of total impulse between grain changes. Based on current ACS impulse requirements, the average ACS motor will be refurbished once every 2 yr. At this time both sets of redundant motor seals will be replaced and all motor components will be thoroughly inspected to ensure continued reliable operation. Motor operation will be trend-analyzed to detect impending failures. Any component that is tending toward out-of-specification performance will be replaced.

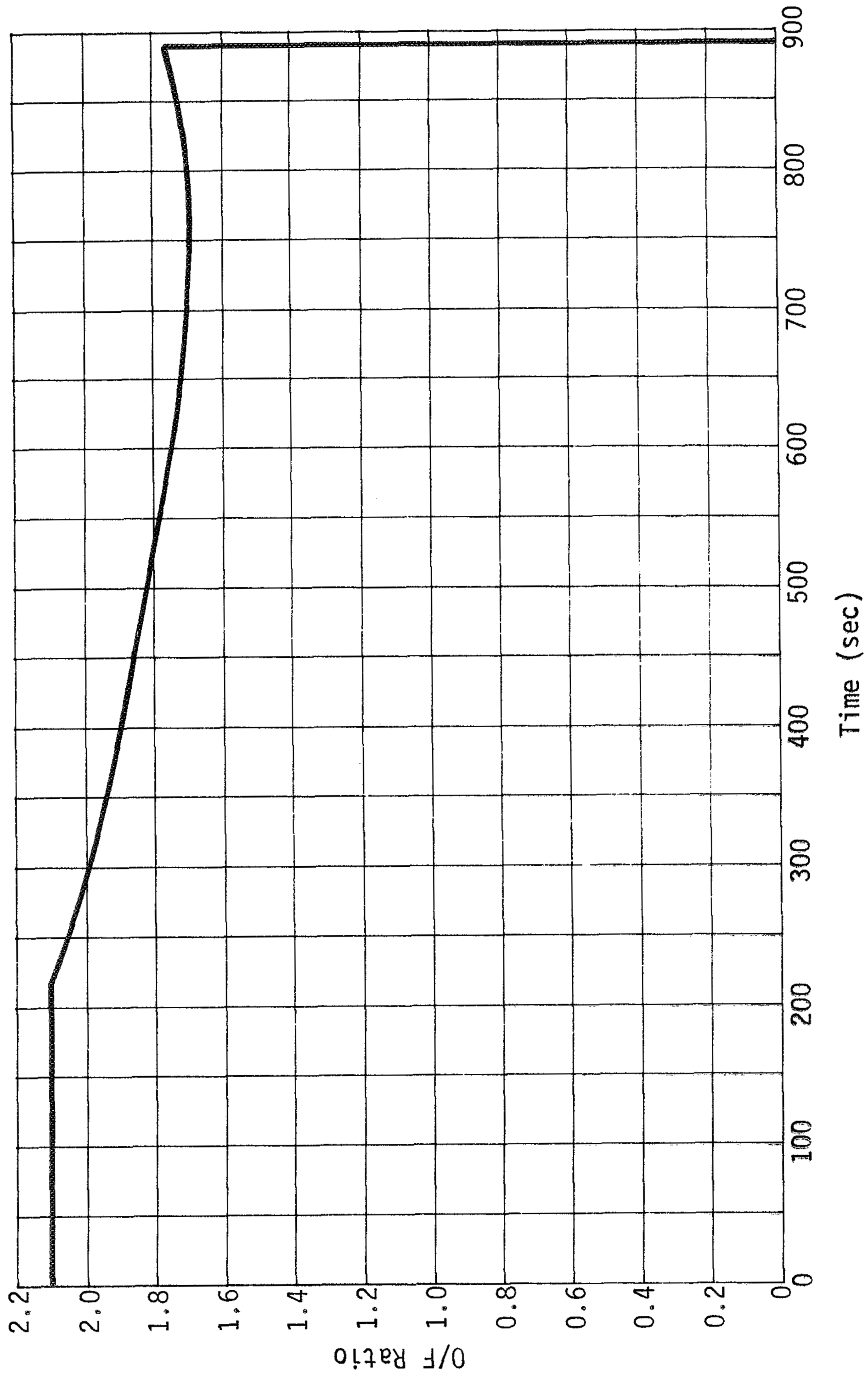

Fig. VI-23 O/F Ratio vs Time for Spin/Despin Motors

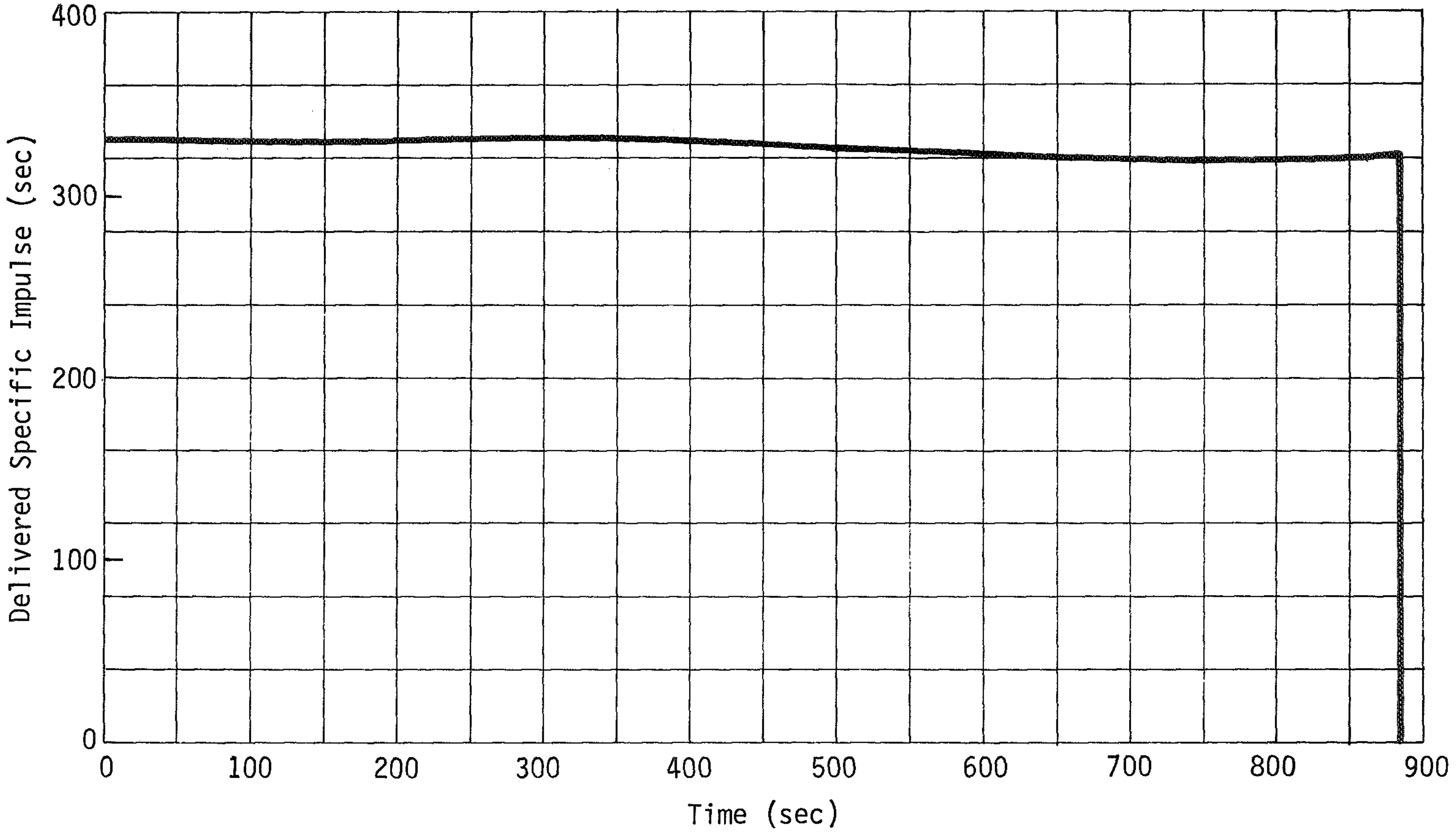

Fig. VI-24 Delivered Specific Impulse vs Time for Spin/Despin Motors

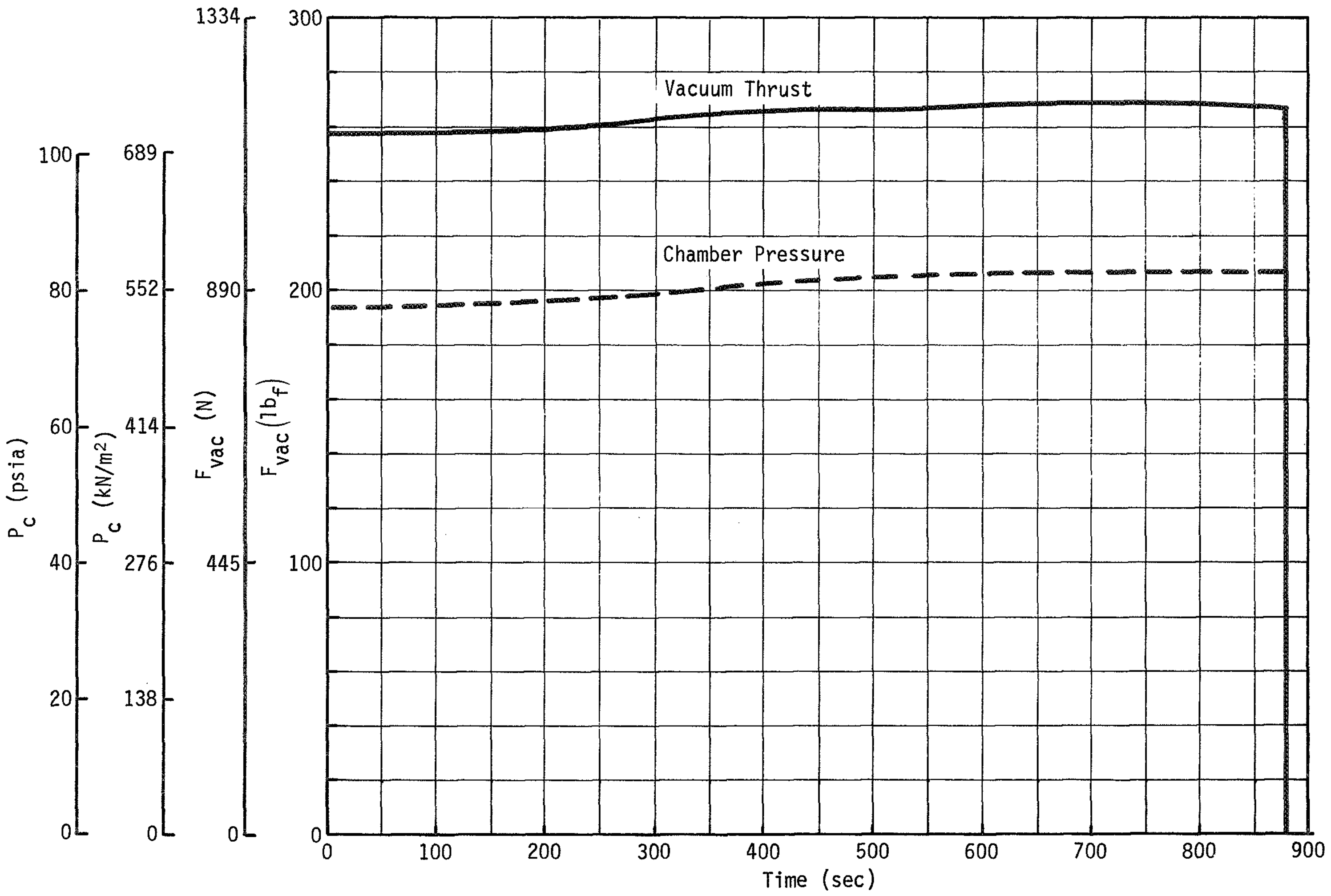

Fig. VI-25 Spin/Despin Motor Performance

Redundancy and overdesign significantly improves APS reliability. The spin/despin motors have redundant oxidizer valves, oxidizer supply lines, and motor mounting locations. Furthermore, the spin/despin system uses three motors, although in an emergency a single motor could complete the maneuvers. Due to the low operating chamber pressure, the motor cases were designed for several times the motor MEOP; this did not significantly increase system weight. All motors use single-piece motor case and nozzle assemblies with a single pinned motor case joint having very high reliability. All fuel grains are cast in trip wire-lined phenolic cartridges. Although the trip wires provide a fail-safe indication of fuel depletion and will signal shutdown, the phenolic cartridge ensures that the forward closure and motor case flange will never be exposed to the combustion gases. The ACS motors are arranged in two redundant sets of four on each pad to provide redundancy for all ACS maneuvers. Each set is connected to a redundant shutdown valve that terminates thrust in case the TCA oxidizer valve fails to open.

Hybrid operation significantly improves the reliability of the APS. Because the hybrid APS uses a solid fuel and a liquid oxidizer, there are no failure modes associated with mixing propellants together at the wrong time, in the wrong places, or in the wrong quantity. Furthermore, the selected propellants are completely nontoxic and nonhypergolic. And because hybrid combustion is a convective heat transfer process, it is insensitive to grain imperfections and chamber pressure variations. The selected design uses a very low chamber pressure, which increases the reliability of the entire system. Hybrid motors can use long-duration igniters to ensure successful ignition without overpressurizing the motor.

A complete reliability study was conducted on the ACS motors, the spin/despin motors, and the OFA. This study used failure rate data from the following four sources:

1) *Failure Rate Data Handbook.* USN Fleet Missiles Systems Analysis Evaluation Unit;
2) *Stūdy of Space Station Propulsion System Resupply and Repair, Final Report.* MCR-70-150. Martin Marietta Corporation, Denver, Colorado;
3) *UTC Hybrid Experience, Test Data.* United Technology Center, West Palm Beach, Florida;
4) Average of typical aerospace components, vendor data.

The following basic assumptions were used:

1) The duration of the mission is 10 yr. However, all spin/despin maneuvers will be completed in the first 18 months;
2) Multiple malfunctions are statistically improbable;
3) No single instrumentation failure can prevent either the ACS motors or the spin/despin motors from completing a given burn;
4) No damage occurs to the motors or resupplied parts due to ground handling or launch;
5) Infant mortality has been eliminated through prelaunch testing and checkout;
6) Maintenance is performed at the recommended intervals. All components are properly checked and functioning correctly before reinstallation. No failures occur as a result of improperly performed maintenance.

The reliability analysis showed that the ACS motors, the spin/despin motors, and the OFA achieve high reliability for their required operating lives. The reliability of the hybrid APS is shown in Table VI-11. A single ACS motor operating for 10 yr and delivering 1/16th of the total ACS impulse has a reliability of 0.9445. Using pairs of motors increases the reliability of a single pair to 0.9969. The reliability of a single thruster pad (eight motors) is 0.9872, and the reliability of the total ACS (16 motors) is 0.9745. Without redundancy, the reliability of the OFA is 0.8791. Redundancy increases this to 0.9924. This results in a total ACS reliability (motors plus OFA) of 0.97. Note that these reliabilities are based on normal operation, and therefore do not include additional redundancies inherent in the present design. For example, a rollup maneuver requires firing one motor on each thruster pad to create pure rolling motion (no pitching or translation). However, should three of the four rollup motors be inoperative, the remaining motor could be used with the pitch motors to create rolling motion and translation. The small translational velocity imparted to the Space Station would have a negligible effect on the orbit. The ACS motor instrumentation has a reliability of 0.9988 per pair of motors and 0.9906 for the entire system. The use of thrust, pressure, and fuel depletion indicators in the ACS motors provides redundancy in measuring motor operating conditions.

Table VI-11 Hybrid APS Reliability Summary

SYSTEM	10-YR RELIABILITY
Attitude Control System	
Single ACS Motor	0.9445
Redundant Pair of ACS Motors	0.9969
Single ACS Pad (Eight Motors)	0.9872
Complete ACS (16 Motors)	0.9745
ACS Instrumentation, One Motor	0.9655
ACS Instrumentation, One Pair	0.9988
ACS Instrumentation, 16 Motors	0.9906
Spin/Despin System	
Single Spin/Despin Motor	0.9913
Three Redundant Spin/Despin Motors	0.9999
Spin/Despin Instrumentation, One Motor	0.9947
Three Redundant Spin/Despin Motors	>0.9999
Oxidizer Feed System	
Single Oxidizer Feed Module	0.8791
OFA, Two Modules	0.9924
Complete Oxidizer Feed System	>0.999

Three-motor redundancy on the spin/despin system provides exceptionally high reliability. The combination of a relatively short mission time (18 months), coupled with relatively frequent refurbishment (at least every 3 months), allows the spin/despin motors to achieve an individual motor reliability of 0.9913. However, using three spin/despin motors and providing each thruster pad with redundant LOX lines increases the reliability of the spin/despin system to 0.9999. The instrumentation for a single spin/despin motor has a reliability of 0.9947 and the reliability for three redundant motors is greater than 0.9999.

2. Safety

Safety and reliability are the two leading factors in Space Station component design because of three operational considerations:

1) The Space Station is man-operated;
2) It must operate in a space environment;
3) It has a 10-yr operational life.

The selected hybrid APS provides certain inherent safety features such as:

1) Inert fuel grain;
2) Nontoxic oxidizer (oxygen);
3) Burning is always downstream of the oxidizer injector;
4) Low operational chamber pressure;
5) Positive motor termination.

Throughout the baseline APS design, these and other design features were incorporated to provide a completely safe operation. These safety features have been discussed in various sections throughout the study and are summarized in Table VI-12.

Table VI-12 Summary of Safety Features

COMPONENT OR DESIGN FEATURE	CHARACTERISTIC	APS MOTOR SYSTEM	
		ACS	SPIN/DESPIN
Oxidizer (Oxygen)	Nontoxic	X	X
LOX	Provides an emergency life-support air supply	X	X
Hybrid Fuel (PMM/PBD)	Inert	X	X
GOX Line Disconnect	Provides indication of potential disconnect failure before disconnect	X	
GOX Valve	Fails in closed position, providing safe motor operation	X	
LOX Line Disconnect	Vacuum-jacketed portion of disconnect is downstream of LOX line to avoid spilling LOX during disconnect		X
Motor Case-to-Closure Attachment	Vents motor gas to space in case of a motor case O-ring failure	X	X
Redundant Motor O-Rings	Reduces chance of motor failure due to gas leak	X	X
Motor Mount Retention	Provides positive attachment under all Space Station environment conditions	X	X
Phenolic Insulation in Forward Closure	Protects forward closure from failure	X	X
Fuel Depletion Detection System	Provides indication of fuel depletion and automatically terminates motor operation	X	X
Unchoked Igniter	Provides for safe storage and handling		X
Igniter Completely Mounted Inside Motor Forward Closure	Protects Space Station from igniter malfunction		X
Propane Bottle	Miniaturized to eliminate toxicity and to avoid explosion hazard	X	
Movable Tube Refurbishment Approach	Provides safe Space Station environment during refurbishment task	X	X
Low Chamber Pressure	Provides high structural safety margin	X	X

An evaluation was performed to identify and assess all the demands placed on the Space Station systems by the hybrid APS. The hybrid propulsion operations area was designed to satisfy all APS maintenance and operation requirements. APS equipment requirements, including those for motor hardware, propellant, spares, and refurbishment equipment, were determined and discussed. Propulsion system maintenance procedures are presented. The crew time required to operate and maintain the APS was evaluated. Finally, the resupply and APS storage requirements were evaluated.

A. APS OPERATIONS AND REFURBISHMENT ROOM

The two APS rooms shown in Fig. VII-1 provide the space and facilities required to perform all maintenance, repair, spares storage, and administrative functions required for the APS. The maintenance and repair facilities required for the APS can also be used to service other systems onboard the Space Station. Due to the safety of the hybrid APS, servicing of other equipment in the APS rooms can be scheduled concurrently with APS operations. Although the size of the APS rooms was minimized to reduce the impact of the APS on the Space Station, the storage capability of the APS room exceeds the needs of the APS, and can also be used for other Space Station subsystems.

The two APS rooms are on the bottom deck of the Space Station. Each room occupies about 20.9 m^2 (225 ft^2), or approximately 1/4 of the lower deck. In addition to the APS rooms, the lower deck contains two docking ports with 1.52-m (5.0-ft) passageways leading to a 3.00-m (10.0-ft) diameter central transit and utility core. There is also space for two additional rooms, each with about 12 m^2 (130 ft^2) of floor space; these rooms are not required for the APS and may be used for storage, laboratories, or other Space Station activities. Sliding pressure doors are provided to isolate each room from the central transit and utility core.

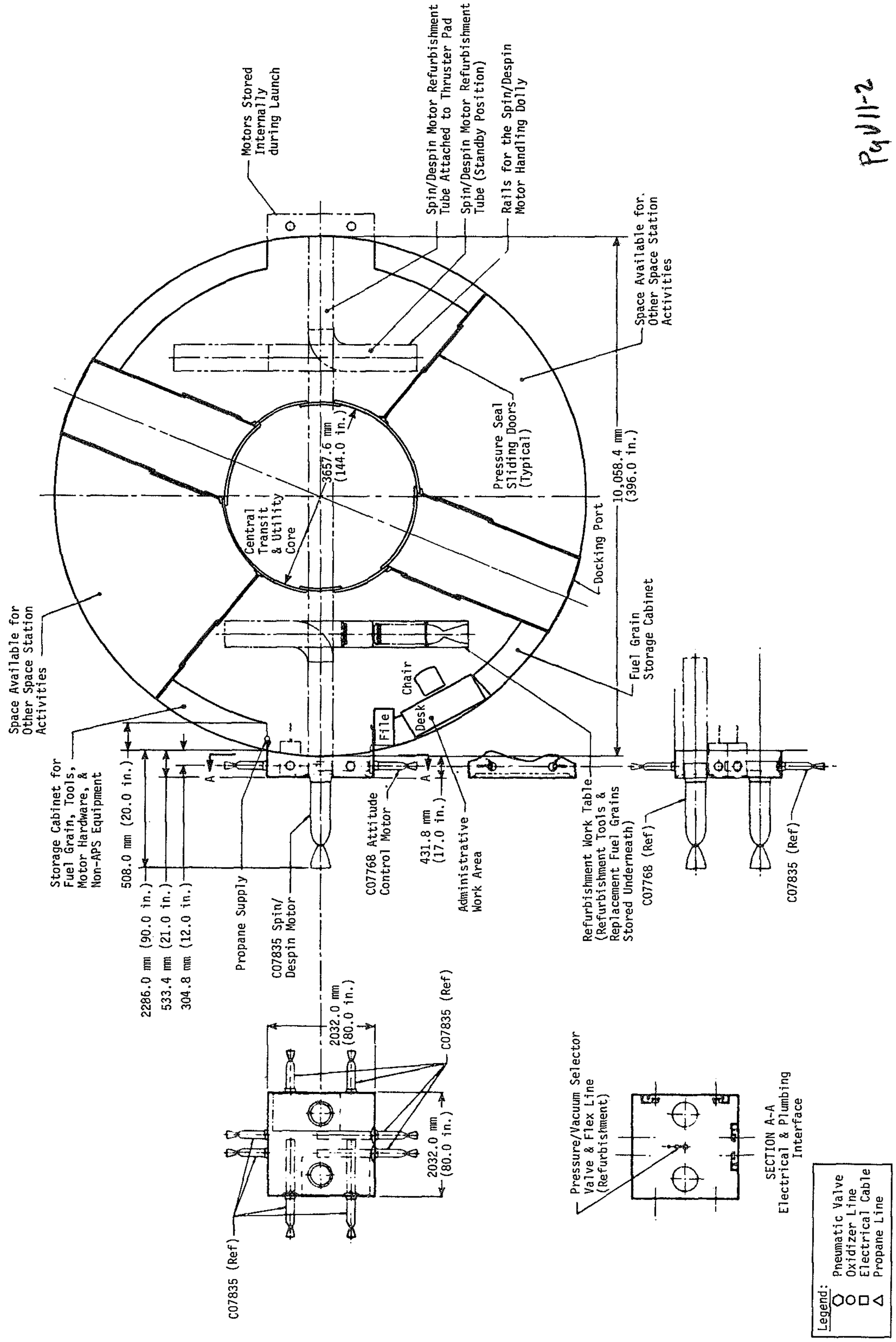

Fig. VII-1 Layout of APS Rooms

The APS rooms are designed around the thruster pads and the propulsion refurbishment work table. The large spin/despin motors are transported on a refurbishment dolly from the thruster pad to the refurbishment table. The dolly rides along tracks in the floor that hold it in place during periods of weightlessness. The tracks extend between the two APS rooms to transport the spin/despin motors from the spinup pad on one side of the Space Station to the despin pad on the other side. Present plans call for five spin/despin maneuvers during the first 18 months. Following these maneuvers, the spin/despin motors, the oxidizer feed system in the cargo module, the refurbishment dolly, and all spares and related hardware may be returned to earth. The onboard storage space may then be allocated to other experiments. The spin/despin motors can be carried from the thruster pad to the work table by one man since they only weigh 14.4 kg $\left(31.7 \text{ lb}_m\right)$ under 0.7-g conditions.

The refurbishment work table is the primary APS maintenance and repair station. This island work table stands 0.91 m (36 in.) above the floor and is accessible from all sides. The storage space underneath the work table holds spare and replacement parts, replacement fuel grains, and refurbishment equipment. Variable intensity lighting over the work bench can provide up to 200 ft-c of illumination for fine inspection tasks. The work table has two sets of recessed cradles to support the ACS motors and the spin/despin motors. It also has straps to hold the motors and the oxidizer tanks in place during refurbishment. The work bench has a compressed air source and a pressure gage for motor leak tests. This work bench acts as the central receiving and inspection station for all APS spare and replacement parts sent from earth. Following approval, all parts are stored for later use. The cabinet next to the work table holds fuel grains and spare parts that will not fit under the work bench.

The cabinets housing the OFA have shelves at the bottom to hold spares and the fluid removal and decontamination tool.

An administrative area is located convenient to the thruster pad, OFA, and the refurbishment work table. The administrative area contains a standard five-drawer file, a desk, and a chair. The desk is 76 cm (30 in.) off the floor, 56 cm (22 in.) deep, and 120 cm (40 in.) wide. All service and repair manuals, inventory records, and maintenance reports will be kept in the administrative files. The administrative desk could serve as a seated work bench. Therefore, it will be provided with 70 to 100-c illumination for administrative recordkeeping and with 150 to 200-c illumination for fine checkout or repair work, either on APS components or other Space Station hardware.

B. APS EQUIPMENT REQUIREMENTS

The equipment required for a hybrid APS are presented in this section. Motor components and spares are evaluated and divided into equipment required at launch and replacement parts to be resupplied during the life of the Space Station. Refurbishment equipment is discussed and conceptual designs are presented for the ACS and spin/despin refurbishment containers. The instrumentation system is evaluated and computer requirements are discussed.

1. Motor Component and Spares

Storage space is provided aboard the Space Station in the refurbishment compartment (see Section VII-A) for the storage of spare parts and replacement equipment. With the exception of O-rings, shear pins, and fuel grains, the motor replacement parts will be complete modular assemblies such as igniters, fluidic assemblies, and sparking assemblies. Replacement support equipment, such as valves, disconnects, electrical cable, seals, and tools, will also be provided as spare parts.

An important feature of the proposed APS system is that each component of hardware and each designed piece of equipment was selected with reliability as one of the important criteria. Consequently, spares have been kept to a minimum. Tables VII-1 thru VII-3 show the equipment and spares aboard the Space Station at launch. There will be a total of 21 Shuttle resupply flights, which means that refurbishment and replacement parts will generally be brought to the Space Station every 6 months. At least every 2 yr, each O-ring and seal will be discarded or replaced because of aging. The stored O-rings and seals will be replaced with fresh stock. When an item is replaced or refurbished, the older stocked item will be used first; thus, the spare and reserve parts will always be fresh.

2. OFA Components

Storage space for OFA spare parts and replacement equipment listed in Table VII-4 is provided onboard the Space Station.

Table VII-1 APS Motor Hardware Aboard Space Station at Launch

ITEM	ACS MOTORS			SPIN/DESPIN MOTORS		
	REQUIRED	SPARES	TOTAL	REQUIRED	SPARES	TOTAL
Case & Nozzle Assembly	16	2	18	3	--	3
Fuel Grain	36	0	36	6	1	7
O-Ring (Motor)	72	10	82	12	2	14
O-Ring (Motor-to-Pad)	72	10	82	6	2	8
Seal (Motor-to-Pad)	16	2	18	3	--	3
Shear Pins	128	12	150	48	6	54
Pin Safety Band	16	2	18	3	1	4
Igniter Assembly (Including Initiator)				6	1	7
Propane Bottle	6	1	7			
Injector	16	2	18	3	1	4
Fluidics Assembly	16	2	18			
Closure & Skirt Assembly	16	2	18	3	--	3
Pressure Transducer	32	3	35	6	2	8
Spark Ignition Assembly						
Electronics Package	16	2	18			
Induction Coil	16	2	18			
Spark Plug	36	2	38			
GOX Control Valve	16	2	18			

Table VII-2 Operational Support Hardware Aboard Space Station at Launch

ITEM	ACS MOTORS			SPIN/DESPIN MOTORS		
	REQUIRED	SPARES	TOTAL	REQUIRED	SPARES	TOTAL
LOX Control Valve				4	--	4
Backup GOX Shutoff Valve	4					
Oxidizer Line Disconnect Assembly	16	2	18	4	--	4
Three-Way Pressure/Vacuum Valve	2	1	3			
Instrumentation Electric Cable	16	2	18			
Igniter Command Signal Cable				4	--	4
Oxidizer Control Valve Command Signal Cable	16	2	18	4	--	4
Propane Line Disconnect Assembly	16	2	18			
Vacuum Line Disconnect Assembly				4	--	4

Table VII-3 Tooling Aboard Space Station at Launch

ITEM	ACS MOTORS			SPIN/DESPIN MOTORS		
	REQUIRED	SPARE	TOTAL	REQUIRED	SPARE	TOTAL
Door Assembly (Refurbishment)	1	1	2	4	--	4
Container Assembly (Refurbishment)	1	1	2	1	--	1
Dolly Assembly (Refurbishment)				1	--	1
Shear Pin Extractor	1	--	1	1	--	1
Micrometer Set	1	--	1			
Magnifying Glass	1	--	1			
Portable High-Intensity Light	1	--	1	1	--	1
Protective Covers						
Motor Port Holes (Launch)	16	1	17	4	1	5
GOX Line	2	2	4			
LOX Line				2	2	4
Propane Line	2	2	4			
Vacuum LIne				2	2	4
Electrical Connector	2	2	4	2	2	4
Seals						
Door Assembly	4	4(2)	10	8	2	10
Refurbishment Container	2	2(2)	6	1	1(2)	4

Table VII-4 OFA Hardware Aboard Space Station at Launch

ITEM	REQUIRED	SPARES	TOTAL
Pressurant Tank	4	--	4
Burst Disc	8		8
Check Valve (Relief)	12	4	16
Pressure Transducer	12	4	16
Fill Valve	8	2	10
Solenoid Three-way Valve	6	2	8
LOX Tank	4	--	4
Solenoid Valve	4	2	6
Quad Valve	4	2	6
Heat Exchanger	4	--	4
Filter	4	8	12
Regular	8	2	10

3. Motor Refurbishment Equipment

The ACS and spin/despin motor system and refurbishment equipment used aboard the Space Station will be maintained in accordance with MIL-STD-470, *Maintainability Program Requirements*. The equipment provided aboard the Space Station is designed for use by Space Station crews in accordance with MIL-STD-1472, *Human Engineering Design Criteria for Military Systems, Equipment, and Facilities*.

To provide a shirtsleeve environment in the refurbishment work area, a removable refurbishment container concept was selected and designed for use aboard the Space Station. The concept makes use of a door assembly, a container assembly, and for the larger spin/despin motor, a handling dolly. Figure VII-2 shows the door assembly and container for both the ACS and spin/despin motors.

a. Door Assembly - The door assembly consists of a sealed frame that attaches to the motor pad and a sliding door that seals the motor port hole. One door assembly is used in refurbishing the ACS motors. The door assembly is attached and removed during the refurbishment process. Since there are only four spin/despin motor mounts (two on each side of the Space Station), each spin/despin mount has its own permanentaly mounted door assembly.

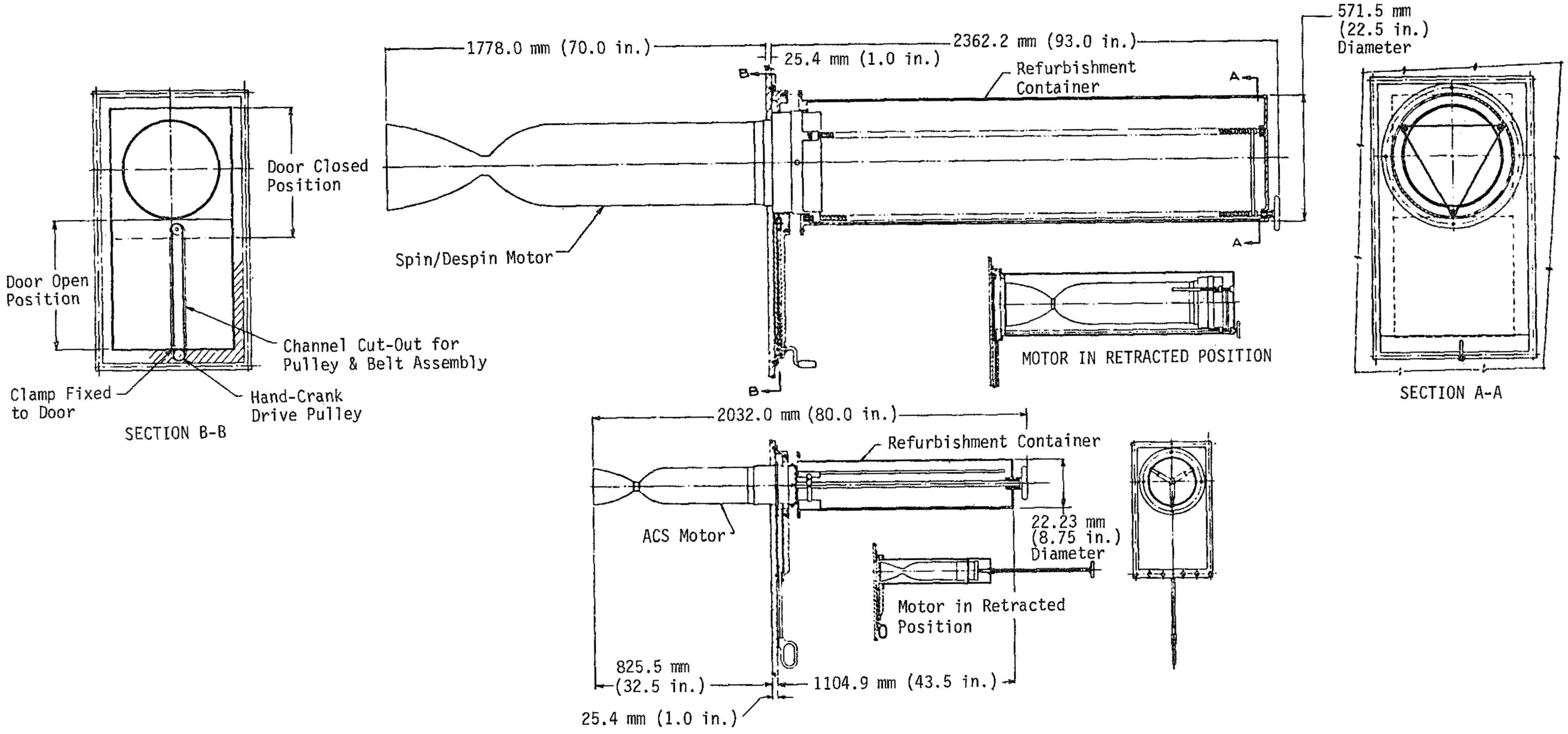

Fig. VII-2 Door Assembly and Container for ACS and Spin/Despin Motors

The sliding door moves on rollers, eliminating a side load on the door seal. Notches are provided on the motor pad that mate with the door rollers when the door is in the closed position. Space Station pressure seats the rollers in the notches, enabling the door seal to seat against the motor pad and seal the port hole.

The ACS door is pushed into position through a push-pull handle. The spin/despin door is positioned through a control crank and a chain driven assembly. The design of the assembly is similar to a clothes line: the chain is fixed to the door and passes around the crank at one end and a pulley on the other end; as the crank is turned, the door moves into position. The door rides in a channel to guide it in a straight path.

The door assembly attaches to the motor pad through a rectangular bolt pattern of latches that lock into position. The size of the door assembly is as follows:

MOTOR	WEIGHT	LENGTH	WIDTH	THICKNESS
ACS Motor	6 kg (14 lb)	635 mm (25 in.)	375 mm (14.75 in.)	51 mm (2 in.)
Spin/Despin Motor	61 kg (135 lb)	1295 mm (51 in.)	724 mm (28.5 in.)	51 mm (2 in.)

b. Container Assembly - The container assembly used with the ACS motors consists of a case, an attach ring, and a push-pull rod. The container has two seals -- one on its surface that mates with the door assembly, and another around the push-pull rod. The case connects to the door assembly through a circular pattern of latches that lock into position. The ring is attached by eight shear pins to the forward closure skirt assembly. The push-pull rod retracts or extends the motor about the container case. A three-rail track inside the case ensures the proper operation of the motor during the retraction and extension operation. A pressure/vacuum gauge is mounted on the side of the container to indicate the pressure within the container. The ring assembly extends 38 mm (1-1/2 in.) past the end of the case, allowing connection to the motor forward closure.

The spin/despin motor container is basically the same as that for the ACS motor container, but is larger and has a more elaborate retraction and extension mechanism. The retraction/extension mechanism consists of three chain-driven ball screws that drive a ring assembly attached to the motor forward closure by 16 shear pins. The hand crank at the bottom of the container moves the motor in and out of the container. The size of the container assembly is as follows:

MOTOR	WEIGHT	LENGTH	DIAMETER
ACS Motor	8 kg (18 lb)	1118 mm (44 in.)	222 mm (8.75 in.)
Spin/Despin Motor	83 kg (184 lb)	2286 mm (90 in.)	572 mm (22.5 in.)

c. Dolly - To facilitate the handling of the spin/despin motor and its refurbishment container, a handling dolly is provided. This dolly runs within a track system on the floor of the refurbishment compartment. Its legs are hydraulically operated, allowing the dolly to be raised or lowered for positioning to the motor pad. The container is easily latched to the dolly. The dolly weight 34 kg (75 lb).

d. Small Hand Tools - A tool kit, consisting of small hand tools and inspection equipment, will be provided to facilitate disassembly, inspection, and assembly of the ACS and spin/despin motors. Tools peculiar to the ACS and spin/despin motors are described below.

Pin Extraction Tool - All pins used in the assembly of the motor and the refurbishment tube are interchangeable. Each pin has a special hole in its head for the pin extraction tool. The end of the tool contains four spring-loaded fingers that expand when the tool handle is pumped. Once expanded, the tool is locked to the pin. The pin can be installed or extracted with the tool. A release mechanism releases finger tension and the tool disengages from the pin.

Micrometer Set - Micrometers are used to inspect the throat and exit diameters of the nozzle. All pin attachment holes are also checked for elongation.

Magnifying Glass - A magnifying glass is used to inspect the motor case, nozzle, and closure for cracks and deformation.

High-Intensity Light - A portable high-intensity light will be used during visual motor inspection. The light provides an emergency light source in case of a power failure.

Vacuum-Tube Voltmeter - A vacuum-tube voltmeter will be used to verify electrical circuits during refurbishment and to troubleshoot an electrical circuit during a malfunction.

Protective Covers - A set of protective covers is included in the tool kit. These covers are used to seal the ACS and spin/despin motor port holes during launch. Other covers are used to protect plumbing and electrical connectors during disassembly for refurbishment.

4. OFA Refurbishment Equipment

The OFA will make use of the tool kit being developed as astronaut support equipment under Contract NAS8-26448.* The tools comprising the inflight maintenance tool kit are presented in Table VII-5. A schematic of the fluid removal device is shown in Fig. VII-3.

After careful consideration of the various methods available for fluid removal, a method was selected that uses the mechanical fittings on the system plus complete fluid removal by a hand suction pump. The hand pump withdrawal device is first clamped to fitting, B, then fittings A and B are backed off, allowing fluid to be removed (by suction) from the system at fitting B, directed into the hand pump, and from there to the waste storage tank. Provisions are included for refilling the system after component removal. This method does require that the system be shut down and depressurized before maintenance is performed.

The leak seal repair kit is used to repair and seal external leaks in the fluid systems. It is composed of Grade T primer; anaerobic adhesive; self-vulcanizing silicon tape; Teflon tape. The leak seal repair kit will have to be modified to handle cryogens.

5. Instrumentation and Computer

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

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

***Modification of an Astronaut's Mock-Up Tool Kit.* MCR-70-383 (Issues 3 and 4), Monthly Status Reports for November 1970 and December 1970. Martin Marietta Corporation, Denver, Colorado, December 1970 and January 1971.

Table VII-5 Integrated Tool List, Inflight Maintenance Tool Kit

TOOL KIT ITEM	ADDITIONAL CRITERIA
Standard Equipment	
Screwdrivers	
Standard Tip, with 3/16-in. wide, 4-in. Blade	
Standard Tip, with 1/4-in. wide, 4-in. Blade	
Phillips Tip, with No. 2, 4-in. Blade	
Socket-Type Tools	
3/8-in. Square Drive Ratchet Handle	30 tooth 8-in. maximum length
Speed Handle	14-in. maximum length
Straight Torque Wrench (5-50 in.-lb)	6-in. maximum length
Torque Wrench (5-150 in.-lb)	Ratchet Type
3/8-in. Square Drive Extensions	
12-in. long	
8-in. long	
4-in. long	
3/8-in. Square Drive Universal Joint	
3/8-in. Square Drive Standard Sockets	
1/4-in. Double Square	
3/8-in. Hexagonal	12 point
7/16-in. Hexagonal	12 point
1/2-in. Hexagonal	12 point
9/16-in. Hexagonal	12 point
5/8-in. Hexagonal	12 point
11/16-in. Hexagonal	12 point
3/8-in. Deep Sockets	12 point
3/8-in. Hexagonal	
7/16-in. Hexagonal	
1/2-in. Hexagonal	
9/16-in. Hexagonal	
Screwdriver Bits, 3/8-in. Square Drive	
High-Torque, No. 1	
High-Torque, No. 2	
Standard Screwdriver Tip, 1/2-in. Wide	1/16 tip 3½-in. maximum length
Standard 1/16-in. Hex Driver	1-in. Shank
Standard 5/64-in. Hex Driver	1-in. Shank
Standard 3/32-in. Hex Driver	3½-in. Shank
Standard 1/8-in. Hex Driver	2-in. Shank
Standard 5/32-in. Hex Driver	2-in. Shank
Standard 3/16-in. Hex Driver	2-in. Shank
Standard 1/4-in. Hex Driver	2-in. Shank
Standard 5/32-in. Square Head	2-in. Shank
Hand Wrenches	
Double Hex, Flank Drive Wrenches	
Long-handled 5/16-in. Combination	6-in. Maximum Length
Flare Nut, 3/8x7/16-in. Double End	7-in. Maximum Length
Flare Nut, 1/2x9/16-in. Double End	8-in. Maximum Length
Flare Nut, 5/8x11/16-in. Double End	8-in. Maximum Length
Open/Box End, 3/8-in. Combination	6 9/16-in. Maximum Length
Open/Box End, 7/16-in.Combination	7 3/32-in. Maximum Length
Open/Box End, 1/2-in. Combination	7 21/32-in. Maximum Length
1 1/8-in.-Capacity Adjustable Wrench	10-in. Maximum Length
3/16-in., 90-deg Hexagonal Allen Wrench	1/2-in. Maximum Length
Pliers	
Needle Nose (Pin-Gripping)	7 15/16-in. Maximum Length
Electrical Connector	10-in. Maximum Length
Channel Lock-Type	
Common Slip-Joint	8-in. Maximum Length
Vise Grip	7-in. Maximum Length
Diagonal Cutter	6-in. Maximum Length
Wire Stripper/Crimper	
Electrical Pin Crimper	
Miscellaneous Tools	
Pin Straightener	
Brass 8-oz Hammer	
Brass Tapered Punch	
Flex Grip-it Tool, 17-in. Maximum Length	
Portable Multimeter	
Inspection Mirror, 12-in. Maximum Length	
16-in. Pinch Bar	
Inserter/Removal Contact Tool	12 ga wire
Inserter/Removal Contact Tool	16 ga wire
Inserter/REmoval Contact Tool	20 ga wire
O-Ring Extractor	
Special Equipment	
Tags, unserviceable condition	
General-Purpose Rag	
Penlight	
Stowage-Locker Latch Release Tool	
Clamp-Type Bench Vise with 2-in. Jaw	
4-in. C-Clamp	
Seal Assembly	
Hatch-Opening Lever Assembly	
Experiment Wrench, 3/8-in. Square Drive Handle	
Tape Measure	
Consumables	
0.032-in.-Diameter Safety Wire	100 ft
Pressure-Sensitive Tape	3/4-in.
Pressure-Sensitive Tape	2-in. x 50 yd
Stranded No. 20 Electrical Wire	50 ft
Stranded No. 16 Electrical Wire	50 ft
Stranded No. 12 Electrical Wire	50 ft
Wire Terminals (Miscellaneous Sizes & Types)	
Electrical Tie Cord	200 ft
Velcro Strip, 1-in. Width, pile	60 in.
Velcro Strip, 1-in. Width, hook	60 in.
Miscellaneous Support Equipment	
Scissors	
Tool Tether	
Spares Translation Carrier	
Translation-Kit Tether	
Task Procedures	
Small Parts Retension Device	
Tool Carrier	
Leak Detector	
Liquid Leaks Repair Kit	
Fluid Removal Device	
Flexible Retention Device	

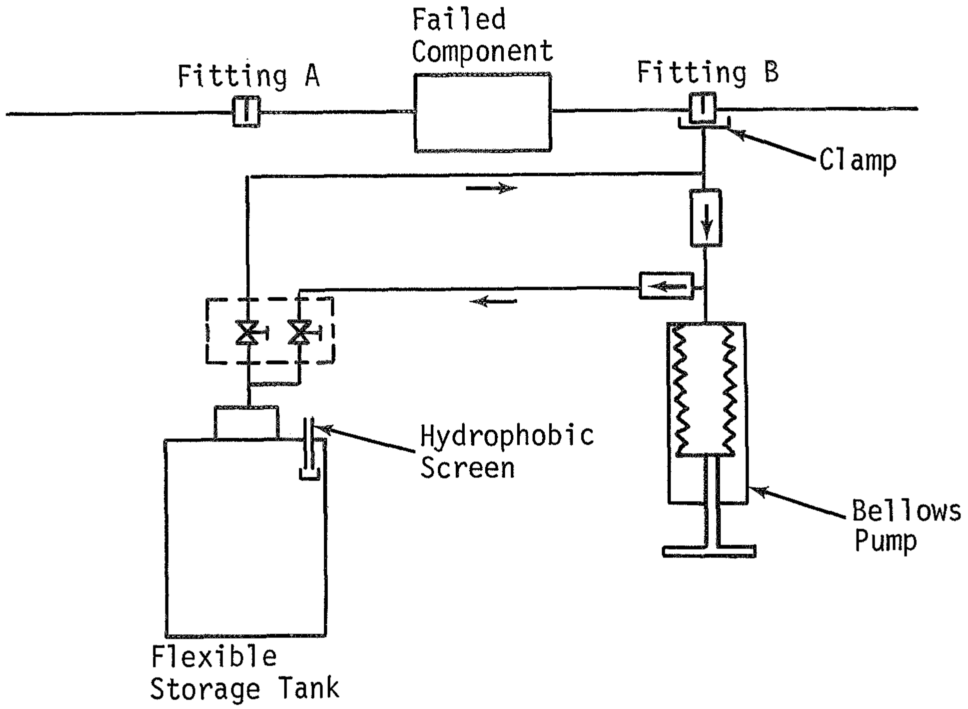

Fig. VII-3 Fluid Removal Technique

The selected instrumentation system for each TCA uses two pressure transducers -- one to measure chamber pressure and one to measure thrust -- and trip wires to signal fuel depletion. These three measurements provide primary detection at all operational motor failures. As shown in Table VII-6, there is redundant detection of most failures.

The instrumentation required for the OFA consists of four pressure transducers per module. These provide for detection of all failures. These transducers are located downstream of the pressurant tank, downstream of the LOX tank, downstream of the regulators, and downstream of the vaporizer.

Thrust measurement is accomplished by measuring the hydraulic pressure in a fluid-filled O-ring on the motor flange. During standby operation, the pressure in this O-ring can be calibrated with internal cabin pressure, which holds the motors firmly in place. Since the motor thrust is only about 10% of the force exerted by cabin pressure, the accuracy of the thrust measurement is only about ±5%. However, this is more than sufficient to provide secondary malfunction detection of most failures, as well as primary detection of an exit cone burnthrough, which is one of the least probable failure modes.

Table VII-6 Malfunction Detection

	DETECTION METHOD*		
MOTOR OPERATIONAL FAILURE MODES	CHAMBER PRESSURE	THRUST	FUEL TRIP WIRES
Ignition Failure	P	S	
Injector Failure†	P	S	
Motor Seal	P	S	S
Fuel Depletion	S	S	P
Aft Closure Burnthrough	P	S	
Throat Erosion	P	S	
Exit Cone Burnthrough		P	
OFA Failure Modes			
Tank Leak	P		
Valve Sticks	P		
Flowrate	P		

*P = Primary detection method; S - Secondary detection method.

†Primarily on spin/despin motors.

A tripwire circuit emplanted in the phenolic fuel cartridge was selected as the primary fuel depletion indicator. A secondary indicator is the chamber pressure and thrust. These will fall off sharply 5 to 10 sec after the tripwire indicates fuel depletion, this secondary indication involves some risk of damage to the $MoSi_2$ coating, especially in the spin/despin motor.

The Bell & Howell/Consolidated Electrodynamics type 4-312-0001 strain gage pressure transducer was selected on the basis of its small size, light weight, and rugged operating characteristics. This transducer has a 0-1034 kN/m^2 (0-150 psia) pressure range with a ±0.50% combined linearity and hysteresis. It operates over a calibrated temperature range of 220°K (-65°F) to 395°K (250°F) with a frequency response of 17 kHz (frequency response is not particularly important for a hybrid APS due to its stable burning characteristics).

The conceptual hybrid APS can achieve high reliability and safety without extensive computer facilities. Monitoring for maximum and minimum values of chamber pressure, tank pressure, and thrust, along with a continuity check for fuel depletion, are the only required automatic MDS requirements during APS operation. Out-of-tolerance conditions would signal a red light if the APS is under manual control since there are no failure modes that require fast response automatic shutdown. If automatic firing is desired, a more elaborate logic loop with an APS shutdown and switching capability would be needed. Automatic trend analysis is of questionable value, considering the reliability of the present system. However, automatic strip recordings of each burn would be useful at refurbishment time as an aid to motor inspection.

It might be wise to use a simplified form of the onboard checkout and monitoring system being developed for the Space Shuttle propulsion systems.* This study is evolving an approach for onboard checkout performance monitoring, emergency detection, and postflight evaluation. An overview of a potential approach is presented below.

a. <u>Preflight Checkout</u> - Preflight checks will be performed only to verify that, after ground operations, all equipment is in the correct condition for propellant servicing and for start, and to establish an acceptable level of confidence in instrumentation. Functional tests will not be conducted to verify operating performance prior to start. This approach assumes that factory acceptance tests and monitoring during ground servicing operations have verified performance capability and that the instrumentation has been brought to acceptable confidence levels. The rationale for this assumption is that if equipment performed correctly throughout its last normal operating cycle (without evidence of failure, degradation, over-stress, or approach of end of normal lifetime), then no significantly greater confidence that it will again perform correctly can be obtained by testing. In fact, since the stresses on propulsion subsystems are primarily self-induced, tests requiring actual subsystem operation would decrease system life. Dry-system functional tests would

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***Space Shuttle Propulsion Systems OnBoard Checkout and Monitoring System Development Study*. MCR-70-274 (Issue 2), Contract NAS8-25619, DRL No. 187, Rev A, Line Item 2. Martin Marietta Corporation, Denver, Colorado, December 1970.

require considerable simulation, would not be realistic in the absence of normal stresses, and would provide little additional confidence over that obtained by leakage checks and by monitoring ground servicing operations such as purging and propellant loading.

Applicable condition indicators will be monitored and evaluated by onboard equipment during ground operations to detect emergencies, detect and isolate faults, analyze trends, and indicate operating-state history.

b. Inflight Monitoring - Performance and condition-indicating parameters will be monitored and evaluated by onboard equipment during and after engine start and during flight. No vehicle-to-ground interface will be used, other than voice communication. The data acquired by monitoring will be processed during flight to:

1) Verify that the system is ready to start;
2) Detect emergencies;
3) Detect and isolate faults;
4) Analyze trends in real-time;
5) Indicate operating-state history;
6) Record performance data.

Ready-to-Start Condition Verification - Appropriate onboard monitoring and evaluation logic will be provided to verify that all applicable equipment is in the correct condition to start whenever an abortive start might result in equipment damage, unsafe conditions, or the need to offload propellants. Monitoring parameters will include applicable valve positions, pressures, temperatures, etc.

Emergency Detection - Appropriate onboard monitoring and processing logic will be provided to detect and provide caution and warning indications for the following conditions:

1) Loss or impending loss of major functions;
2) Flight safety parameters exceeding safe limits;
3) Redundancy reduced to safe level;
4) Hazardous leakage.

Fault Detection and Isolation - Fault detection and isolation logic will be accomplished through onboard monitoring and evaluation, to the extent that failures are identified and isolated. Fault isolation will be accomplished as soon after detection as is necessary to identify lost redundancy and to initiate corrective or safing action when applicable. In cases where no redundancy exists and where corrective or safing action is taken in response to failure detection only, diagnosis for fault isolation may be performed on stored data at a later time.

The rationale for taking all data for isolation of inflight failures during or immediately after detection of the condition is that in many cases the operating conditions and actual sequence of events before, during, and after the failure must be known in order to discriminate between cause and effect. Also, transient or intermittent faults may not be isolatable in later tests without resorting to a highly realistic simulation of conditions and events.

Real-Time Trend Analysis - Trend analysis will be performed on elements known to exhibit measurable symptoms of impending malfunction, provided they are not fail-operationally redundant and provided failure is likely to cause significant secondary damage. Analysis will be performed in real time if corrective action is available in flight or if caution and warning is necessary when a failure is probable.

This approach constrains the extent of trend analysis to a realizable and economically reasonable level. Without these constraints, the quantities of measurement channels, data storage capacities, and processing loads became significantly more difficult to justify on the basis of improving the probability of mission success.

Operating-State History - Where correlation exists, or is likely, between a line replacement unit's performance and its operating time, stresses, number of on/off cycles, number of revolutions or strokes, or combinations of these, a history of operation of the line replacement unit will be maintained in computer storage. When the unit's operating history exceeds its operational lifetine, a postflight printout will provide notification of required replacement.

These operating histories will not be continuous, but will be periodic or on-condition updated totals of the accumulated time, cycles, etc, either at discrete states (on, standby, etc) or at discrete stress levels (20% overtemperature, for example).

Replacement based on statistical correlation of performance and operating history is a particularly valuable approach in cases of identical redundant LRUs having a strong correlation of performance with operating history. The stronger the correlation, the higher the probability that all of the identical units will fail during the same flight.

Performance Data Recording - Performance data will be acquired and recorded only during times of possible activity of interest. Various data compression techniques can be used to further reduce the quantity of recorded data. However, accomplishing any significant amount of compression either greatly overloads the computers during peak processing times and requires considerable additional data storage capacity to temporarily hold data until they can be processed for compression, or requires an additional computer dedicated to data compression. The selected approach is to provide enough recording capacity to store the required uncompressed data in a suitable format and to suitably identify the data as to time and parameter to allow efficient processing for reduction and evaluation.

c. Display - The types of information to be displayed are:

1) Operator or crew instructions, such as procedures for manual operations or checkoffs, both on the ground and during flight;
2) System status, such as operating modes and redundancy levels;
3) Propellant quantities and consumption rates;
4) Malfunction detection or prediction notification and identification, both during ground operations (when personnel are onboard) and during flight (when corrective action by the crew is possible);
5) Caution and warning indications;
6) Postflight printouts of maintenance data.

C. ASSEMBLY, MAINTENANCE, AND REPAIR PROCEDURES FOR THE TCA

Scheduled maintenance will be performed during motor refurbishment. All hardware will be designed on this philosophy. During refurbishment, the motors will be inspected and cleaned, the O-ring seals will be replaced, the electrical connections and plumbing lines will be checked, the motors will be reloaded with new fuel grains, and pyrogen igniter will be installed on the spin/despin motor. The components use modular designs so that when a malfunction occurs, the complete part or unit is replaced rather than repaired. After replacement, the part or unit can either be discarded, returned via a Shuttle to a flight command center for repair, or repaired aboard the Space Station. Space Station repair will be kept to a minimum and will consist of making adjustments or calibrations, rather than making repairs.

The ACS motors will be refurbished after 6.5 minutes of operation, and the spin/despin motors, after 15 minutes of operation. Refurbishment deals with five main operations:

1) Disassembly;
2) Removal;
3) Refurbishment;
4) Installation;
5) Reassembly.

Table VII-7 summarizes the steps involved in performing the the above five operations. Figure VII-4 presents a pictorial presentation of the refurbishment task. The following discussion will consider refurbishment both for the ACS motor and the spin/despin motor.

1. Motor Refurbishment Task

The motor has completed its operation and the firing control console indicates the fuel grain has been consumed. Refurbishment will be scheduled and performed at the crew's convenience.

a. Disassembly - Disassembly begins while the motor is cooling. Before disconnecting the motor, the crew will don protective gloves and eye shields, and verify that all motor systems are inoperative and in a safety position. The GOX oxidizer line and the propane ignition line will be disconnected at their quick disconnects (the LOX oxidizer line and LOX vacuum-jacketed line will be disconnected). The electric cable will be unplugged from the forward closure, and the motor safety latch system will be removed.

Table VII-7 Refurbishment for APS Motors

DISCONNECT	REMOVE	REFURBISH	INSTALL	CONNECT
1. GOX Line (LOX Line)	1. Attach Container	1. Detach Forward Closure (& Remove Container/ Dolly Assembly)	1. Attach Container to Door Assembly	1. Motor Safety Latch
2. Propane (Vacuum Line)	2. Evacuate	2. Inspect	2. Evacuate & Pressure-Check	2. Electric Cable
3. Electric Cable	3. Pressure/Leak Test	3. Remove Residual Material & O-Ring	3. Open Door & Extend Motor	3. Propane (vacuum Line)
4. Motor Safety Latch	4. Retract Motor & Close Door	4. Install Grain & O-Ring	4. Equalize Station/ Container Pressure	4. GOX Line (LOX Line)
	5. Equalize Station/ Container Pressure	5. Attach Forward Closure (& Position Container/ Dolly Assembly)	5. Remove Container (& Dolly Assembly)	
	6. Remove & Position on Refurbishment Table	6. Pressure Check		

Operations in parentheses refer to the spin/despin motor only and replace items on the same line that are for the ACS motor.

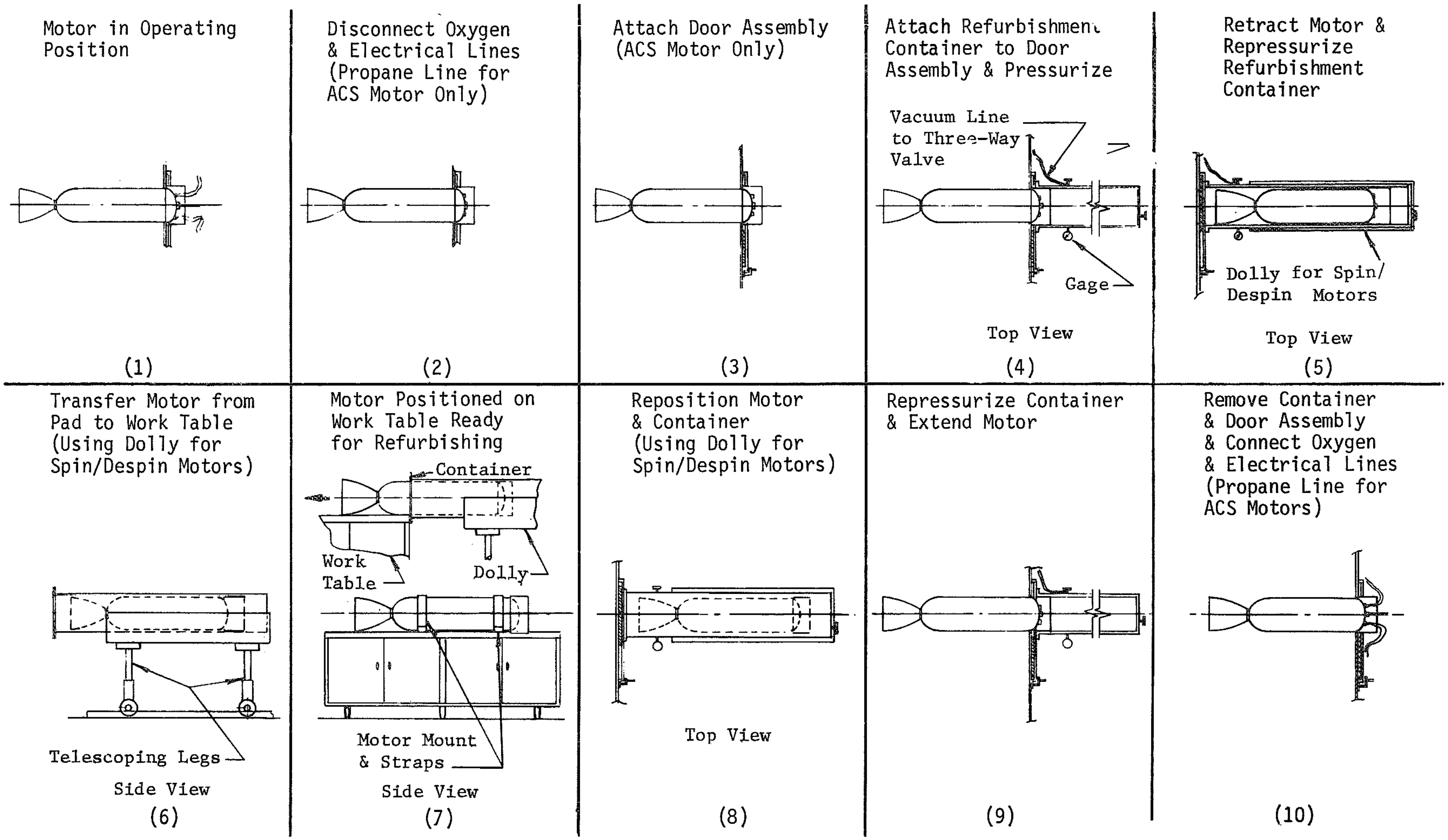


Fig. VII-4 Refurbishment of APS Motors

The motor is now being held in position on the pad due to the Difference between the Space Station pressure of 70 kN/m^2 (10 psia) acting against the forward closure assembly and the vacuum pressure acting on the motor case; this creates a force of 1645 N (380 lb) to hold the ACS motor in position. [For the spin/despin motor, this creates a force of 7870 N (1770 lb) to hold the motor in position.] Dust caps are installed on both the pad and motor connectors after disassembly to prevent contamination of the GOX (LOX) or propane (vacuum) lines and to protect the pin connectors on the electrical cable.

b. Removal - The first step in the removal operation is to install the door assembly. Before installing the door assembly, the door seal is checked for any discrepancies and the door operation checked for ease and smoothness of operation. The door assembly is positioned under the motor and bolted to the motor pad through a pattern of quick connect latch connectors that are locked in position.

The refurbishment container assembly is checked for seal integrity and for smoothness of retraction mechanism. The retraction assembly contains a ring that attaches to the motor forward closure, a push-pull rod, and a track assembly to guide the motor into the refurbishment container. The attachment ring extends about 38 mm (1½ in.) past the end of the container to allow pinning of the ring to the forward closure. Four (eight) pins are used to hold the ring to the closure. Using the motor for leverage, the refurbishment container is moved into position and bolted to the door assembly through a pattern of quick connect latches that are locked in position.

The removal procedure for the spin/despin motor is basically the same as that for the ACS motors, but the door assembly and the refurbishment container for the spin/despin motors are slightly different. For the spin/despin motor, the door assembly is permanently mounted and the door operated by a chain-driven pulley assembly. The retraction mechanism uses an attachment ring traveling on three chain-driven ball screws. The container assembly rides on a dolly that operates on a track system on the floor of the refurbishment room. The legs of the dolly are hydraulically operated so that the refurbishment container can be exactly positioned to the height of the spin/despin motor during the attachment procedure.

A three-way pressure/vacuum valve is connected to the refurbishment container via a flexline and the container is evacuated. Vacuum is held for one minute and the container seal is checked for integrity (a vacuum/pressure gage on the wall of the container indicates any leakage). If there is vacuum leakage, the seal between the container and the door assembly and the seal at the push-pull rod will be checked to determine which seal (or seals) need replacement. Before replacing seals, the pressure in the container is equalized to the ambient Space Station pressure through the three-way pressure/vacuum line. If the container/door seal needs replacement, the container will be disassembled from the door assembly and the seal will be replaced. The push-pull rod seal can be replaced while the container is attached to the door assembly. After seal replacement and reassembly, the seal is again vacuum-checked.

With vacuum existing at both ends of the motor, one crew man pulls the pull rod, which, in turn, retracts the motor into the refurbishment container. Then the pull rod is locked in position and the door is pushed across the motor port hole to seal it. (The sliding door assembly has rollers that facilitate door operation and allow the door to be moved without dragging on the seal. Notches are provided on the motor pad that mate with the rollers on the door assembly. When the door assembly reaches the proper position, the rollers mate with the notches and the door seal comes in contact with the motor pad.) Pressure is allowed to build up in the container through the three-way pressure/vacuum valve until the pressure within the container reaches the level within the Space Station. This prevents contamination of the LOX or vacuum lines and protects the pin connectors on the electrical cable.

Once the door assembly is in position and sealing, the vacuum line is disconnected. The container holding the retracted motor is unlatched from the door assembly, positioned on the dolly, and transported to the refurbishment table. The pushrod (ball/screw hand crank) is unlocked, and the motor is extended out of the container and strapped to the refurbishment table. The refurbishment container assembly is removed and stored during refurbishment. For the spin/despin motors, the motor case is fastened to the refurbishment table with the closure attached to the refurbishment container.

c. Refurbishment - The forward closure is disassembled from the case by removing the pin safety band and the eight pins holding the closure to the case. The closure is placed on a special refurbishment fixture and the spark plug for igniting the ACS motor is removed and replaced. Unused fuel grain material is removed from the case and the closure-case O-ring is discarded. An inspection is made to determine nozzle throat erosion, nozzle exit cone integrity, and case integrity. The forward closure is inspected and checked for pin hole elongation, electrical connector continuity, GOX (LOX) line injector integrity, and propane (vacuum) line connector integrity. The motor pad GOX (LOX) and propane (vacuum) flex lines are checked for discrepancies. A continuity check is given to the electrical cable, verifying circuit operation.

During refurbishment, all discrepant, malfunctioning hardware will be replaced and a fresh hybrid fuel grain will be assembled into the motor case. A new closure-to-case O-ring is installed and the closure is assembled to the case. At this time, the fuel depletion electric wire is connected to an internal plug. The closure is attached to the case with eight shear pins and the pin safety band is installed.

After assembling the forward closure to the case, a pressure check is performed to verify the integrity of the motor O-ring seal. An internal motor presure of 1034 kN/m^2 (150 psia) is maintained for 1 minute. If the O-ring fails, it is replaced and the motor is retested.

A special seal is provided between the motor and station motor mount. This seal is filled with a nonflammable, noncompressible fluid and is used with a pressure transducer to indicate motor thrust. This seal is located on the forward closure skirt and is inspected at refurbishment. A special testing device is used to verify proper operation of the thrust sensing assembly and to verify its ability to seal. If a replacement is necessary, the seal and pressure transducer are replaced as a unit and retested.

d. Installation - After the motor assembly is completed and the refurbishment container ring is attached and pinned to the forward closure, the motor is unstrapped from the refurbishment table and retracted into the refurbishment container using the container pull rod. Then the rod is locked in the retracted position. The refurbishment container with the retracted motor is positioned and attached to the door assembly. The three-way pressure/vacuum line is attached to the container assembly and the container is evacuated and held under vacuum for 1 minute. If unacceptable pressure leakage is noted, either the container-to-door seal or the retraction mechanism seal will be replaced. If the container-to-door seal needs replacement, the container will have to be unlatched from the door assembly. The retraction seal can be replaced with the container attached to the door. Before seal replacement, the container will be repressurized to the level within the Space Station. After seal replacement, the container is again evacuated and the seals are checked.

With the container holding vacuum, the door is opened, exposing the motor mount port hole. The motor is extened into operating position. With the motor in its operating position, the container is pressurized and maintained at Space Station pressure for 1 minute. If leakage is indicated by the container pressure gage, the motor/station seal will be replaced as previously described. After seal replacement, the container is again pressurized to cabin pressure and checked for leakage.

With the motor extended into its operating position the container can be removed. First the three-way pressure/vacuum valve is disconnected. Then the container is unlatched from the door assembly and allowed to slide 38 mm (1½ in.) down the retraction mechanism, exposing the pins attaching the container ring to the closure. The pins are removed and the container assembly is withdrawn from the motor. As a final step for the ACS motor, the door assembly is unlatched from the motor pad and removed.

The spin/despin motor is installed using the same procedure as described above for the ACS motor. The hydraulically operated legs on the dolly assembly position the motor for installation to the motor pad. After motor installation, the dolly and container assembly are removed. The door assembly is not removed (because of its size and weight), but remains installed under the motor.

e. Reassembly - The final operation in the refurbishment task is to connect the motor pad plumbing and electrical connections. All dust and protective covers are removed and the GOX (LOX) oxidizer line, the propane ignition (vacuum) line, and the electrical cable are connected and locked in position. As previously mentioned, a force of 1645 N (380 lb) holds the ACS motor in the operating position due to the pressure difference between the vacuum of space and the pressure within the Space Station. The corresponding force for the spin/despin motor is 7870 N (1770 lb). As an added safety feature, the motor is latched to the motor pad, providing a positive attachment if Station pressure is lost during flight.

D. ASSEMBLY, MAINTENANCE, AND REPAIR PROCEDURES FOR THE OFA

Table VII-8 shows the order of operation for all assembly, maintenance, and repair procedures for the selected OFA.

Table VII-8 Repair Procedures for Oxidizer Feed Assembly

PRESSURANT MODULE

Burst Disc or Relief Valve

1. Isolate Failure
2. Remove Vent Line
3. Remove Base Fitting
4. Remove & Store Part
5. Install New Part
6. Attach Base Fitting
7. Attach Vent Line

Pressurant Tank

1. Isolate Failure
2. Remove Fill Line
3. Remove Relief Line
4. Remove Transfer Line
5. Remove Four Quick-Release Fasteners
6. Remove & Store Tank
7. Install New Tank
8. Attach Four Fasteners
9. Attach Transfer Line
10. Attach Relief Line
11. Attach Fill Line

Three-Way Valve

1. Isolate Failure
2. Bleed Down Pressurant
3. Remove Pressure Transducer
4. Remove Transfer Line to Oxidizer Tank
5. Remove Crossover Line
6. Remove Electrical Line
7. Remove Bolts Holding Three-Way Valve in Place
8. Remove & Store Valve
9. Install New Valve
10. Attach Retaining Bolts
11. Attach Electrical Line
12. Attach Crossover Line
13. Attach Transfer Line to Oxidizer Tank
14. Attach Pressure Transducer

Pressure Transducer

1. Isolate Failure
2. Bleed Down Pressurant
3. Remove Electrical Line
4. Remove Transfer Line
5. Remove Transducer from Valve Fitting
6. Remove & Store Transducer
7. Install New Transducer
8. Attach Transducer to Valve Fitting
9. Attach Transfer Line
10. Attach Electrical Line

OXIDIZER MODULE

Oxidizer Tank

1. Isolate Failure
2. Remove Pressurant Line
3. Remove Transfer Line
4. Remove Relief Line
5. Remove Fill Line
6. Remove Six Quick-Release Fasteners
7. Remove & Store Tank
8. Install New Tank
9. Attach Six Fasteners
10. Attach Fill Line
11. Attach Relief Line
12. Attach Transfer Line
13. Attach Pressurant Line

Burst Disc or Relief Valve

1. Isolate Failure
2. Remove Vent Line
3. Remove Base Fitting
4. Remove & Store Part
5. Install New Part
6. Attach Base Fitting
7. Attach Vent Line

Three-Way Valve

1. Isolate Failure
2. Bleed Down Oxidizer
3. Remove Pressure Transducer Fitting
4. Remove Transfer Line to Control Components
5. Remove Crossover Line
6. Remove Electrical Line
7. Remove Bolts Holding Three-Way Valve in Place
8. Remove & Store Valve
9. Install New Valve
10. Attach Retaining Bolts
11. Attach Electrical Line
12. Attach Crossover Line
13. Attach Transfer Line to Control Components
14. Attach Pressure Transducer

Pressure Transducer

1. Isolate Failure
2. Bleed Down Oxidizer
3. Remove Electrical Line
4. Remove Transfer Line
5. Remove Transducer from Valve Fitting
6. Remove & Store Transducer
7. Install New Transducer
8. Attach Transducer to Valve Fitting
9. Attach Transfer Line
10. Attach Electrical Line

CONTROL COMPONENTS

Module 1 - Shutoff Valve & Check Valves

1. Isolate Failure
2. Isolate System Using Three-Way Valve
3. Bleed Down Residual Oxidizer
4. Remove Electrical Line
5. Remove Fitting on Shutoff Valve
6. Remove Fitting on Check Valve
7. Remove & Store Module
8. Install New Module
9. Attach Fitting on Check Valve
10. Attach Fitting on Shutoff Valve
11. Attach Electrical Line

Pressure Transducers

1. Isolate Failure
2. Bleed Down Residual Oxidizer
3. Remove Electrical Line
4. Remove Both Fittings
5. Remove & Store Transducer
6. Install New Transducer
7. Attach Both Fittings
8. Attach Electrical Line

Module 2 - Vaporizer, Relief Valve, & Burst Disc

1. Isolate Failure
2. Bleed Down Residual Oxidizer
3. Remove Fitting on Upstream Pressure Transducer
4. Remove Fitting on Downstream Pressure Transducer
5. Remove & Store Module
6. Install New Module
7. Attach Fitting on Downstream Pressure Transducer
8. Attach Fitting on Upstream Pressure Transducer

Module 3 - Filter & Regulators

1. Isolate Failure
2. Bleed Down Residual Oxidizer
3. Remove Fitting from Pressure Transducer
4. Remove Fitting from Three-Way Valve
5. Remove Four Quick-Release Fasteners
6. Remove & Store Module
7. Install New Module
8. Attach Four Fasteners
9. Attach Fitting to Three-Way Valve
10. Attach Fitting to Pressure Transducer

E. AUXILIARY POWER AND CREW REQUIREMENTS

Auxiliary power and crew requirements have been minimized to reduce the impact of APS operation on other Space Station activity. APS operation will be handled remotely, eliminating any onsite support. ACS operation could even be handled automatically by the fire control system. Refurbishment accounts for most of the APS manpower and electrical power requirements. Maintenance, refurbishment, and resupply of the ACS motors requires roughly 3/4 man-hr per month for 10 yr. The spin/despin motors require about 4 man-hr per spin or despin maneuver. The OFA requires approximately 4.75 hr per year, including the resupply periods.

1. Auxiliary Power Requirements

The APS has minimal auxiliary power requirements during propulsion operation, as shown in Table VII-9. The oxidizer control valves draw between 0.5 and 1.5 amp at 28 vdc during motor operation, while the instrumentation only draws 0.2 amp. The ignition circuits draw power for such a short time that they make a negligible contribution to power requirements. The backup GOX valves (N.O.) would only be used if a TCA oxidizer control valve failed to close. The backup valve would remain closed until the motor with the defective GOX valve had been disconnected. In the interim, the GOX supply would be shut off to four ACS motors on one paid, but the four other motors would still be available to complete any attitude control manuever.

During refurbishment, lighting accounts for almost all the auxiliary power requirements. A three-way valve located on the thrust pad is used for 2 to 3 minutes to draw a vacuum in the motor refurbishment container before withdrawing or extending the motor. However, the electrical power used for this operation is small compared to the power required to properly illuminate the room per MIL-STD-1472. Using standard, warm white fluorescent light with a 50% utilization factor, 14 amp at 28 vdc will be required to provide 4.6 lumens/in.^{2} (50 ft-c) of illumination in the APS room during motor refurbishment. During the 25 to 40 minutes when the refurbishment container is attached to the pad, an additional 10 amp will be required for pad lighting. Similarly, while the motor is being refueled and inspected on the work table, 7 amp will be required to light that area. Since an ACS fuel grain is consumed about every 1½ months, the ACS power requirements are about 0.37 kwh/month, almost entirely due to lighting during refurbishment. Similarly, a spinup or despin maneuver (three motor firings and refurbishments) will require about 2.7 kwh due to lighting requirements.

Table VII-9 Auxiliary Power Requirements

TIME	COMPONENT	ACS		SPIN/DESPIN MOTORS		OFA	
		CURRENT AT 28 vdc (amp)	OPERATION	CURRENT AT 28 vdc (amp)	OPERATION	CURRENT AT 28 vdc (amp)	OPERATION
During Motor Operation	Oxidizer Control Valve	0.5	Continuous	1.5	Continuous		
	Fuel Depletion Tripwires	0.1	Continuous	0.1	Continuous		
	Ignition System	1.0	0.1 sec	5.0	0.1 sec		
	Pressure & Thrust Transducers	0.1	Continuous	0.1	Continuous		
	Backup GOX Shutoff Valves	1.5	Only Used in the Event of TCA GOX Valve Failure. Power Remains on until Defective Motor Has Been Disconnected.				
	Solenoid Valves					0.6	Continuous
	Three-Way Solenoid Valves					1.0	Continuous
During Motor Refurbishment	Three-Way Vacuum Valve	1.0	2 minutes/ Refurbishment	1.0	3 minutes/ Refurbishment		
	Room Lighting,* 4.6 ℓ/m^2 (50 ft-c)	14	1 hr/ Refurbishment	14	1½ hr/ Refurbishment		
	Pad Lighting, 9.3 ℓ/m^2 (100 ft-c)	10	25 minutes/ Refurbishment	10	40 minutes/ Refurbishment		
	Work Table Lighting, Up to 18.6 ℓ/m^2 (200 ft-c)	7	15 minutes/ Refurbishment	7	35 minutes/ Refurbishment		

*Assumes a 50% utilization factor with standard, warm white fluorescent light.

2. Crew Requirements for the TCA

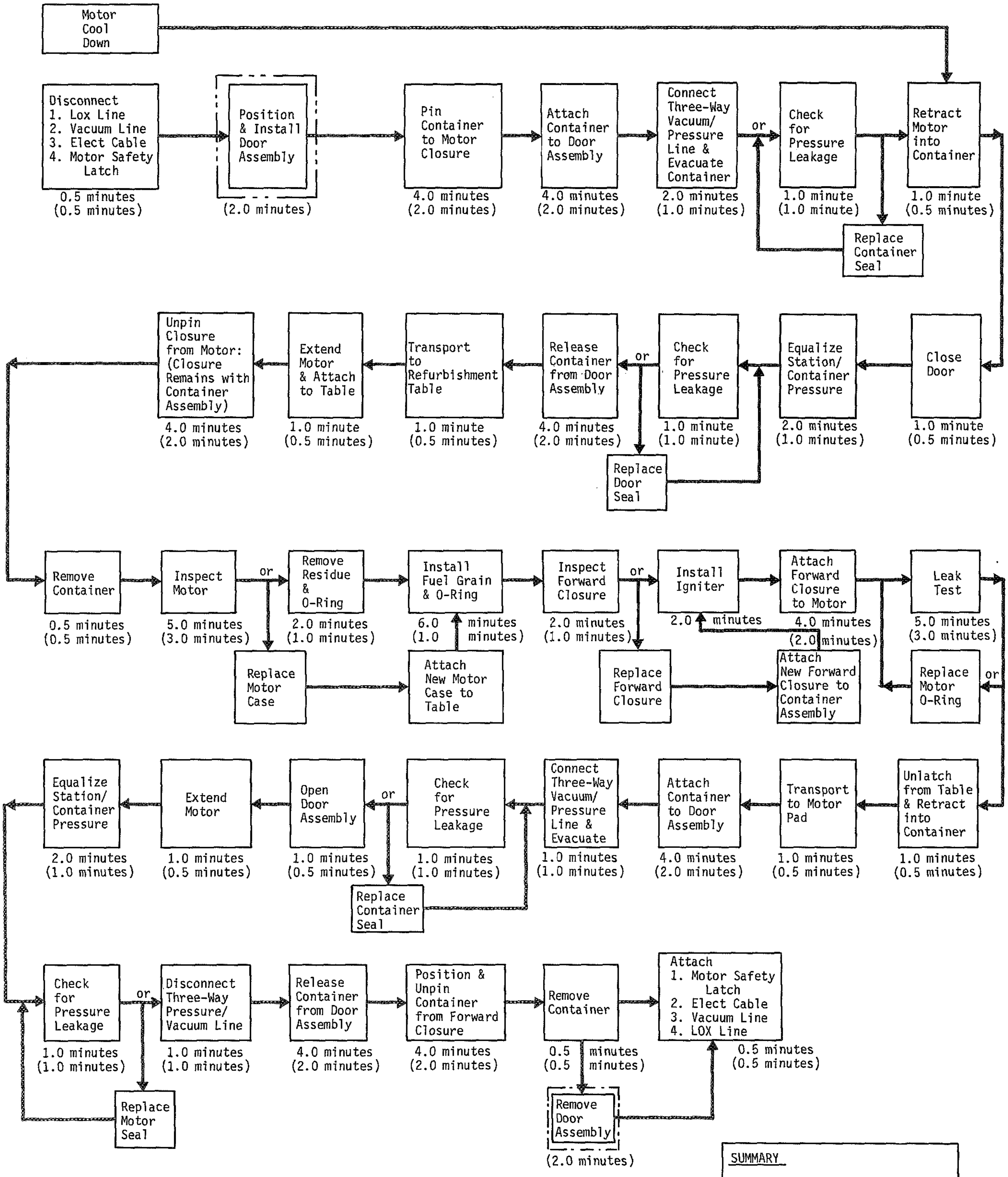
The baseline APS motors can be assembled, disassembled, refurbished, and inspected by one crewman. The loaded APS motor in its refurbishment container (in an 0.7-g Space Station environment) weighs less than 23 kg (50 lb) and is not more than 1118 mm (45 in.) long and 22 mm (8 3/4 in.) in diameter. The larger and heavier spin/despin motor and refurbishment assembly is handled with the help of a dolly that rides on rails and can be easily manipulated around the refurbishment compartment. The dolly has hydraulically operated legs that can be used to position it to the height of the motor pad and refurbishment table.

The spin/despin motor fuel grain is segmented. None of the segments weigh (in an 0.7-g space station environment) more than 15 kg (35 lb).

A timeline analysis was made to determine the time required to refurbish both an ACS and a spin/despin motor. Figure VII-5 shows a step by step analysis of the refurbishment procedure. Time values were assigned to each step based on engineering estimates and on the following assumptions:

1) One crewman is performing the refurbishment operation;
2) All motor hardware and refurbishment tooling is available in the refurbishment compartment;
3) There will be no replacement of motor parts, O-rings, or seals;
4) The refurbishment door assembly used for the spin/despin motor is fixed to the motor pad and need not be installed or removed;
5) The crewman is familiar with the refurbishment procedure;
6) The refurbishment begins and ends with the motor mounted on the pad in operating position.

The analysis showed that it requires 44 minutes to refurbish an ACS motor and 76 minutes to refurbish the larger spin/despin motor.



SUMMARY

Motor	Time (minutes)
Spin/Despin	76
ACS	(44)

Fig. VII-5 Refurbishment Timeline

It takes three spin/despin motors to accomplish either a spin or despin gravity maneuver. These three motors can be mounted in any one of four motor mounts (two per pad). Since a spin will be followed by a despin, either of the following refurbishment approaches can be used:

1) Fire all three motors during the maneuver and refurbish all three motors after the maneuver has been accomplished. (Note that one motor must be removed and reinstalled during the maneuver);
2) Refurbish concurrently with the manuever.

Based on the selected design, if the motors are refurbished during the firing, it would take 2.5 hr to accomplish the spin or despin maneuver and the minimum turnaround time would be 1.5 hr. If all three motors are refurbished after the maneuver, it will take 1.5 hr to accomplish the maneuver and the maximum turnaround time would be 4 hr. Since a period of 1 to 3 months exists between a spin or despin maneuver, the refurbishment schedule would depend on the crewman's duty requirements during a maneuver. If refurbishment could be accomplished in a gravity environment, it would provide for natural working conditions without the effects of weightlessness. For a spin maneuver, the recommended approach would be to refurbish after the maneuver has been completed, allowing the refurbishment work to be accomplished in a 0.7-g environment. During a despin maneuver, refurbishing concurrently with the maneuver would minimize the work to be done in the zero-g condition. It should be noted that a gravity environment is not a requirement. All operations for refurbishing both the spin/despin and ACS motors can be accomplished while in a zero-g condition.

3. Crew Requirements for the OFA

To minimize the total maintenance time, identical components/modules requiring replacement at the same time can be replaced during one maintenance operation, saving preparation and travel time. We assumed half of the filters are replaced after each pressurant and oxidizer resupply (every 6 months).

If all the components with 3-yr lives were replaced during one maintenance period, available crew time might be exceeded. Therefore, we suggest that only half the valves, components, and transducers be replaced at one period. The components in the half of the system that was active immediately after orbit insertion should be replaced first after 3, 6, and 9 yr. Components in the initially redundant standby half of the APS should be replaced at 3-1/2 and 6-1/2 yr.

Primary scheduled maintenance functions for the OFA consist of:

1) Checking the pressure;
2) Replacing filter elements;
3) Testing the fittings for leaks.

Pressures are checked before and after each resupply. This is estimated to require 10 minutes per OFA, or a total of 20 minutes per resupply. The total time per year is 80 minutes, assuming resupply every 90 days.

The crewtimes required for the remaining scheduled maintenance functions are presented below.

Table VII-10 Estimated Crewtimes for Scheduled Maintenance

FUNCTION	CREWTIME PER OFA (minutes)
Review Procedures	4
Obtain Spares	3
Travel to Assembly	5
Remove Cover	10
Replace Filter	3
Tighten Fittings (1/2 minute each)	58
Replace Cover	10
Return from Assembly & Stow Gear	5
Perform Administrative Functions	5
TOTAL PER ASSEMBLY	103

The total estimated scheduled maintenance time per year for the OFAs is 286 minutes.

F. APS RESUPPLY AND STORAGE REQUIREMENTS

1. Resupply

Resupply for the APS system encompasses all the activities from terrestrial storage, inventory control, and ground handling to inflight refurbishment of the propulsion system. This section discusses those aspects of resupply that are unique to the proposed ACS and spin/despin propulsion systems.

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

1) Consumables,
    a) LOX,
    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 and Cure with Time:
    a) Valves,
    b) Filters,
    c) O-rings,
    d) Seals.

A schedule for resupply is shown in Table VII-11. Resupply quantities of the consumable items were determined from the total impulse required to perform the ACS and spin/despin maneuvers given in Table II-2. The resupply schedule is based upon a Shuttle flight every 6 months except during the artificial-g experiments, when a cargo module is docked to supply LOX. The first Shuttle flight would be flown 3 months after launch; 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-yr Space Station orbit.

Each item aboard the Station will be identified by a serial number for inventory control. An inventory check will be made every 6 months prior to the Shuttle flight. At this time, unscheduled supply items will be determined and ordered. As new resupply items arrive, they will be visually inspected, logged onto an inventory list, and stored in the refurbishment compartment.

Table VII-11 Scheduled Resupply (6-Month Shuttle)

Months after Launch	0 LAUNCH	3	6	9	12	15	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	Total
Shuttle Flight Number		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
	Units																						
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

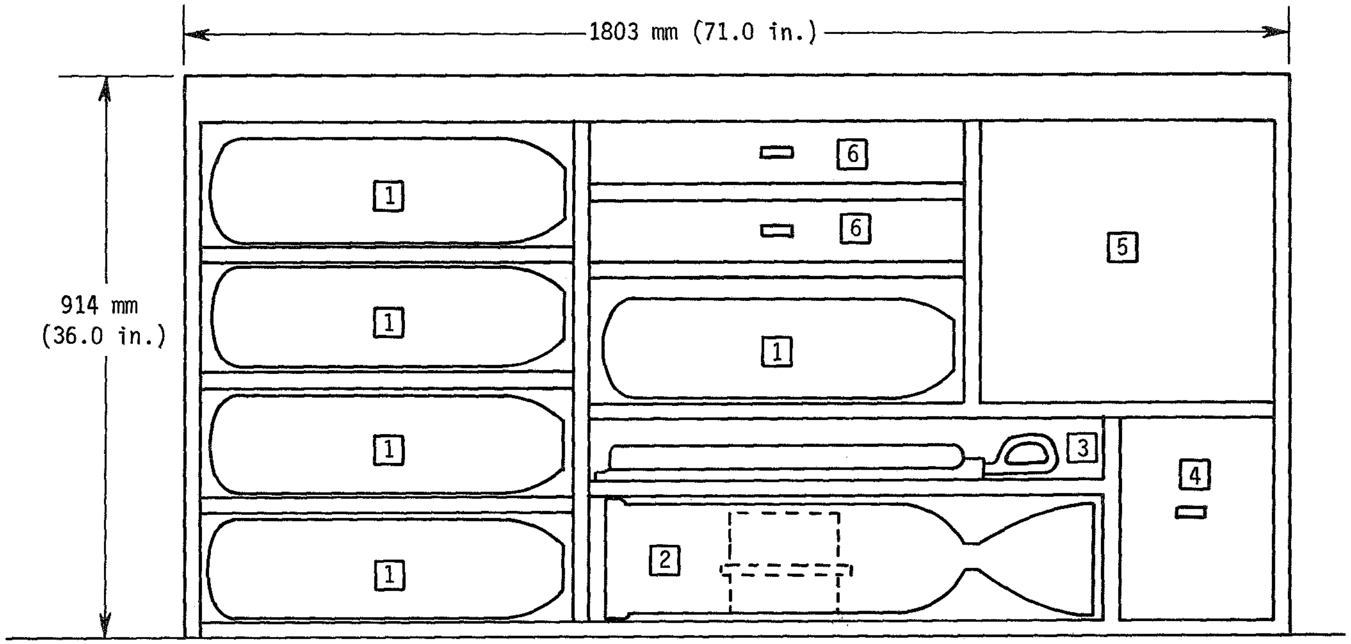
2. APS Storage Requirements

Storage of all APS related hardware in the refurbishment rooms was selected as the best approach since it simplifies motor maintenance tasks and provides better inventory control. The APS rooms (Fig. VII-1) provide storage space for all APS motor hardware and substantial amounts of non-APS related equipment. There are three principal component storage areas in the APS rooms -- two storage cabinets and the space underneath the work table. The file cabinet in the administrative area is primarily intended for records pertaining to the APS or other Space Station subsystems. With the exception of the spin/despin refurbishment container and dolly assembly, these three storage areas have sufficient capacity to hold all APS related equipment during the 10-yr life of the Space Station. The refurbishment container/dolly assembly rolls between the two APS rooms on tracks and is located in the standby position in either room when not in use.

APS equipment and spares have been stored to facilitate motor refurbishment. During launch the 16 primary ACS TCAs and the three spin/despin TCAs would be stored inside the Space Station, firmly lashed to the floor. Once in orbit, all 19 TCAs would be placed in their firing positions and only be retracted for refurbishment, or in the case of the spin/despin motors, for return to earth. Therefore, APS storage facilities must hold all replacement fuel grains and spare components.

About 0.84 m^3 (29.6 ft^3) of storage space has been provided underneath the motor refurbishment work table (Fig. VII-5). Since this location is the most convenient for motor maintenance, the work table storage area has been configured to hold ACS fuel grains and motor spares. With the exception of the ACS refurbishment container, all ACS equipment is stored at this location. Figure VII-6, which shows the layout of the work table storage area, assumes 25-mm (1-in.) shelf and partition thicknesses.

The two storage cabinets (Fig. VII-7) in the APS rooms provide room for spin/despin fuel grains and igniter assemblies, with extra space for non-APS related storage. The cabinet nearest the work table has been designed to hold three spin/despin fuel grains, stored vertically with the forward segment on the bottom. During refurbishment, the segments are removed one at a time from the top and inserted into the motor. This cabinet also holds seven replacement igniter cartridges. Approximately 0.3 m^3 (10.5 ft^3) is available in this cabinet for non-APS related storage. After 18 months, when the spin/despin system has completed its mission, the entire cabinet will be available. The far cabinet holds an additional two spin/despin fuel grains and the ACS refurbishment container. During the first 18 months, this cabinet provides 0.81 m^3 (28.8 ft^3) of non-APS related storage; after 18 months, an additonal 0.57 m^3 (20.0 ft^3) becomes available.



1	10 ACS Fuel Grains (5 pairs)
2	1 Spare TCA
3	1 Refurbishment Door Assembly
4	1 Spare GOX Valve 1 Spare Ignition System 2 Replacement Propane Bottles
5	Test & Inspection Equipment
6	Replacement O-Rings, Small Hand Tools, & Spare Motor Pins for ACS and Spin/Despin Motors

Fig. VII-6 Work Table (ACS Motor) Storage Area

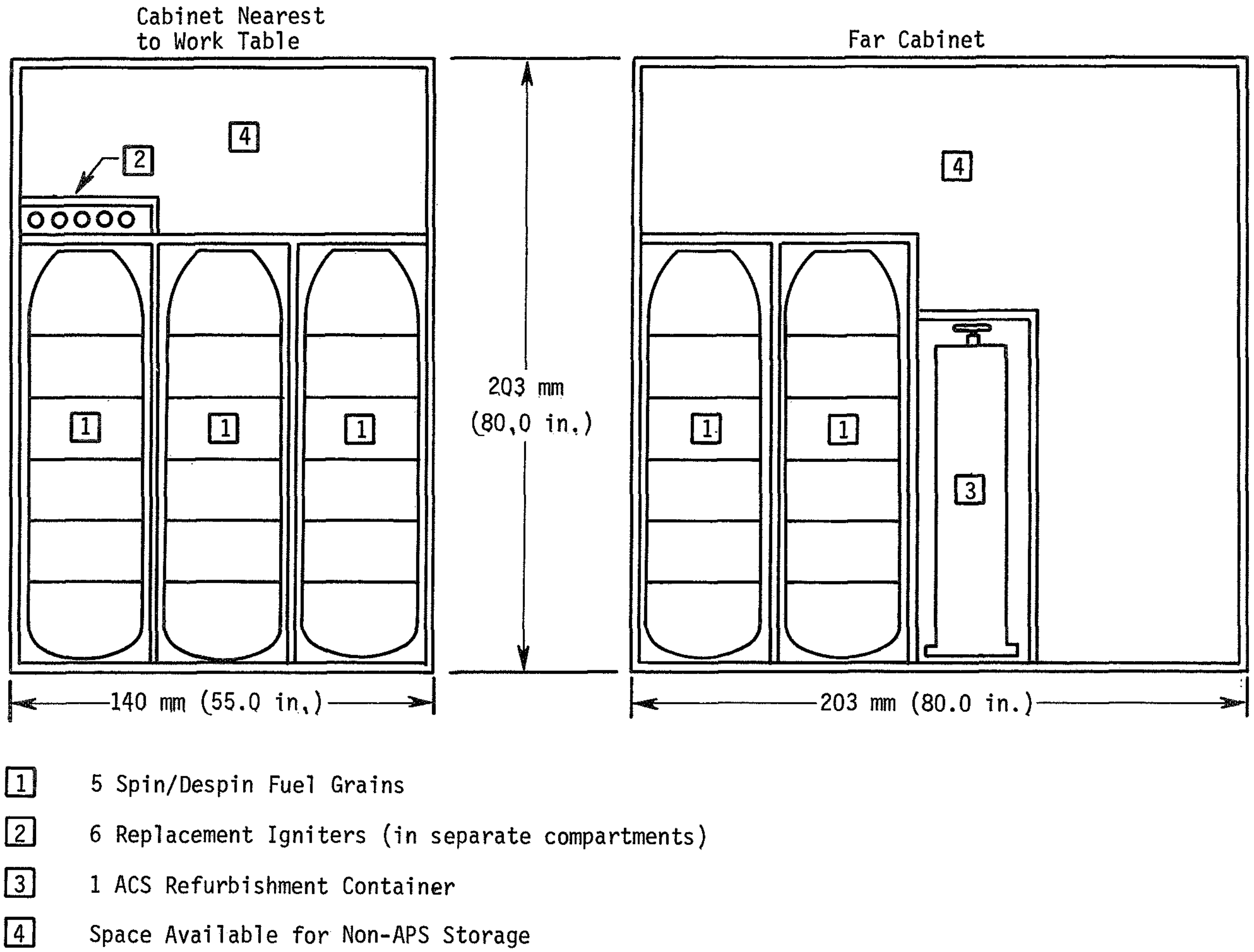


Fig. VII-7 APS Component Storage Cabinets

A major goal of this program was to identify new technology requirements associated with the hybrid APS being considered for the Space Station.

This section compares the technology needed with the technology status presented in Chapter VI. The OFA and the TCA are discussed separately for ease of discussion.

A. OXIDIZER FEED ASSEMBLY

The technology required for the OFA is well in hand. There is little need for further research, although much development is required. The programs recommended below are development programs.

1. Development of Three-Way Valves

The three-way valves used in the hybrid APS have different operational requirements than those normally encountered by three-way valves. They must be capable of interconnecting any two of three ports (the crossover port or feed port to the attitude control thrusters, plus connecting the feed to the crossover).

We recommend that a development program be initiated to develop and demonstrate these valves. These valves would be of use in any propulsion system where redundancy is required.

2. Development of Electromechanical and Mechanical Bellows Systems

Initial studies indicated that both the electromechanical bellows and the mechanical bellows feed systems are attractive, since they eliminate the need to use a gas pressurant to expel the LOX and eliminate the lines and components associated with such a system. The mechanical bellows system uses the spring force of the bellows and an additional spring in place of the electric motor of the electromechanical device. This provides a safe, simple system that offers weight advantages as well as reliability. Development and demonstration of these systems are recommended.

3. Development of Inflight Maintenance Experiment

An inflight maintenance experiment for propulsion is required to provide further definition and development of Space Station operational and technology concepts, system designs, and crew performance evaluation criteria.

None of the space flights to date have included any definitive experiments on inflight maintenance, nor has any extensive maintenance been required for the operating systems. Experiment M-508, scheduled for Skylab I, is the first experiment designed to acquire basic human factors data in a zero-g environment.

The objective of the inflight maintenance experiment for propulsion shall be to demonstrate the ability to accomplish selected, significant tasks that will be representative of the maintenance and resupply required during long-duration manned space missions for propulsion subsystems. The experiment shall possess commonality with the other subsystems for a Skylab-type vehicle so that maximum data are obtained. The experiment shall be designed to provide data for the entire area of integrated maintenance/resupply, including equipment design for maintenance and resupply, fluid phenomena in zero-g, human factors, astronaut performance in a zero-g environment, and procedural information.

The experiment shall consist of three phases:

Phase I	Experiment Definition
Phase 2	Prototype Design, Build, and Ground Development Tests
Phase 3	Flight Design, Build, and Tests

a. Phase I - Experiment Definition - This phase shall define candidate tasks for experiments; the experimental configuration; tests and the associated test equipment required for Phases 2 and 3; budget and schedule for Phases 2 and 3; detailed outline of the experiment, including what can be accomplished with ground simulation, KC-135 flights, and space flight tests. Maintenance tasks to be considered may be either preventive (scheduled) or corrective (unscheduled), and can be summarized into the following functional elements:

- Test/Check
- Calibrate
- Adjust
- Remove/Install
- Replace
- Repair/Overhaul
- Protect
- Service
- Clean
- Purge
- Filter
- Decontaminate
- Visual Check
- Inspect
- Composite Test
- Align
- Store
- Handle
- Monitor

Resupply tasks shall consider both the transfer of liquids and the transfer of solids.

b. Phase 2 - Prototype Design, Build, and Ground Development Tests - Prototype and ground tests shall be performed for all tasks where the flight environment does not influence the results. Various simulation techniques will be employed.

c. Phase 3 - Flight Design, Build, and Development Tests - Flight tests shall be performed for all tasks where the results can be influenced by the peculiarities of the environment, such as in a zero-g environment. In addition, a separate test shall be conducted to verify that the results of the ground tests are not influenced by the flight environment.

4. Development of Zero-g Fluid Transfer Methods

The objectives of the fluid transfer tests will be to verify predicted performance, investigate and resolve any design uncertainties, and, if possible, establish empirical criteria where existing data are found to be inadequate for the blowdown method. The test plan will outline the types of tests to be performed, the purpose for performing the tests, hardware required, test conditions and procedures, number of tests, data to be collected, expected results, and the test schedule. If propellant simulants are recommended for any portion of the experimental program, their use will be justified by showing how their use will be beneficial and how meaningful results will be obtained.

The two basic types of tests to be considered are ground evaluation tests and orbital experiments. Ground evaluation tests include 1-g bench tests; drop-tower tests; and KC-135 aircraft tests. Minus 1-g outflow tests, where the tank is inverted and liquid is outflowed from the outlet at the top of the tank, are included in the 1-g bench tests.

Under a current program, Contract NAS9-10480, we are evaluating, designing, and delivering a passive control system for the subcritical storage and outflow of cryogens in the space environment. This effort includes the formulation of a detailed ground evaluation test plan to verify system performance, which will be beneficial to the proposed APS program.

An attempt will be made to devise ground tests that will conclusively verify the selected fluid transfer concepts. Certain aspects of the system that are critical to satisfactory operation and that cannot be verified or proven within the capability of the ground test facilities will be clearly identified, and their implications will be discussed relative to successful operation of the transfer system. The specific requirements for conducting a meaningful orbital experiment will be incorporated into an orbital test plan. The data required and the manner in which the data will be used to achieve the intended objective will be firmly established. A goal will be to maintain simplicity while providing a minimum volume and weight package without sacrificing the validity of the results. With these requirements in mind, the test package design, instrumentation requirements, experimental procedures, and data acquisition methods can be determined. These variables permit definition of the required operational conditions.

5. Development of Capillary Screens for Cryogens

Controlled experiments are required for screen expulsion systems. We recommend that a study program be initiated to develop practical cleaning methods, filling techniques, and gaging techniques.

6. Development of Maintainable Components

To date, space flight propulsion hardware has been designed with only two main criteria: optimum performance and lightweight design. None of the components developed to date have been designed for inflight maintenance, which is a basic requirement on the Space Station. The reliability required by a long-term space mission cannot be achieved unless the capability exists to replace or repair components.

One method of reducing spares and piece parts is to have common components for like functions; that is, to design components that function for several systems, rather than for a particular system. Another consideration is to use a common valve body for several functions, such as for a shutoff valve, regulator, check valve, etc. This latter approach would standardize the valve body, which has the largest area and weight of a valve assembly, and could lead to a considerable savings in terms of reduced spares.

Components designed into a single compact module would reduce weight, leakage paths, and allow the replacement of either a single component or the entire module. A design program similar to the modular concept was initiated by the Navy. Although the requirements were not exactly the same, they did establish that components could be efficiently combined into a subsystem module.

We recommended that a program be initiated to design and test representative propulsion components that require minimum inflight maintenance.

7. Development of Fluid Fittings

Today's technology for separable fluid connectors is directed toward ultratight sealing characteristics at extreme temperatures and pressures. Fluid fittings designed for inflight maintenance require a different set of criteria. They must seal after repeated assemblies and disassemblies; the threads must not gall; and the seal must be reparable, require simple tools for assembly, and provide reasonable sealing characteristics. A design and test program should be initiated to provide fittings that will meet these criteria for inflight maintenance.

8. Development of Long-Life Test Program

Accelerated testing is not an accepted method of demonstrating the life and reliability of a component used in a long-duration mission. Qualification data cannot be obtained when the real time available for testing is less than the mission duration. It is a fact that the majority of the components that will be used on the Space Station have not demonstrated the long-term reliability that will be required for the 10-yr mission. We recommend that long-life demonstration tests commence as soon as possible on basic components and materials so that long-life reliability data can be gained before the Space Station mission. This test program would also serve to correct basic design deficiencies that only show up in an extended duration test.

B. THRUST CHAMBER ASSEMBLY

Several advanced technology programs are recommended to further reduce the maintenance repair and resupply requirements of a hybrid APS. During this study, many alternative design approaches were evaluated, but only those that represented demonstrated technology were retained for final selection. However, several of the systems rejected on the basis of their technology status promise significant improvements in maintenance without extensive development. Long-term manned space missions that involve inflight maintenance represent a significant departure from conventional design approaches. Therefore, tests to demonstrate the effectiveness of the selected maintenance approaches are very important to the long-term success of an APS aboard a manned Space Station. Three basic programs are recommended to demonstrate the effectiveness of selected maintenance, repair, and resupply approaches for 10-yr aboard a manned Space Station and to extend the state-of-the-art for further reductions in maintenance requirements.

1. Demonstration of Low-Pressure, Radiation-Cooled Hybrid Motors

Hybrid motors have routinely been tested at a chamber pressure of one atmosphere, and boundary layer characteristics have been studied in a number of cases. Similarly, film cooling and radiation cooling have been used in liquid engines for years. There is no question that a hybrid ballistics propulsion system can be tailored to achieve long nozzle life by combining low-pressure operation with film and radiation cooling. However, there are several important unknown areas that could increase or decrease motor maintenance requirements. Some of these areas are:

1) What is the maximum motor performance that is consistent with long nozzle life?
2) What effect does repeated temperature cycling have on the $MoSi_2$ protective coating?
3) Would motor burnout without fuel depletion wires damage the $MoSi_2$ coating?
4) What effect does long-term storage in space, with repeated vibration and oxidizer-rich ignition transients, have on the $MoSi_2$ coating?

The answers to these questions can have an important effect on the maintenance and resupply requirements for a hybrid APS, and they should be properly evaluated in a test program.

2. Complete Ballistic Characterization of GOX/(PMM/PBD) in the Selected Motor

The hybrid APS design is unusual due to the extremely long burntime. The oxidizer mass flux (and consequently the fuel regression rate) varies over a wide range during motor operation. Although a number of tests have been conducted with the selected propellants in small motors, many more tests will be required to completely characterize this propellant system. Precise information on the effects of oxidizer mass flux, chamber pressure, injector configuration, and fuel grain design is necessary to accurately define motor operating characteristics. Achieving lower minimum regression rates would increase the maximum total impulse or permit shorter/lower thrust motors with the same total impulse. Transient response is also an important operating characteristic and should be evaluated as a function of fuel burnback position.

3. Advanced, Low-Maintenance Ignition Concepts

Several advanced, low-maintenance ignition concepts were evaluated during the study. The selected approaches use demonstrated technology to achieve safe, reliable ignition of both the ACS and spin/despin motors. Hybrid motors, though extremely safe, are relatively easy to ignite once the oxidizer is introduced into the combustion chamber. Both selected ignition approaches use chemical energy to heat the oxygen and initiate the hybrid combustion process. The ACS motors burn a small amount ($\sim$1 gm) of propane with GOX for ignition, while the spin/despin motors mix warm, fuel-rich igniter products with LOX to achieve ignition. However, the use of a purely electrical ignition system would eliminate the problems of propane storage and distribution, as well as igniter storage and handling.

One of the unique aspects of the present mission from the standpoint of ignition is the availability (if not abundance) of electrical power. The heated oxidizer line approach discussed in Chapter IV is the safest, most reliable ignition system studied. This approach was not selected because ordinary propulsion systems do not carry the required electrical power and because the electrically heated oxidizer approach has never been demonstrated.

However, a resistance heating element or a spark discharge can be used to heat the oxidizer to about 810°K (1000°F), and this appears to be a straightforward extension of existing technology.

We recommend that a development program be initiated to demonstrate a purely electrical ignition of a GOX or LOX hybrid motor. Prime design objectives would be safety, low maintenance, high reliability, minimum size and weight, and low power consumption. ACS motor ignition should require heating the GOX to 810°K (1000°F) for a period of no more than 0.100 to 0.200 sec.

The total electrical energy required for ignition [0.0007 kwh per start, or 0.026 kwh per ACS motor fuel grain (assuming 10-sec burns)] is insignificant compared to the 0.56 kwh required to properly illuminate (per MIL-STD-1472) the APS room during the 45 minutes of ACS motor refurbishment. However, the instantaneous power levels are relatively high. Fortunately there are several design approaches that can reduce power requirements by an order of magnitude and thus greatly simplify an electrical ignition system. Candidate design approaches should be studied and the most promising concepts should be evaluated in actual hybrid ignition tests.