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FINAL REPORT

STUDY OF SPACE STATION PROPULSION SYSTEM RESUPPLY AND REPAIR

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FOREWORD

This report was prepared by the Martin Marietta Corporation under Contract NAS8-25067, "Study of Space Station Propulsion System Resupply and Repair," for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the Technical Direction of the Engineering Division, of the George C. Marshall Space Flight Center with Mr. Keith Coates as Technical Monitor.

ABSTRACT

This report describes the effort accomplished under Contract NAS8-25067 to determine the feasibility and practicability of providing a resupply and repair capability for a Space Station bipropellant propulsion system. The program encompassed a study of inflight maintenance, orbital resupply, reliability, fault isolation and detection, logistics, and safety.

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I. INTRODUCTION

The primary purpose of this study was to determine if it is feasible to resupply and repair a Space Station bipropellant propulsion system. The output of the effort was more far reaching, however; the aim was to determine how to maintain the integrity of a propulsion system for ten years, to identify the elements of design and technology required to accomplish this task, and to establish the optimum methods of orbital resupply and repair.

NASA is presently planning a large space base for the 1980 time frame that will maintain 50 to 100 men in earth orbit. The space base will have an operational life of at least ten years. A 12-man Space Station will be launched in the mid 1970's that will become a modular portion of the space base. The realization of a ten-year mission in space dictates a new approach to propulsion system design. In previous and current space efforts, the subsystem reliability was satisfied by component redundancy and rigorous component testing. This approach was practical because of the relatively short mission durations. For very long missions, critical subsystems must be designed so that the crew can resupply and repair the system to maintain its original integrity. This study attempts to define feasible concepts and propose possible means for practical accomplishment of these design goals.

The objectives of this study were accomplished in four phases:

1) A task to conceive the various approaches applicable to resupply and repair;
2) An evaluation and definition of the concepts;
3) Detailed definition and analysis of the preferred approaches; and
4) Conceptual design.

This final report describes the work performed in each major subject area, together with all findings, data, and conclusions.

II. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

This chapter summarizes the more significant findings and conclusions derived from this study; and are categorized under the basic technology headings that comprise the remainder of this final report. Only the main points of the study are extracted; the details and supporting data will be found in the body of the report.

While the baseline subsystem investigated in this study was a bipropellant auxiliary propulsion system (APS) for the Space Station, it became evident throughout the study that a large portion of the concepts, findings, and conclusions are equally adaptable to other mechanical and fluid subsystems on the Space Station.

1. Inflight Maintenance

This study has concluded that inflight maintenance (IFM) is not only feasible for the Space Station, but an absolute requirement to develop a system that will achieve a ten-year life. Propulsion systems to date have not had missions of sufficient duration to warrant inflight maintenance. In the past, the development of propulsion system design has placed very little, if any, emphasis on the requirement for inflight maintenance. All of the emphasis was generally placed on performance and reliability. For missions of short duration, the reliability requirements were largely achieved by the judicious use of redundancy. The reliability studies in this program have concluded that redundancy is not sufficient by itself, and that incorporation of an inflight maintenance capability will improve the ten year system reliability by 0.297. Thus, resupply of commodities and the capability to repair a system are necessary to meet a ten-year mission.

It was determined that the optimum level of repair for the Space Station APS is to remove and replace at the component/module level; and, for most failures, to return the failed component to earth for disposition. However, the capability must exist, in the Space Station General Purpose Laboratory, to make simple repairs when necessary and critical to system operation. A component/module can be defined as a series of components, grouped by commodity, and designed into a single module so that any single component on the module can be removed by itself, or the entire module can be removed from the system. Engine replacement should be at the module level (i.e., three to four engines per module). It would be feasible, however, to remove and replace individual engine assemblies in the General Purpose Laboratory.

The factors that determine the maintenance concept for a system are: performance constraints; mission duration and scheduled events; resupply interval; crew size, time, and skill; fault detection and isolation techniques; weight and volume penalties; functional design constraints; and component life and failure rate. It was concluded that the specific results of an inflight maintenance analysis can only be applied to an individual subsystem. Although similarities exist between systems, and some concepts are adaptable to all subsystems, it was found that no generalities can be drawn for the optimum level of repair. For example, a Mars mission that is payload-limited may require highly trained crew members and repair at the piece part level.

Every component or subassembly in the system must be reparable at the lowest level specified, regardless of the probability of failure or predicted maintenance time per year. As a minimum this must include means to detect and isolate the failure, isolation valves and provisions for fluid removal, spares, procedures, and crew training.

It has been determined that all APS inflight maintenance can be performed from within the Space Station and no EVA will be required. The propulsion system can be mounted in an internal arrangement, rather than a pod mount on the vehicle exterior skin.

The propellant tanks should be housed in compartments, both for damage control and to prevent any propellant leakage into the Space Station. In addition, hypergolic propellant storage tanks must be physically separated. The compartments should be normally vented to space vacuum with the capability of being pressurized for subsystem repair functions. The propellant transfer lines running from the storage compartment to the engines must also be enclosed in an enclosure vented to vacuum. These design considerations are necessary to prevent propellant leakage or spillage into the Space Station from a single failure mode.

Toxic propellant vapors in the spacecraft are one of the greatest potential hazards in the maintenance of a propulsion system, although proper design and safety procedures will preclude the hazard. Less than 1 mm of liquid monomethylhydrazine will raise the toxicity level in the Space Station to the maximum acceptable concentration, however the vaporization rate for this fuel is such that sufficient time is available to take corrective action. Fluid removal and decontamination is an absolute requirement before any maintenance operation on the APS propellant subsystem. One of the most critical and pacing technology items identified in this study was the development of an effective fluid removal and decontamination tool. As a backup safety precaution, the segment housing the propellant system must be isolated from the Space Station and crew members will be required to wear flexible protective clothing ("splash suits") when opening up a propellant system. The design of the Catalytic burner in the Space Station environmental control system should consider the requirement to remove propellant contaminants in the event of a propellant spill.

If leakage is directed away from the spacecraft interior, external leakage criteria for the nitrogen and propellant systems need not be as stringent as they have been on past programs. It was concluded that the leakage criteria for each fitting could be relaxed to an equivalent of 1 x 10^{-6} cc/sec of nitrogen, with a permissible inflight degradation to 1 x 10^{-4} cc/sec (bubbletight). Mechanical fluid connectors are recommended over other types of joints such as brazed or welded joints. Fittings designed for inflight assembly and disassembly have been identified as a future technology requirement. Specific requirements for such a fitting are identified in this report.

Propellant vapors or massive spills to the exterior of the spacecraft are not tolerable because of contamination to the experiments, solar arrays, and optical and thermal surfaces. For these propellants, a vapor exclusion device such as a cold trap must be inserted in the vacuum vent line to freeze out the propellant vapors prior to venting to the exterior of the spacecraft.

2. Orbital Resupply

It is concluded that orbital resupply of the APS commodities can be accomplished with established techniques and equipment.

Pressurant can be resupplied most efficiently by modular replacement of the storage vessels. Safe and efficient installation of the pressurant spheres can be assured by providing manually isolation valves and quick disconnects of conventional design. Safe handling of the resupply assembly can be assured by a straightforward packaging design to avoid mechanical damage during transportation. Because of the relatively small size and mass of the required package, transportation can be quickly and efficiently provided by an individual crew member. If required, larger packages can be efficiently handled by more than one crew member using auxiliary handling equipment. Modular replacement was selected over simple expansion of a high-pressure gas source mainly because of the excessive residuals that result from the latter method. Because of these inherent residuals, which are compounded by the thermodynamics of the expansion and compression processes, modular replacement is recommended for *gaseous* resupply regardless of the quantities involved. Because of added system complexity, power requirements and/or integration problems, more sophisticated pressurization techniques such as cryogenic storage, recompression of ullage, or volatile liquid pressurants are not warranted for the pressurant quantities required by the baseline APS - approximately 14 lb of nitrogen per resupply interval.

For the baseline propellant quantities -- 500 lb per resupply -- the optimum method of propellant resupply is by pressurized transfer through fluid distribution lines. The recommended energy source for propellant transfer is a conventional, 250 to 50 psi, blowdown pressurization subsystem. Pumped transfer is judged to be unsuitable because of power requirements and added system complexity. This is particularly true for the relatively low operating pressures required for propellant transfer, essentially vapor pressure plus flow losses. Ullage may be satisfactorily controlled by a capillary screen or by any of several positive expulsion devices. In view of the requirement for refurbishment of logistics vehicle systems, the transverse collapsing metal bladder is considered to be the most suitable expulsion device for this application, primarily because of its potential for low cost expendable use, thus greatly reducing refurbishment problems.

Modular replacement of the propellant storage tanks was rejected primarily because of the requirement for excessive crew involvement, the additional crew hazards involved, and because of the decontamination requirements. The recommended system for the integrated APS consumables requirement is schematically illustrated in Fig. VI-2 (Chapter VI). This system employs the recommended methods of resupply discussed above. In addition, it provides for recovery of contaminated propellants from the Space Station by use of the logistics vehicle supply tanks as receivers for waste propellant.

Based solely on minimum weight and associated cost per payload pound, three months was found to be the optimum resupply interval for the recommended system. A six-month resupply interval is recommended, however, when considering other factors such as crew involvement, the shuttle schedules on the crew/cargo modules, system checkout and activation, ground crew time, refurbishment costs, and additional safety hazards.

An alternative mode for resupply of the *total* consumables requirement of the Space Station would be a supply module, or "parked pantry." This would include consumables for the environmental control and life support systems as well as the APS. Use of the modular approach will significantly reduce the requirement for inflight maintenance and/or development of long-life components; since major portions of the operating systems are part of the replaceable module rather than the Space Station itself.

Refurbishment of the shuttle subsystems will become a significant factor in program costs and shuttle turnaround time. Achieving a low cost logistics capability will also require rapid and economic inspection, refurbishment, and reuse of the APS resupply system. In most instances this can be achieved to a large extent by simply recognizing the importance of these factors when selecting components for the resupply system.

3. Maintainability

The average unscheduled maintenance time for the APS is predicted to be 74 minutes per year. The engine solenoid valves are the most unreliable components in the system, and thus require the most maintenance time -- 31 minutes per year average. Actually the complete engine module will be replaced regardless of the failure within the module. Therefore, the average time required to correct random failures in the engine module is estimated to be 50.5 minutes per year.

It was determined that a preventive maintenance philosophy was required to maintain the system integrity for ten years. The scheduled replacement interval (3 years) was governed by the age life or calendar life of the component, rather than cyclic life.

It has been established that high reliability valves are now capable of a three- to five-year calendar life depending on seal material and valve type. Cyclic lives in excess of one million cycles can be obtained upon specification. The total predicted replacement time for scheduled maintenance of the APS is 194 hr in ten years and is a direct function of component life. When considering all of the subsystems in the Space Station, the time required for scheduled maintenance could involve a large portion of the mission. Future technology development for the Space Station must consider the development of long life components to improve total component life and thus decrease the total commitment for scheduled maintenance.

The recommended minimum onboard spares for the APS consist of one complete engine module, two three-way solenoid valves, and one nitrogen regulator. This recommendation assumes the capability of a three-month resupply interval for spares.

It was determined that the baseline engines (22-lb thrust) were not satisfactory for the spin-despin functions because the engine burn life would be exceeded before the first 75 days of the mission. Consequently, higher thrust engines would be more appropriate for the spin/despin function.

4. Reliability

An attitude propulsion system can be designed that will meet the ten-year mission requirements. The system developed during this study has a predicted ten-year reliability of 0.969 as compared to 0.416 for the original baseline system. This degree of reliability can be achieved by: (1) adding isolation valves and fittings to provide an inflight maintenance capability; (2) redundancy of all operational components with the exception of the propellant tanks; (3) by a configuration that allows resupply and repair to one-half of the system while the other half is in operation; (4) adding isolation valves on the propellant tanks. The largest increment of reliability was achieved by providing an inflight maintenance capability.

Redundancy is required for all critical functions on the Space Station, particularly where very short reaction times are required. The control moment gyros have been designated as the primary attitude control system for the Space Station. The propulsion system studied in this program could be considered to be a primary system for Space Station maneuvering.

The recommended ten-year APS configuration (Fig. II-1) described in this study was accomplished without an overall increase in the baseline hardware. In fact, the system had an overall reduction of two nitrogen spheres, four filters, and 40 transducers.

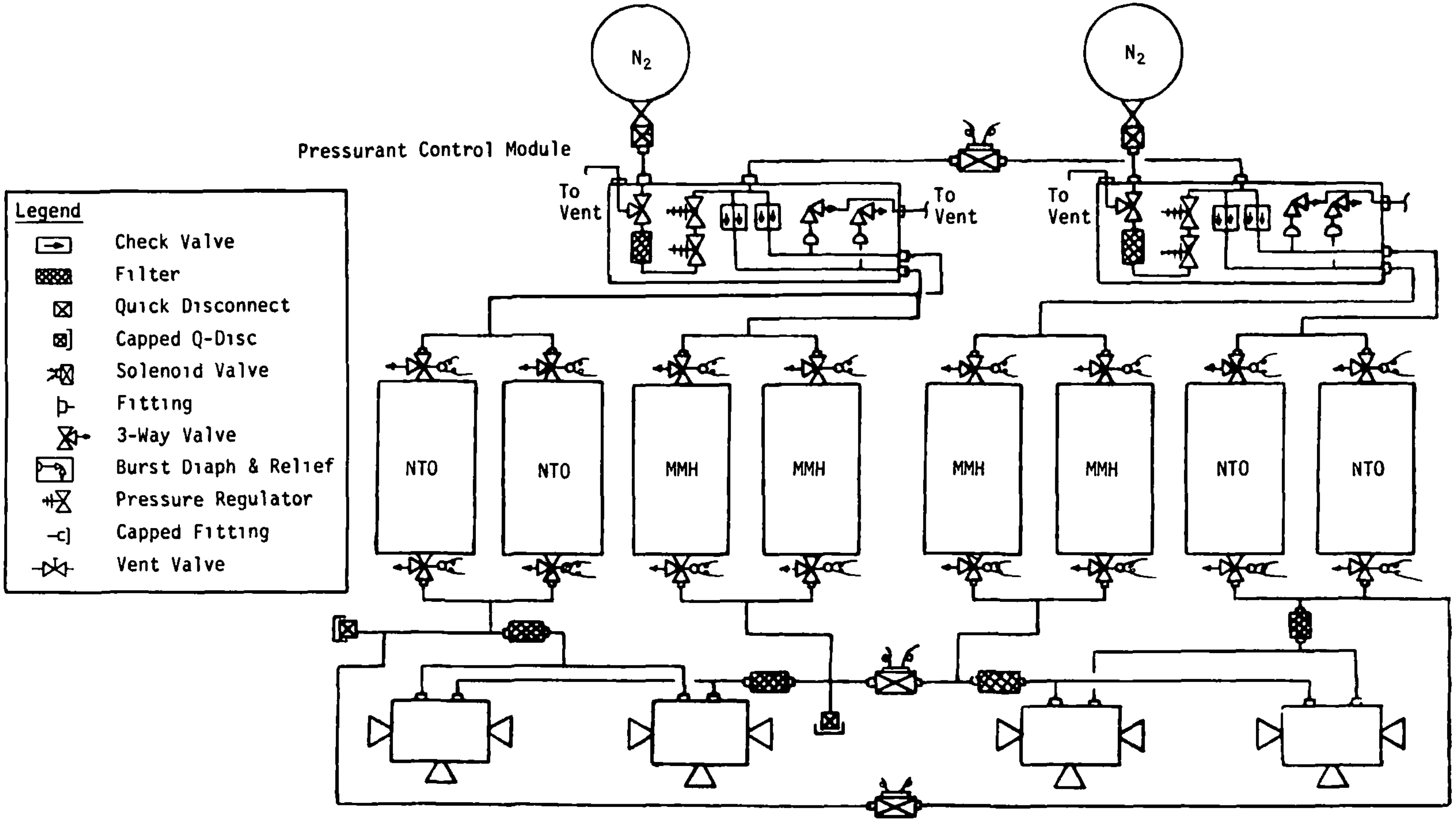


Fig. II-1 Recommended APS Schematic

5. Fault Detection and Isolation

A systems analysis was conducted as part of this study to determine the extent of the instrumentation and associated logic required to perform fault detection and isolation on the APS. The two Space Station guidelines used as a basis for the study were:

1) The Space Station will have an onboard checkout system (OCS) for fault isolation and detection;
2) The Space Station operation will be largely autonomous from ground station control.

This study concluded that the onboard checkout system is completely adaptable to fault isolation of the APS without incurring any additional instrumentation. Further, it was concluded that fault isolation must correspond to the lowest level of repair planned, and that manual fault isolation without the benefit of a computerized checkout system would be a very time-consuming process requiring a highly trained crew. It was determined that the five checkout and fault isolation tests required for the APS were minimal in relation to the other subsystem requirements on the Space Station.

It is important that the overall instrumentation requirements for the Space Station be integrated both for optimization and commonality of data. A large decrease in instrumentation requirements can be expected as an outcome of an optimization analysis. This study concluded that the Onboard Checkout System could be used for APS fault detection and isolation without incurring any more instrumentation than that normally required for a manned mission. Fifty transducers were required for the APS, as integrated with the Onboard Checkout System.

For the APS it was determined that no more instrumentation was required for component level repair than for module level repair, although the software logic was increased substantially.

B. RECOMMENDATIONS

1. NASA Emphasis on Inflight Maintenance

In order to meet the mission requirements of the Space Station, NASA must recognize that inflight maintenance is a companion technology to the design of subsystems, and that strong emphasis is required by NASA early in the program. NASA must not only place requirements on the various Space Station contractors, but must also specify integrated criteria and an overall plan.

Without an integrated plan and subsequent control by NASA, the benefits to be gained from inflight maintenance and commonality will not be realized. It is recommended that NASA place strong emphasis on inflight maintenance early in the Space Station program with continued strong direction throughout the program.

2. System Integration for Inflight Maintenance

It has become apparent in this study that one central organization or integrator is required to effectively coordinate inflight maintenance for the multitude of systems and associated contractors that will become a part of the Space Station. A central systems group is required to standardize design criteria, to demand commonality, and to implement a standard plan for fault isolation, crew training, procedures, logistics, and design.

It is recommended that one central organization be established early in the Space Station definition program to define, implement, and coordinate the inflight maintenance program for the Space Station.

3. Future Technology Requirements

One of the objectives of this study was to identify those areas of future technology investigation and/or development required for the Space Station.

Eleven specific areas of future technology are listed below and described in detail in Chapter X. It is recommended that further effort be continued in these specific areas:

1) Inflight maintenance experiment;
2) Fluid removal and decontamination;
3) Waste fluid disposal,
4) Component design for maintainability;
5) Fluid fittings design and test;
6) Tube repair techniques;
7) Long life test program;
8) Shuttle resupply system refurbishment;
9) Leak prevention and repair;
10) Fault detection and isolation;
11) Flex hose development.

III. BASELINE CONFIGURATION AND GUIDELINES

The type of system and baseline considered for the study is described in this chapter. The baseline requirements can greatly influence the results of a study on resupply and repair. For example, size and complexity of the system greatly affects the conclusions on the resupply mode and repair techniques. The type of propellants also determine the safety considerations. One of the largest pacing factors in a study such as this is the mission duration. This influences the complete evaluation; including redundancy configurations, reliability, maintainability estimates, spares requirements, repair techniques, and resupply. The following two sections describe the baseline used during the study, and the Space Station guidelines that were a part of the Space Station Phase B study.

A. STUDY BASELINE AND GUIDELINES

This program was directed toward a study of resupply and repair for a hypergolic bipropellant auxiliary propulsion system (APS) on an earth-orbital Space Station. The data shown in Table III-1 is the original baseline system data and served as a point of departure for the study. Figure III-1 shows a schematic of the APS baseline.

After the contract was initiated, the decision was made that the Space Station guidelines should take precedence over the initial study baseline where there was a conflict in requirements that would affect the study effort or results. The intent of this study was to follow the Space Station Phase B study as closely as possible so that the study results would be relevant and useful to the Space Station. This study is considered to be a supporting study to the Space Station.

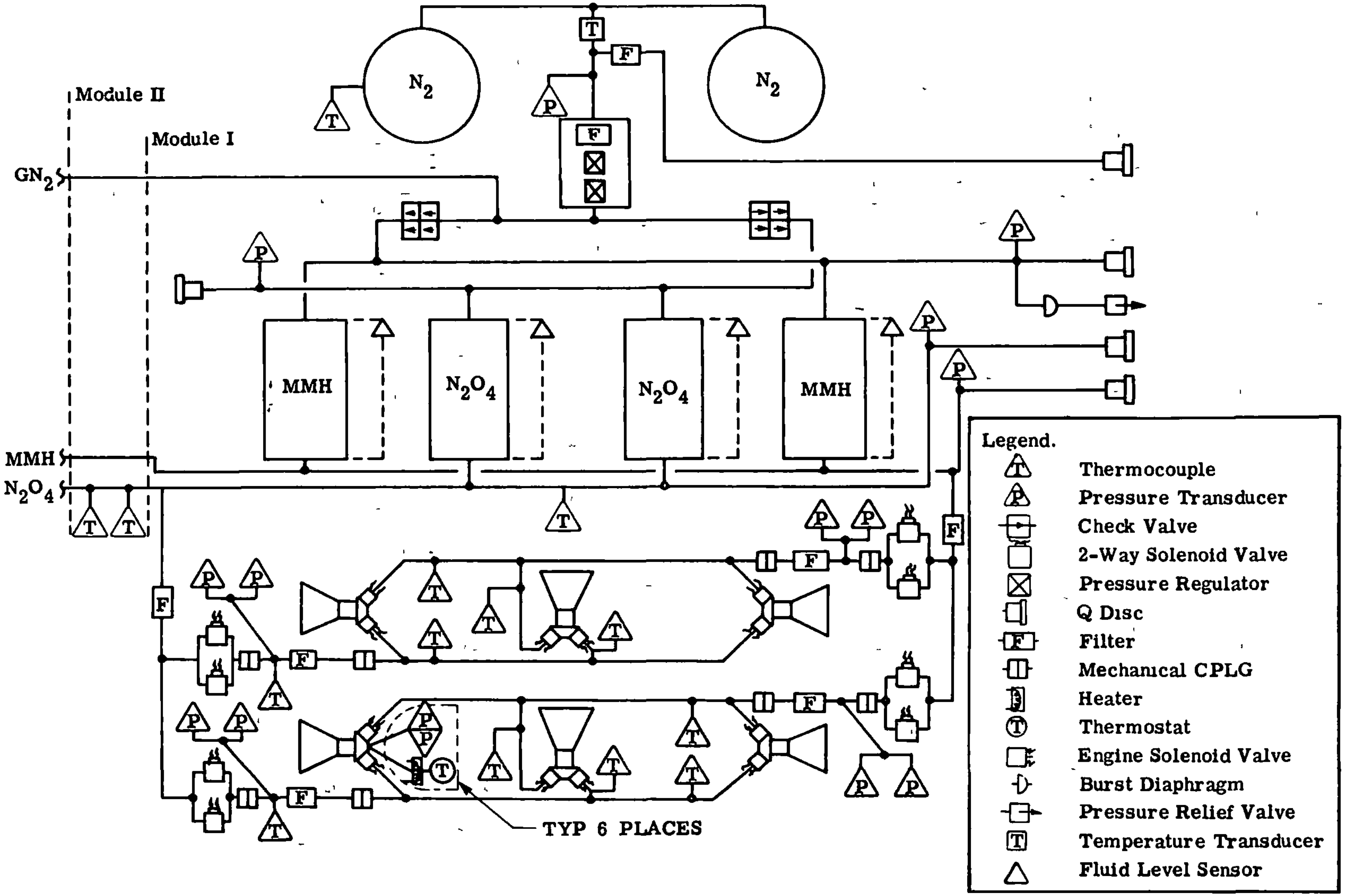


Fig. III-1 Baseline APS Schematic

Table III-1 Baseline System Description

System Configuration: Orbital Workshop APS [Workshop Attitude Control System (WACS)]

Propellants: Nitrogen Tetroxide, Monomethylhydrazine

Pressurant: Helium or Gaseous Nitrogen

Propellant Capacity: 860 lb @ 1.62 mixture ratio

Pressurant Capacity: 30 lb of GN_2

Operating Pressure:

- Pressurant (Max): 3200 psi
  - (Nom): 3200 to 350 psi
- Propellant (Max): 300 psi
  - (Nom): 220 psi

Thruster Size: 20- to 100-lb Thrust (Radiation Cooled)

Tube Joining Technique: Primarily an All-Brazed System

Service Connectors: Capped Quick Disconnect

Propellant Tanks: Metal Bellows Type

Orbital Environment: Pressure and Temperature for a Nominal 200-n-mi Orbital Altitude

Total Impulse: 1×10^6 lb-sec

Max Number of Component Replacements: Five

Operational Life: 5 years

Table III-2 shows the average impulse requirements defined in the McDonnell Douglas Phase B Space Station Design Reference Model (DRM). These requirements were used throughout the majority of the study. This table defines a low-thrust system (Resistojet) and a high-thrust system. The high-thrust impulse consists of two distinct requirements, one for maneuvering and the other for the spin/despin operation. The spin/despin and gravity gradient is used one time for the partial gravity experiment and requires a large amount of impulse within a short time frame. With a "one-shot" system, used early in the mission, it was not anticipated that resupply or repair will be required for this system. One of the original guidelines in the study was that no system larger than the baseline should be considered. Therefore, the system that received the majority of the study effort was a system used for attitude control and maneuvering functions, which amounts to a propellant usage of approximately 1000 lb per year.

The largest perturbation between the baseline and the Space Station guidelines was a change in the baseline to a ten-year mission instead of five years. The mission revision changed the impulse requirements, maximum number of component replacements, and total number of resupply intervals. The propellant requirements (per year) was revised slightly upward (860 to 1000 lb) to be in accordance with the Space Station requirements.

The following basic guidelines were formulated as part of this study:

1) The primary objective is to determine the feasibility and practicability of providing a resupply and repair capability for an earth-orbital Space Station bipropellant propulsion system;
2) It shall be an objective to identify those propulsion areas that would require further immediate technology investigation and/or development to meet the operational date of 1975;
3) The study will use a WACS as a baseline and will be restricted to a WACS-size module until additional input is received from the Space Station studies;
4) Where the study guidelines tend to conflict with current Space Station study guidelines and such conflict affects the subject study effort or results, the Space Station study guidelines should take precedence;

Table III-2 APS Impulse/Weight Requirements

			Propellant Weight		
				High Thrust	
Time Period	Function	Impulse (lb-sec)	Low Thrust ΔW (lb)	Spin/Despin ΔW (lb)	Maneuvering ΔW (lb)
0-45 Days Zero-g Mode (belly-down)	Events (High Thrust)	120,000 (est)	--	--	480
	Orbitkeeping (Low Thrust)	9,000	26	--	--
	CMG Desaturation*(Low Thrust)	51,950	147	--	--
45th Day	Spin-up† (High Thrust)	493,000	--	1970	--
45-75 Days (Artificial-g Mode) (Solar Inertial)	Gravity Gradient†(High Thrust)	1,275,000	--	5100	--
	Sun Track†(High Thrust) (15 Day)	142,000	--	570	--
75th Day	Despin†(High Thrust)	493,000	--	1970	--
	S-II Stage Deorbit	1,515,000			
2½ - 18 months Zero-g Mode (belly-down)	Events (High Thrust)	325,000 (est)	--	--	1300
	Orbitkeeping (Low Thrust)	280,000	800	--	--
	CMG Desaturation (Low Thrust)	208,000	1540	--	--
18-24 months Zero-g Mode (belly-down)	Events (High Thrust)	125,000 (est)	--	--	500
	Orbitkeeping (Low Thrust)	280,000	800	--	--
	CMG Desaturation (Low Thrust)	537,000	595	--	--
Arrival of First Buildup Module					
24-36 months Zero-g Mode (belly-down)	Events (High Thrust)	250,000 (est)	--	--	1000
	Orbitkeeping (Low Thrust)	1,800,000	5150	--	--
	CMG Desaturation (Low Thrust)	1,430,000	4080	--	--

*17-ft moment arm.

†140-ft moment arm, Space Station to hub; 160-ft moment arm, S-II to hub.

5) It will be assumed that Space Station attitude can be maintained by another attitude control system such as control moment gyros (CMGs), while repair functions are being performed on the APS;
6) The propulsion system design is not constrained to a pod-type mount on the vehicle skin;
7) The study will be limited to the mechanical portion of the system and associated instrumentation. The electrical control circuitry shall not be defined;
8) The thermal requirements shall be considered, but detailed thermal analysis will not be undertaken;
9) Repair or resupply concepts should minimize the requirement for EVA;
10) The only requirement for the auxiliary propulsion system is in orbit, not during boost;
11) Establish the resupply/repair requirements imposed on the logistics craft rather than optimizing the type and size of the craft;
12) All hardware that is replaced must be collected and placed inside the logistics craft for return to earth;
13) Assume no continuous ground monitoring of the attitude control system.

B. SPACE STATION GUIDELINES AND CONSTRAINTS

Space Station guidelines and constraints pertinent to this study are presented in this section. They were extracted from the Space Station Phase B Statement of Work, dated 28 April 1969.

1. Space Station

Space Station is defined as a completely self-contained module including all systems and provisions for supporting a 12-man crew and a multidisciplinary experiments and applications program in low earth orbit. To obtain a high degree of program flexibility, the station design shall accommodate separately launched modules for crew expansion, new subsystems, and new payloads. Furthermore, the Space Station shall be designed to serve, with minimum in-orbit modification, as a module or prototype module for a space base that will be assembled in orbit at a later date.

The Space Station guidelines and constraints are:

1) It shall be designed to have a minimum operational life of ten years with resupply;
2) Space Station will include both artificial-g and zero-g operations;
3) The Space Station module shall be cylindrical with a maximum diameter of 33 ft;
4) The Station will be divided into separate pressure compartments so that any single compartment can be isolated in case it is damaged or rendered untenable;
5) The Space Station shall incorporate at least five docking ports. Each port shall provide a clear opening at least 5 ft in diameter for cargo transfer;
6) The Space Station shall be capable of independent operation with a full crew of 12 for periods up to six months following the initial resupply mission;
7) Stabilization and control subsystems shall be designed so the Space Station is stabilized by control moment gyros during both zero- and artificial-gravity operations. Reaction controls will be used for attitude control and orbitkeeping;
8) The basic subsystems will be designed for a long life, and for ease of repair and replacement in flight;
9) As equipment becomes obsolete, it will be replaced with new and better equipment and areas of a given module will be converted or remodeled after the original functions have been served;
10) The floors shall be normal to the radius of rotation and the furnishings shall be in an upright position in the launch configuration and during artificial-gravity assessment;
11) Each of the subsystems shall be designed with large margins and with provisions for inflight maintenance, repair, and replacement.

2. Program

The program guidelines are as follows:

1) A primary goal of the Space Station program is achieving a major reduction in the cost of space operations;
2) The first Space Station (crew size 12) will be flown as an operational vehicle in 1975;
3) A data relay satellite system will be operational before the Space Station reaches flight status.

3. Logistics Systems

The logistics systems transport crew members to and from the station, supply the station with expendables, new equipment, and experiments, and return data, specimens, and other cargo to earth. Two classes of logistics systems will be considered: advanced, low cost systems; and more limited systems derived from current spacecraft and launch vehicles.

4. Mission Control

The mission control responsbilities are as follows:

1) The crew of the Space Station will be assigned greatly increased operational control of the mission, and, as a goal, will be autonomous when the space base is operational. To the extent possible, the crew will be given the responsibility for checkout and status monitoring of onboard subsystems, fault isolation, maintenance, calibration, and repair of onboard subsystems and experiments and other equipment;
2) The crew shall be freed of routine operations to the greatest practical extent by the use of automated systems;
3) Full advantage shall be taken of onboard systems for checkout, fault isolation, guidance and navigation, programing, and data processing and editing, and of other features providing the Space Station and the logistics spacecraft with a high degree of autonomy;
4) Space base activities will ultimately be staffed with specialists with a minimum of astronaut-type training or physical conditioning. They will also include engineers and technicians with a specialized background in instrumentation and system operation and repair.

5. Safety

The safety requirements of the Space Station are as follows:

1) Redundant safety-critical systems shall be placed in separate compartments to ensure that a single emergency or failure shall not destroy both the primary and redundant systems;
2) Provision shall be made so that an emergency situation, with the exception of prime structure failure, can be isolated, contained, and controlled;
3) Safety-critical equipment shall be designed to allow emergency operation by using redundance and/or separation of parallel or similar functions, and the placing of such redundant or parallel equipment in isolation compartments or locations;
4) Potentially explosive containers such as high-pressure vessels or volatile gas storage containers shall be placed outside of and as remotely as possible from crew living and operating quarters, and wherever possible isolated. The possibility of providing such containers with special pressure release valves and/or vents should be explored;
5) If dangerous liquids must be handled on the Space Station, positive standards for handling such liquids in the ambient environment shall be provided;
6) Interlocks, automatic valves, or other means of isolation shall be provided for liquid and gas systems so that a maintenance effort shall not inadvertently result in liquid or gas leaks to the cabin and eventually to the environmental control system (ECS).
7) Intravehicular and extravehicular activity (IVA and EVA) equipment shall be designed to allow the astronaut ready access to items to be serviced or maintained;
8) Self-test and self-diagnostic equipment shall be installed in conjunction with the safety-critical systems, to allow constant monitoring and the detection and location of active and incipient failures in these critical areas;
9) EVA operations shall be minimized to the maximum extent possible.

IV. INFLIGHT MAINTENANCE

The need to determine the feasibility and practicability of providing a repair capability for an earth orbital Space Station Auxiliary Propulsion System (APS) is confirmed by the fact that today's systems will not maintain a reliability consistent with a 10-year manned space mission. This means that future long-duration manned space missions will require a drastic improvement in spacecraft capabilities to attain satisfactory probabilities of mission accomplishment. The anticipated increase in reliabilities of components and systems will not be sufficient in themselves to achieve the overall assurance that is required. The solution to this problem lies in the inclusion of appropriate onboard resources to augment or maintain, through the mission, the high reliability that a spacecraft initially possesses. In the past, for the relatively short missions, redundancy and overdesign of system hardware was the approach taken to achieve mission success. However, there is a point where a repair capability offers more return than redundancy alone. To determine this crossover point many factors must be considered, including length of mission, mission objectives, system design, system requirements, accessibility, and crew capabilities, to mention only a few. Therefore, to determine the optimum inflight maintenance (IFM) and repair program for a Space Station APS, one must first know and understand the mission objectives and then integrate the IFM program for the APS into the Space Station Logistics Plan.

A. FEASIBILITY OF IFM

When planning the operation of an APS for a long-term space mission, it is essential to identify factors and influences that can have a significant effect on mission success. When adverse conditions are identified or anticipated, it is necessary to provide a means to compensate for them. Therefore, some form of contingency protection must be made available.

The system designer has four basic options in the selection of a contingency protection to achieve the desired operational capability. They are to:

1) Overdesign system hardware;
2) Accept some degree of degraded performance;
3) Incorporate redundancy in the system hardware;
4) Provide IFM capability.

These options are interrelated and one approach does not necessarily exclude the other three. The approach will depend on technology level (state of the art), system design complexity, mission duration, reliability criteria, resupply interval, crew availability, and safety, etc. This portion of the study is an outgrowth of the recognized need for the development and implementation of the most realistic approach to contingency protection for long-term space missions -- an IFM capability. Defined simply, IFM consists of all actions necessary for retaining a system, subsystem, or component "in" or restoring it "to" a specified condition during spaceflight missions.

Figure IV-1 shows the interfaces and interdependency of IFM for the APS with other elements of the Space Station. The relationship of the APS to the Space Station and the operational requirements for the APS will create certain IFM demands. These demands are peculiar for each mission and are caused by one or more of the following conditions:

1) Random failure;
2) Damage, human- or environment-induced;
3) Wearout;
4) Resource consumption (normal or emergency).

Once the mission demands have been identified, the next step is to identify the resource demands and how they will be applied. Maintenance resources consist of technology, people, material, and services applied individually and collectively at the right place, at the right time, in the required amounts, and in an operable condition. These resources possess a variety of characteristics that materially affect their application. In all cases, however, the resource selected must meet the demand in order to have an operable IFM Plan.

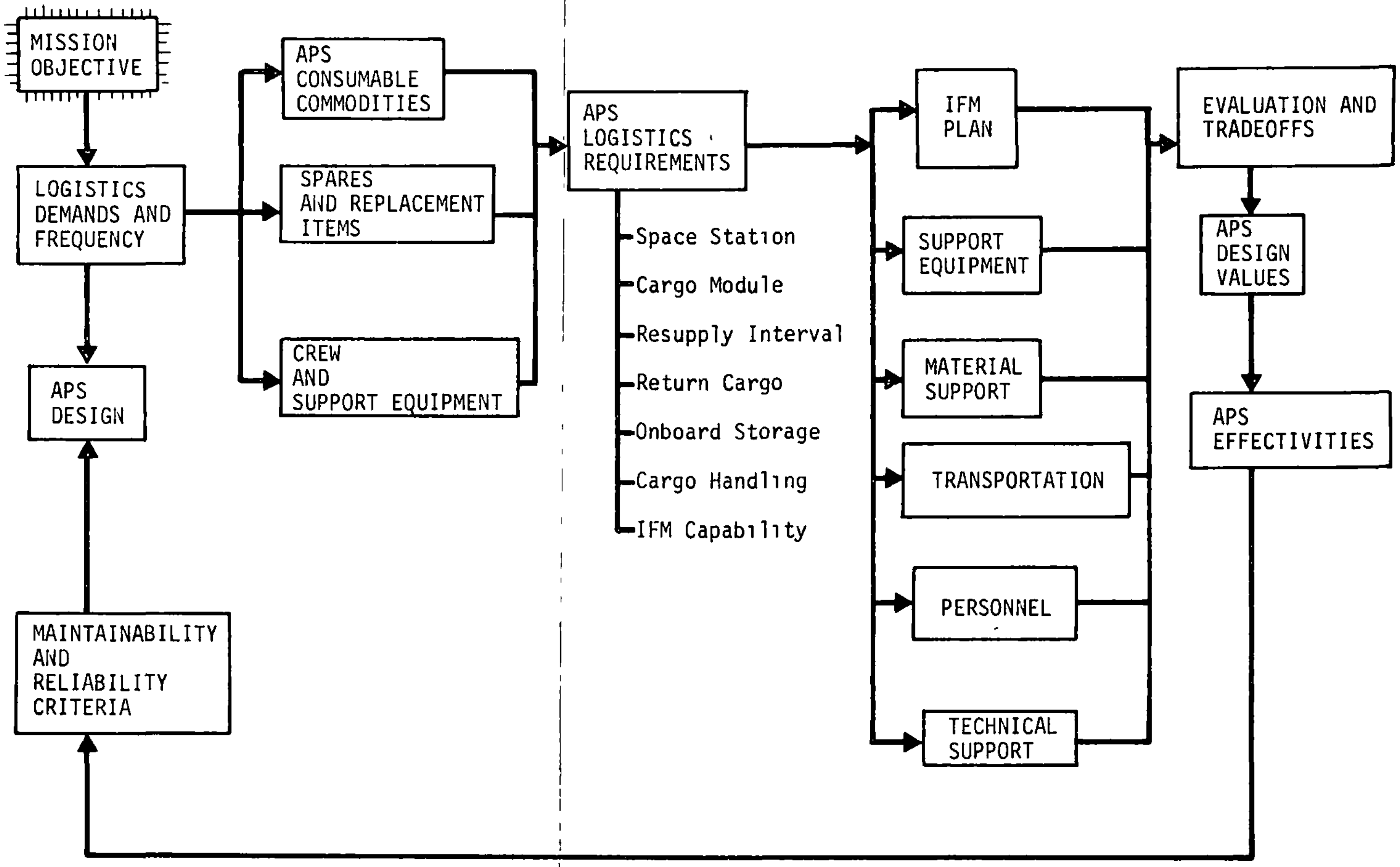


Fig. IV-1 APS Logistics Plan

B. TECHNICAL APPROACH TO IFM

With the multitude of decision factors which have either a direct or indirect effect on the IFM plan, a mission-oriented IFM concept must be developed. One way of developing the IFM concept is shown in Fig. IV-2. By following this scheme the optimum IFM plan should be established. During the development of the concepts, all tasks are classified in categories as either preventive (scheduled) or corrective (unscheduled) maintenance.

Some of the factors that affect the maintenance concept are: (1) performance constraints; (2) mission duration and scheduled mission events; (3) resupply interval; (4) crew size and available discretionary time and crew skill; (5) fault isolation technique; and (6) mission module weight and volume penalties. These factors are the operational and performance factors that must be considered in developing an IFM concept for the APS. In addition, there are hardware and design factors that will influence the IFM concept. These factors are functional design constraints, component life, and failure rate.

The four basic maintenance concepts considered in developing an APS IFM capability are:

1) Remove item and replace with spare, repair failed item;
2) Remove item and replace with spare, discard failed item;
3) Remove, repair, and replace same item;
4) Repair item in place.

The first concept, remove item and replace with spare, then repair failed item, is described below as an example of a maintenance concept. The first step is the indication of system failure, fault location, and the corrective action instructions. This information will be displayed on the onboard checkout system display panel and by a predetermined code the crew member will be advised of what action he must perform. The alternative available to the crew will depend on the type of failure and its criticality to the mission. When the repair is to be made, the failed item is isolated from the system and the fluid removed from the system. The failed item would then be removed and replaced with a spare. After testing for leakage, the fluid is bled into the repaired section and the system checked out before returning the system to an operational status. The failed item would be repaired, tested, and returned to storage as a spare.

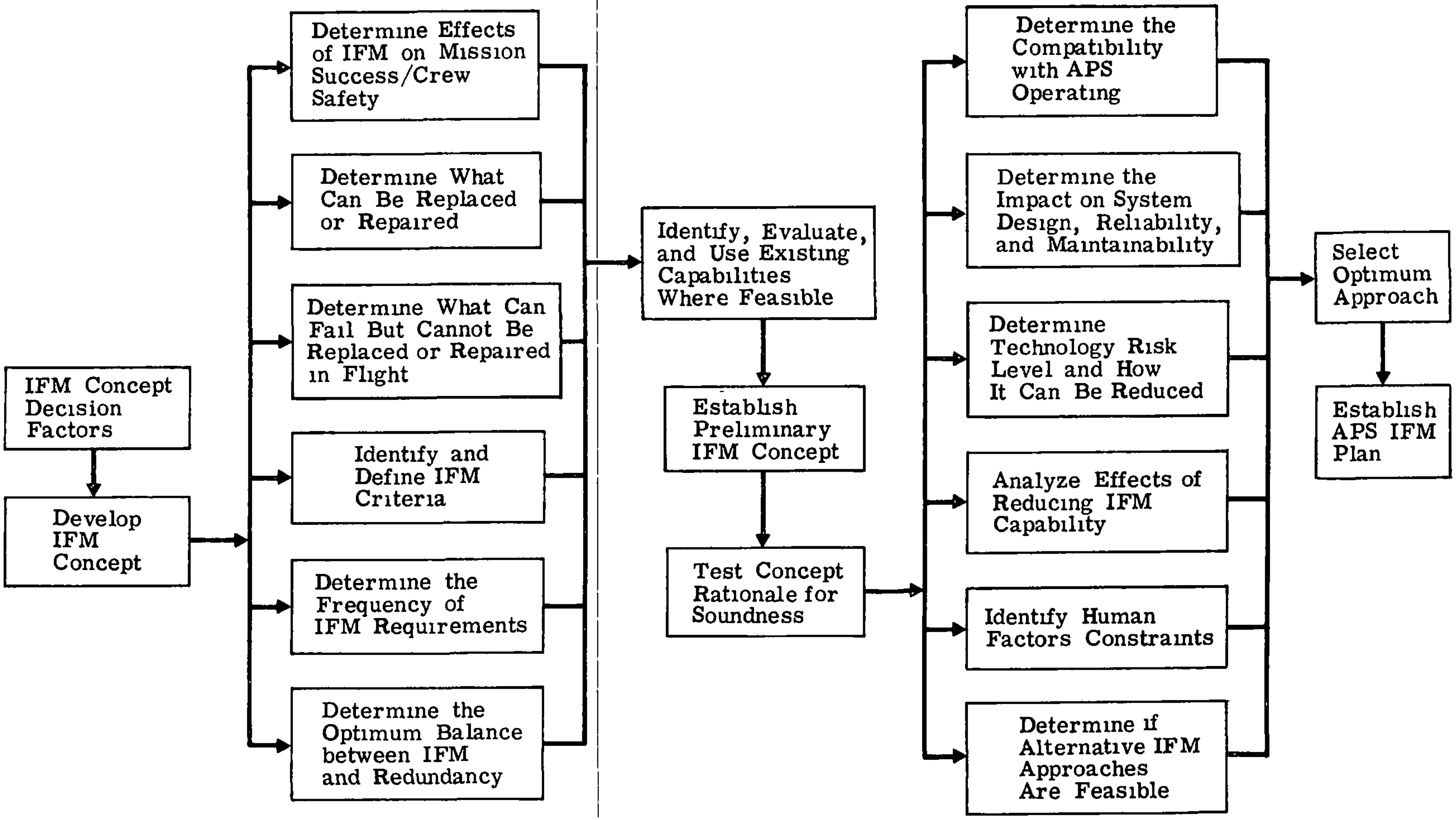


Fig IV-2 Auxiliary Propulsion System IFM Concept Development

The requirements for an inflight maintainable system are determined by performing a step-by-step functional analysis of all possible IFM concepts and then analyzing what is required to accomplish each function. The decision to use a particular IFM concept has a definite effect on the requirements for specific resources such as spares, repair kits, procedures and techniques, repair time, etc, as shown by the functional flow and requirements matrix in Fig. IV-3.

Anticipatory malfunction detection, such as electrical, noise, thermal, visual devices, and sonic monitoring can be used as a means of delaying scheduled maintenance until a wearout failure is imminent. These devices can also be used to anticipate random failures so that repair tasks may be scheduled into the daily workload. Reliability of crew performance must also be predicted to determine the extent to which the system must be designed, either to compensate for the crew's maintenance limitations or take advantage of their maintenance capabilities.

It is apparent that maintainability of the APS or any other system can be directly related to its complexity, the mean-time-between-failure (MTBF), and the ease of effecting component/module/system replacement. It is also desirable for the hardware to be so designed that as new and better equipment (components) is developed, the obsolete equipment can be removed from the system and replaced with the new. In the same respect, a maintenance concept that is flexible enough to adapt to and be compatible with new maintenance techniques and fault isolation instrumentation is desirable.

	Mode	OCS	Manual or Automatic	Manual or Automatic	Manual	Manual	Manual	Manual	Manual	Manual or Automatic	OCS		
Requirements	System Design		Build Isolation Capability Into System Design Either At Component or Subsystem Module Level.	Provide Purge Or Evacuation Ports Into System Design At Component Or Subsystem Module Level	Provide Removal Capability (QD's) In System Design at Component or Subsystem Module Level Package Design for Easy Accessibility & Removal	Provide Spare Storage Plan Consider Storing Critical Items Adjacent To Operating Part To Save Time Package Design for Easy Accessibility & Installation	Component Design for Simple Disassembly & Assembly		Package Design For Easy Accessibility & Installation	Design System To Bleed In Through Purge or Evacuation Ports Or Provide Special Ports Equipment For Recharge Stored Commodities For Recharge		Storage Space For Spares (OCS) Will Advise Crewman Where to Store	Storage Space For Failed Items Replenish At Recycle Time
	Maintainability Support Equip			Purge Equipment Portable Or Fixed Installation Evacuation Equipment Portable or Fixed Installation	Tools	Tools	Work Station With Special Jigs & Fixtures Cleaning Equipment Special Tools Piece Part Spares Step by Step Procedure (OCS)	Tools Test Equipment Pressure Source Pressure Readout Leak Check Continuity Voltage Amps	Tools				

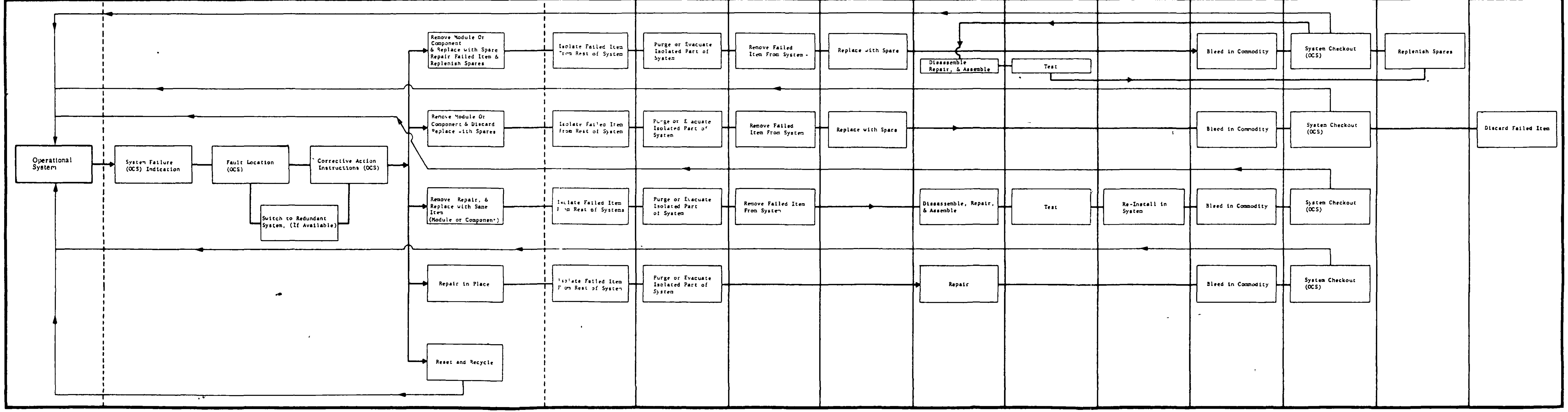


Fig. IV-3 IFM Functional Flow and Requirements Matrix

C. IFM CONCEPT EVALUATION

In evaluating the four basic IFM concepts, it is found that three of these are similar in that the failed component or assembly must be removed from the system. This places a requirement on the system design and packaging. Each component or assembly that is expected to fail at some time during the mission must have a parallel redundant backup or be designed so that it can be removed and replaced. The possibility of failure is evident for all components that make up the APS. Therefore, some kind of remedy must be provided to assure mission success. The greatest improvement in mission reliability is achieved by the use of isolation valves, and separable fittings with reusable seals, which is also a requirement in providing an IFM capability. This fact is further demonstrated in the reliability analysis. In the two concepts that require the repair of the removed failed item, more support equipment for repair and testing of the item will be required, but the repair kits will have less volume, weight, and cost than a complete spare. In the concept of replacing the failed item with a spare and then repairing the failed item and replenishing the spares with the repaired item, the extra volume, weight, and cost penalty of the complete spare will be borne only once at launch.

The concept of repairing a failed item in place is not applicable for most components at present. To incorporate this maintenance philosophy in a system or the Space Station would require major new development of components and extremely close integration of system design as well as extensive training of the crew. This concept does offer many advantages, however, in the saving of volume, weight, and cost by using repair kits.

The normal onboard system checkout equipment can be used to test a repaired portion of the system, thereby eliminating the need for extra support equipment. This concept may be very attractive for a mission, such as Mars, where volume and weight is a premium or no resupply is anticipated.

As can be seen from the above statements, which were substantiated during the course of this study, no one maintenance concept can be applied unilaterally. The maintenance concept for each subsystem should be determined by careful consideration of subsystem design features and parameters and the relationship of the system to the Space Station as a whole.

Another major area that requires consideration at the time of developing an IFM capability is the degree of fault detection and isolation. Even when man is available to perform maintenance activities, there can be a considerable difference in the level of maintenance that can be performed, depending on the fault detection and isolation capability provided. This is as much of a factor for an IFM capability as the replaceable component level designed into the system or the crew skills involved. The ultimate design for ease of maintenance would be an automatic fault detection and isolation capability that would be able to identify any item that might have to be replaced. The fault detection and isolation techniques applicable to the Space Station APS is more fully defined in Chapter VIII, Fault Detection and Isolation.

It is concluded that the optimum method of IFM for an earth orbital Space Station APS is to remove and replace on a component or module level with in-place repair of the plumbing. The faulty component or module would be returned to earth for repair or discarded. In some cases it may be possible to perform some repair on a failed component after it has been removed, such as replacements of seals, poppets, solenoids, etc. However, the capability must exist in the Space Station general purpose laboratory to make simple repairs when necessary and critical to system operation.

D. BASELINE SYSTEM ANALYSIS

The first step in developing an IFM philosophy for the APS was to analyze the baseline system and the components that make up the system. This was necessary to determine the actual configuration and functional capabilities of the APS. The baseline APS is depicted schematically in Fig. IV-4 and pictorially in Fig. IV-5. As can be seen by the schematic, no single failure will cause the system to become nonoperational but there is no way to isolate any portion of the system in case of a failure, except for the engines.

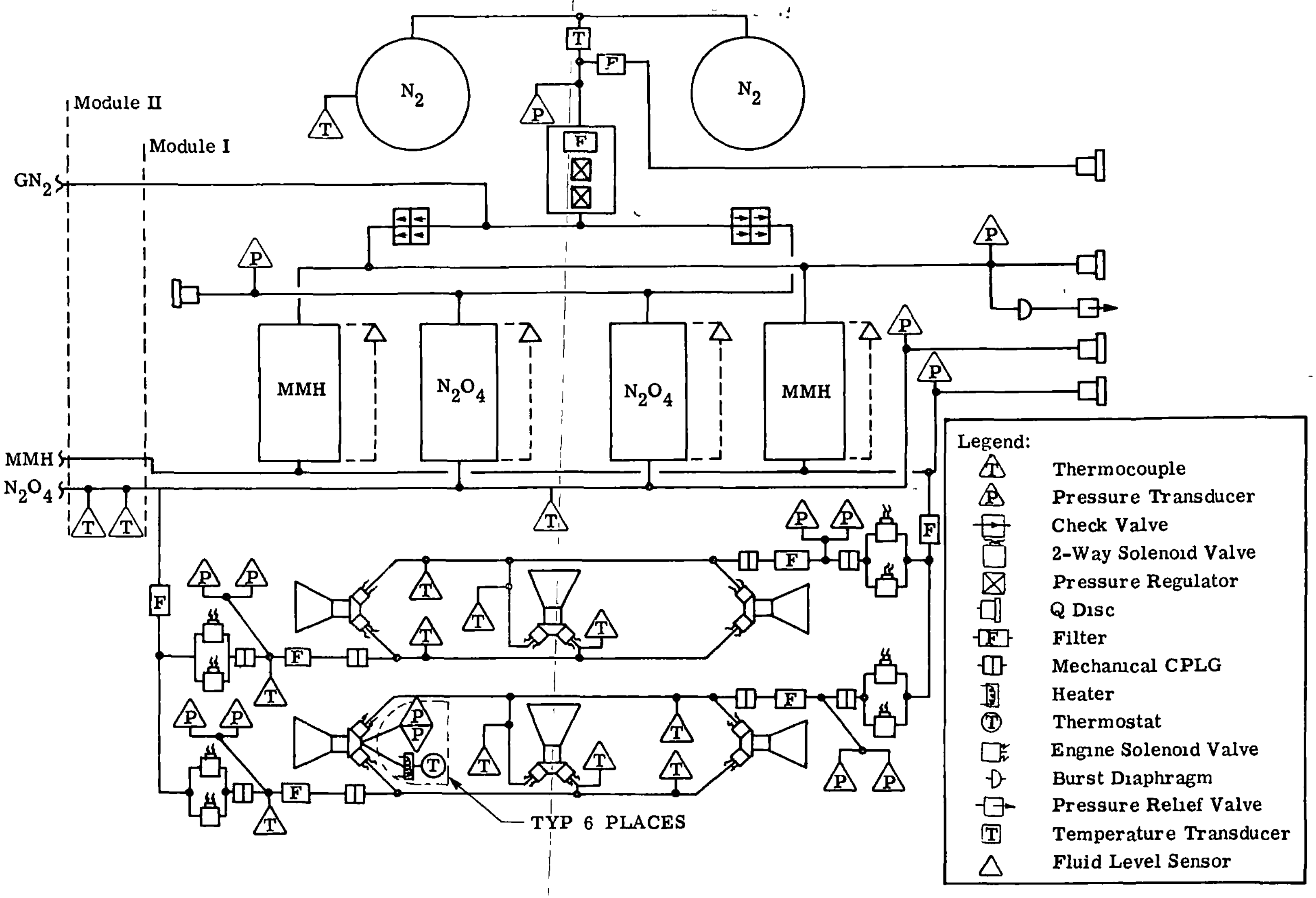


Fig IV-4 Baseline APS Schematic

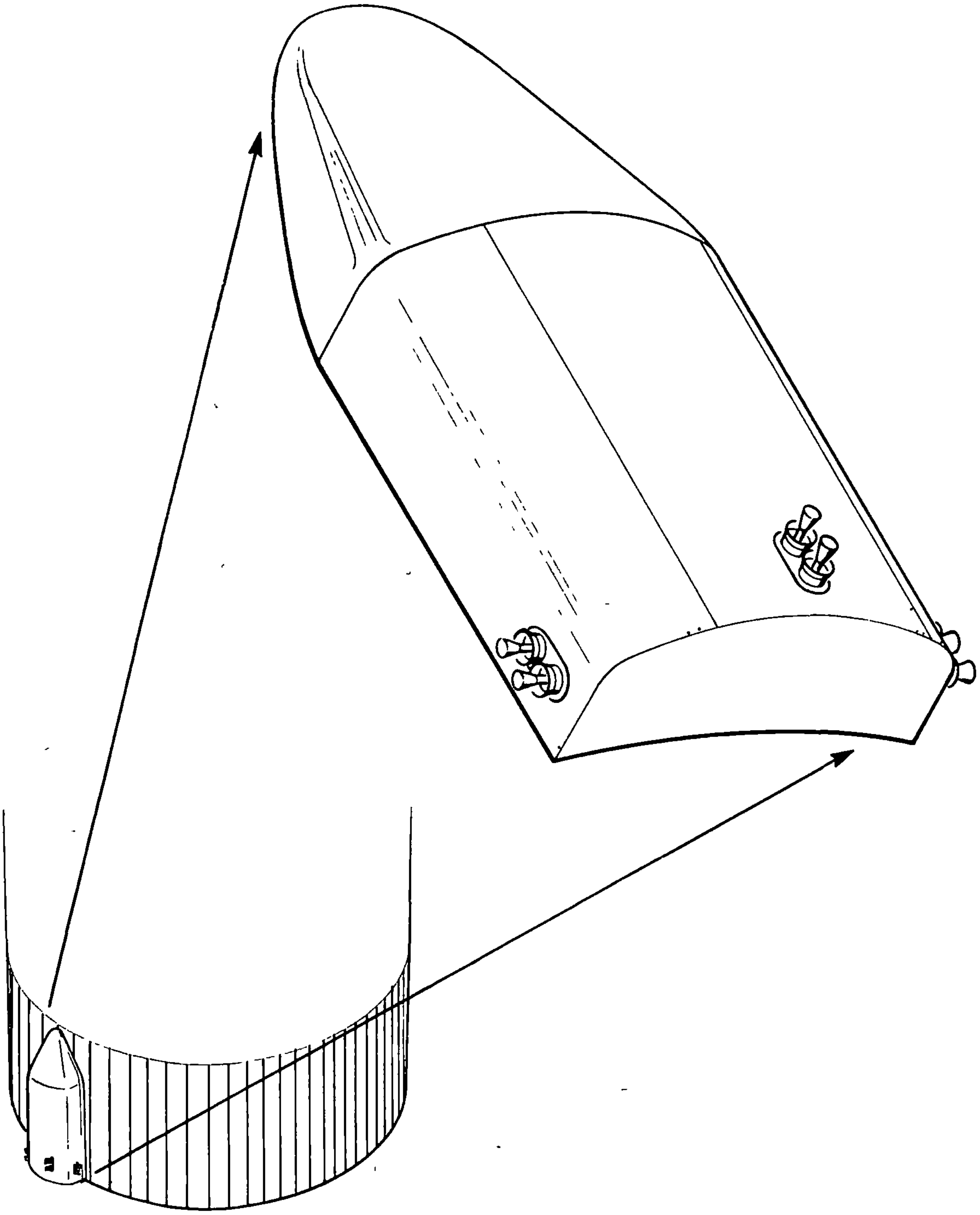


Fig IV-5 Baseline APS Pod

In applying the various repair concepts to the baseline APS, it is found that the system requires extensive EVA and tube brazing to effect either system, module, or component removal and replacement. This could be averted if the APS was mounted to a docking ring on one end of the space station. In case of a failure or during resupply, the logistic vehicle would dock and remove the failed or expended system and redock a complete full system. This concept places mission constraints on both the Space Station and the logistic vehicle. Therefore, this approach was not further considered as an optimum approach for an IFM capability. This action did not eliminate the pod configuration completely because techniques could be developed as illustrated in Fig. IV-6, where the pod is removed and replaced from within the Space Station, or the components could be so packaged that they were accessible through removable panels on the interior skin of the Space Station. Final APS requirements, which will determine size, will be a major factor in determining if the complete pod can be replaced. If the present APS size, weight, and packaging were considered, this method would not be attractive. The approach of making the components accessible through removable internal panels is more feasible even though it would require complete repackaging and use of separable fittings.

Another IFM requirement is to remove and replace components when they fail or reach a scheduled replacement time in the program. The failed component would be either repaired or discarded. Here again, the baseline APS packaging does not lend iteself to this concept. As shown in Fig. IV-7 the baseline APS schematic, replacement of a component such as a pressure regulator, solenoid valve, or tank would involve removal of the remaining pressurant or propellant, removing several parts that are secured with many small bolts, unbraze the interconnecting tubing to remove component, replace component, rebraze tubing, test, and then resupply. All of these maintenance tasks would have to be performed during astronaut EVA.

The remaining IFM concept of repairing the failed component in-place is not feasible or possible on the baseline APS for the reasons identified above.

It is apparent from this analysis that the baseline APS, as configured, is not adaptable to providing an IFM capability. The only possible concept that would be feasible would be the removal and replacement of a complete pod, assuming the interconnecting lines were accessible. Therefore, a pod assembly similar to the baseline that is only accessible by EVA and replaced as a complete pod is not recommended or feasible for the following reasons: (1) excessive EVA by several astronauts; (2) extensive handling equipment due to size; (3) large impact on logistic vehicle; and (4) no flexibility in maintenance or system operation.

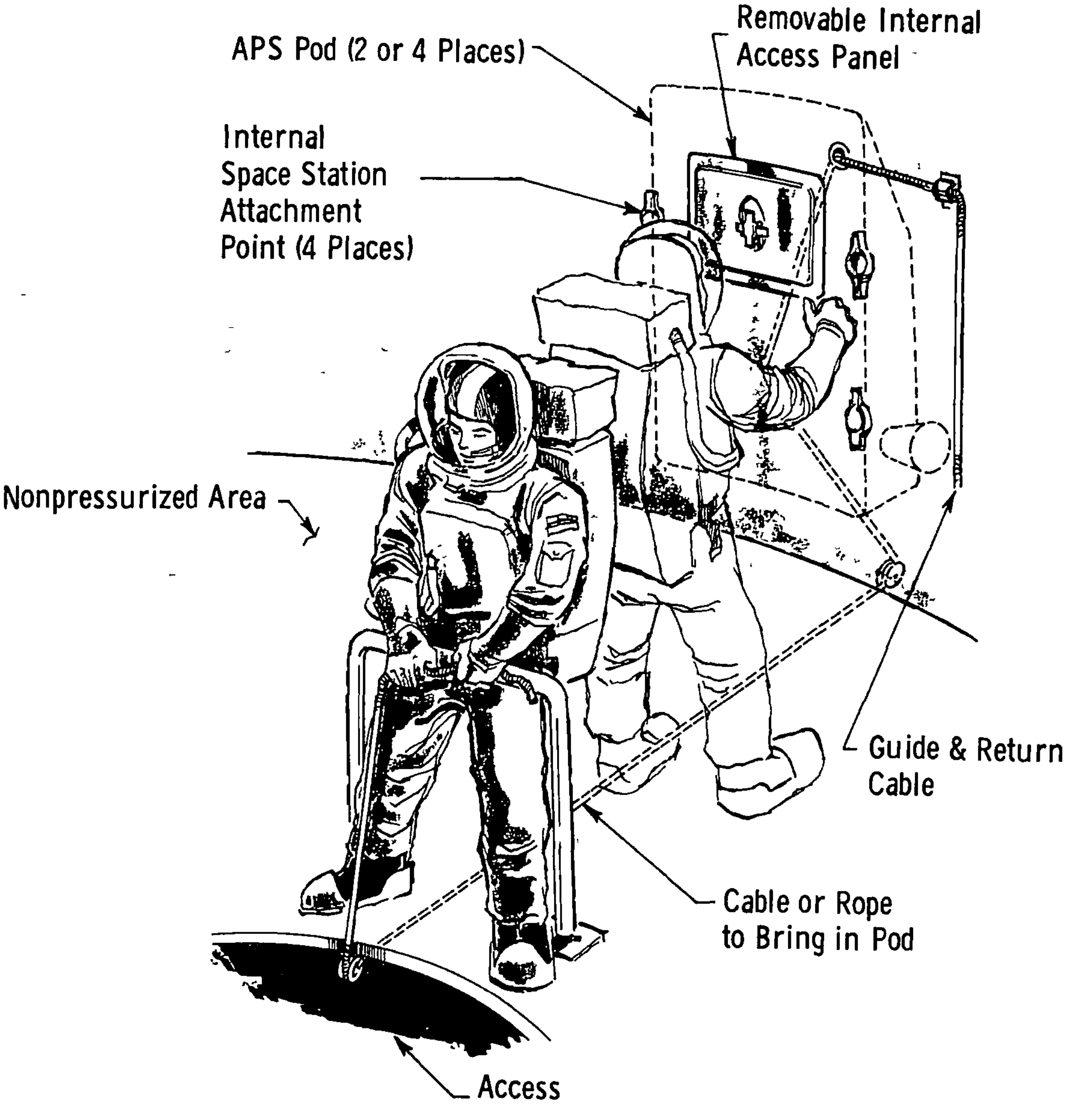


Fig. IV-6 APS Pod Removal/Replacement

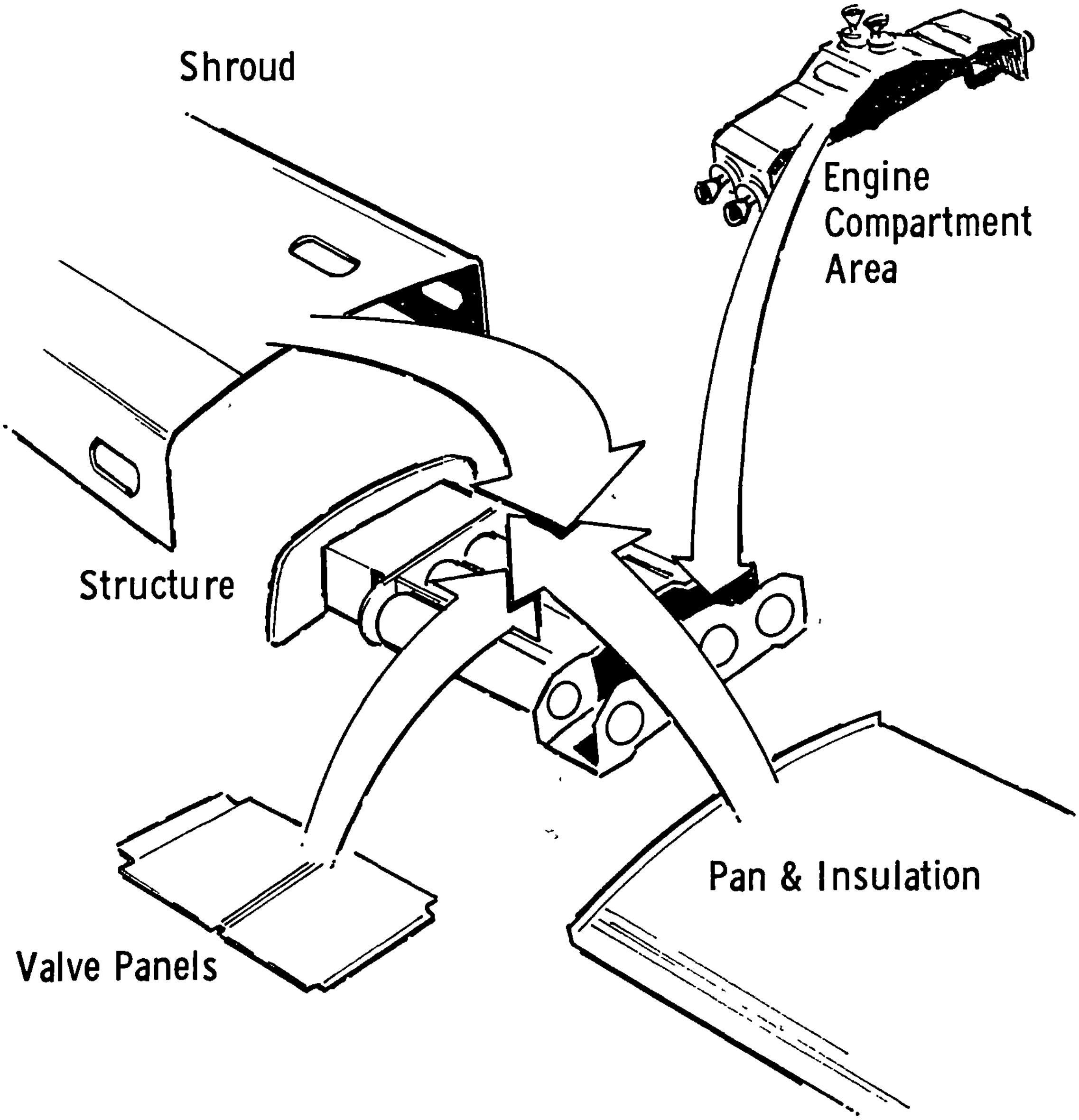


Fig. IV-7 Baseline APS Maintenance

1. Modified Pod Concepts

In the pod concept, the designer has several options in both system configuration and location of pods to provide an IFM capability. One approach to the pod concept is to have the externally accessible pod and system designed so that components or a cluster of components (module) can be easily removed and replaced with a minimum number of connections and structure removal. Incorporated into this design would be isolation valves and quick disconnects to provide component isolation and removal with simple hand tools. Some undesirable features about the external pod are the requirements for an aerodynamic and protection cover and insulation which must be removed to perform maintenance tasks, complete remote monitoring and switching control, and extensive EVA. For these reasons, this approach is not recommended.

Therefore, the only feasible approach relative to IFM requires locating the pods on the Space Station so they are accessible from inside the Space Station. This approach would have access doors or panels operable from within the Space Station to permit removal/replacement of all components or modules. This would eliminate EVA and the requirement to remove the protective shroud and insulation to perform IFM. With this approach, either the modular packaging or individual components could be used. Therefore, as mentioned before, packaging is a prime factor in providing an IFM capability for the pod configuration. The three main levels to be considered in the physical arrangement within the pod or Space Station are the system, system modules, and components. These are closely related to each other and are individually vital to the crew's ability to successfully perform IFM.

Therefore, it is recommended that if the pod concept is adopted to house the APS using present-day components and technology, the pod should be designed so that all components are accessible and removable from within the Space Station. A technique in performing maintenance tasks on an externally mounted pod is illustrated in Fig. IV-8. A portable vacuum glove box is placed over the access panel to provide a crewman protection from toxic vapors while working in a shirtsleeve environment and a clean area to perform maintenance tasks. A desirable design requirement would be to have the area within the pod capable of being pressurized during maintenance and/or resupply tasks. This would allow maintenance on all pressurant components in a shirtsleeve environment without the glove box. The design considerations that are valid for the other concepts such as isolation valves, separable fittings, and purge/bleed capability are also required for this approach.

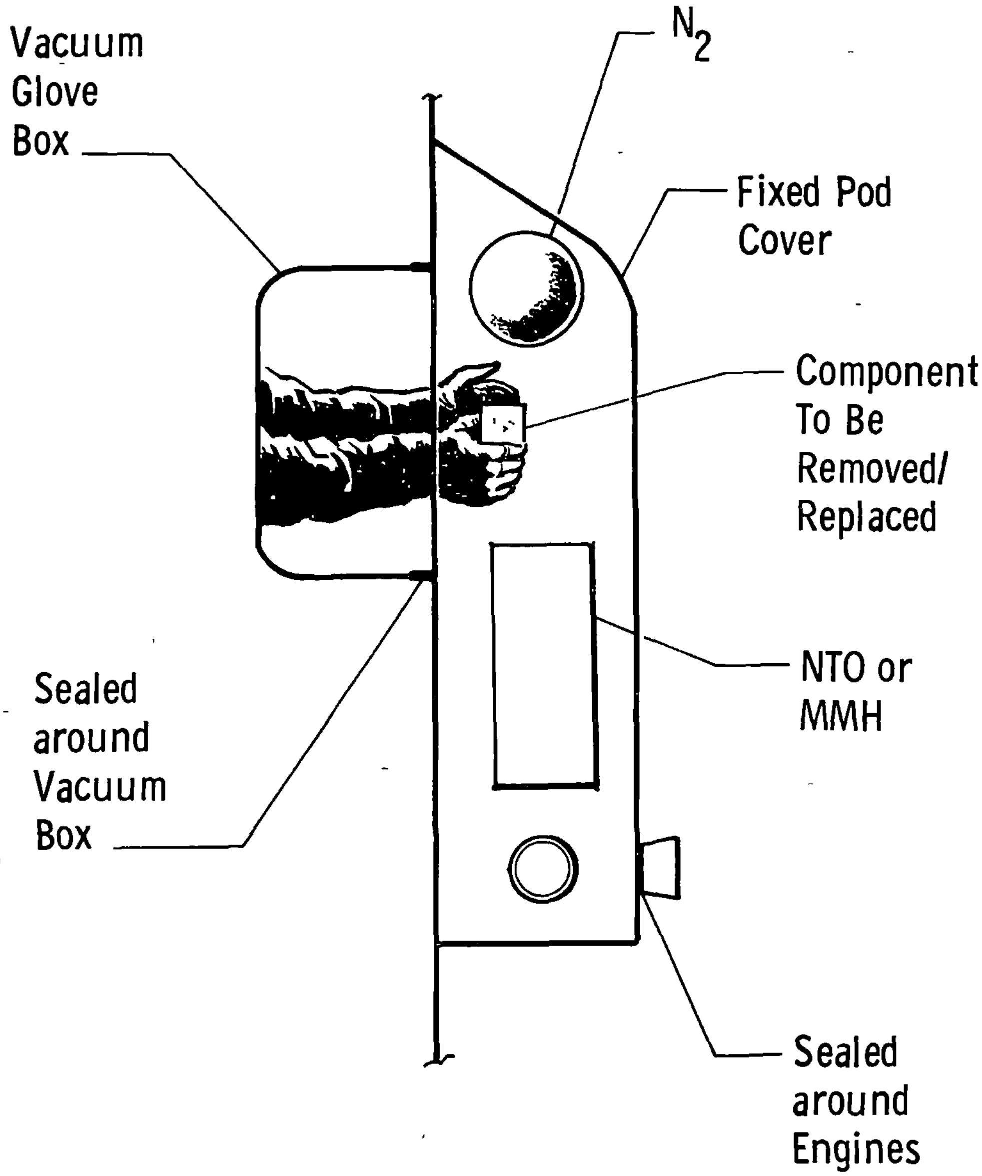


Fig. IV-8 Portable Glove Box Concept

Some disadvantages of the internally accessible pod approach are: (1) higher weight due to thermal requirements and structure required for packaging to achieve accessibility; (2) less reliability with either the two- or four-pod configuration; and (3) packaging complexity. In the two-pod configuration the lower reliability is due to the possible damage to a good engine if the adjacent engine fails by explosion; in the four-pod configuration the lower reliability is due to the greater number of components to retain some redundancy and still operate the system.

2. Modification of Baseline APS

To have an inflight maintainable system the baseline schematic and configuration must be modified. The first attempt was to use the existing components and add only the items necessary to have an IFM capability. The first modification consisted of adding three-way isolation valves, and the addition of self-sealing quick disconnects and mechanical fittings to the extent necessary to remove each component from the system with simple hand tools. These additions increase the leakage paths for the system, however, the advantages they offer more than offset the induced leakage potential.

The changes made to the baseline APS are illustrated in Fig. IV-9, which shows a preliminary modified APS schematic. It was realized that packaging, monitoring instrumentation, fault detection, and physical location in or on the Space Station are also major factors in determining an IFM capability. However, this modified schematic does show the minimum items that are necessary to achieve an IFM capability. The isolation valves not only provide a more easily maintainable system, but increase reliability of the system. The separable fittings will provide the capability to remove and replace components either on a scheduled basis or for random failures with simple hand tools (wrenches, etc).

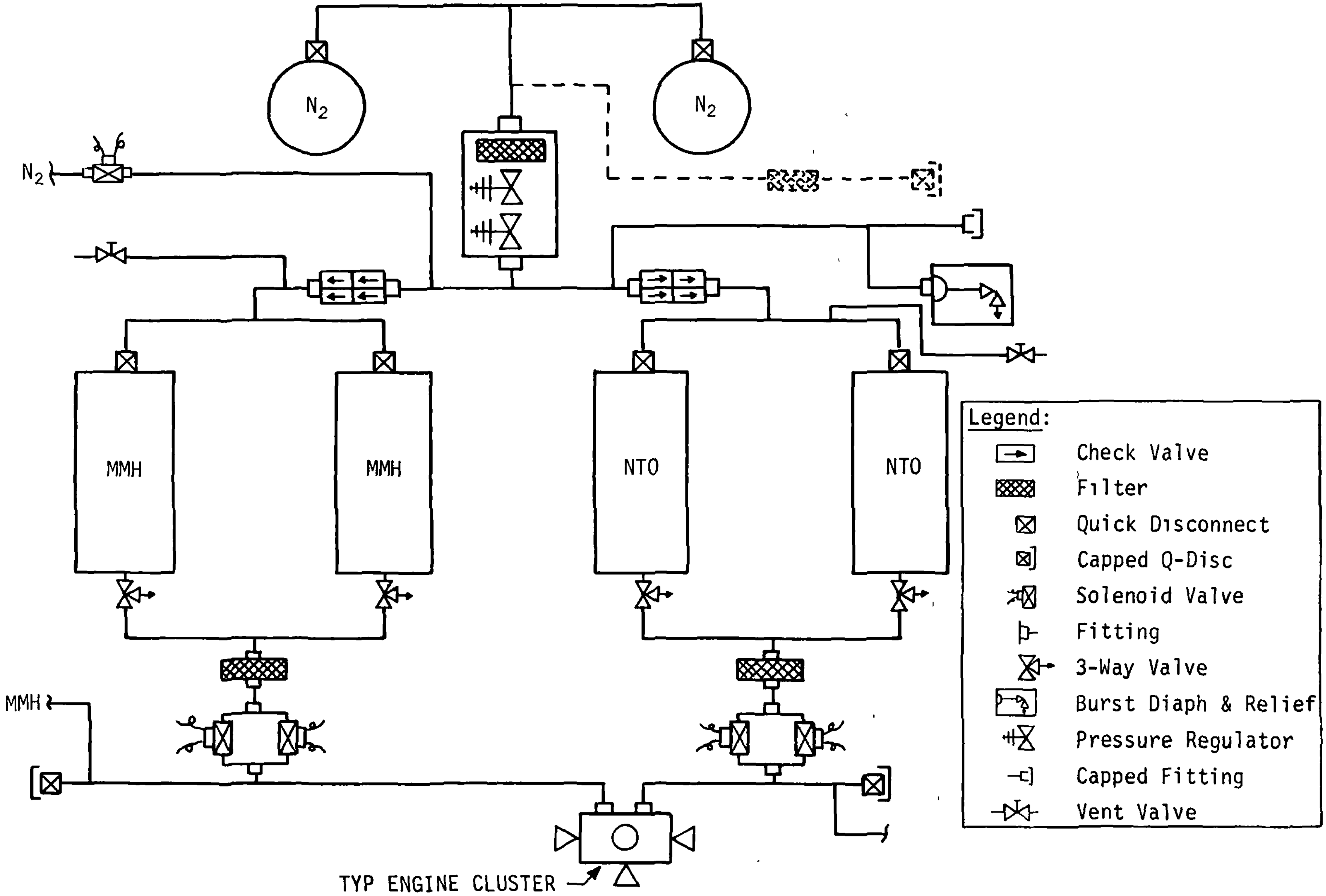


Fig. IV-9 Minimum Requirements for Maintainability

E. MODULAR CONCEPT

The modular concept involves the grouping of components and subassemblies so that inflight maintenance is optimized. Components can be effectively grouped, by commodity and/on anticipated life expectancy, into a single module body, thereby reducing external leakage paths and providing a minimum volume and weight. Repair or replacement can be performed on the entire module, or on any subassembly within the module, with only a minimum level of crew training required. Crew time required to repair or replace would also be minimized.

In a typical bipropellant propulsion system, the system can be divided into four modules to facilitate maintenance. These modules are: (1) pressurant storage; (2) pressurant control; (3) propellant storage; and (4) engine module. This concept is depicted schematically in Fig. IV-10, and represents the recommended APS configuration for an optimum IFM capability.

1. Pressurant Storage Sphere

The pressurant storage sphere assembly would consist of a nitrogen sphere, a manually operated valve, a self-sealing disconnect, and a protective covering. Figure IV-11 shows a typical pressurant storage sphere. The exact number of spheres will depend on Space Station requirements and the system designer. However, based on the Space Station baseline requirements, the designer has the option of two to four spheres for the system. Actually, one sphere could fulfill the pressurant requirements, however, for safety and some backup, a minimum of two is recommended. The advantages of two spheres over four is that it reduces total weight and increases reliability slightly. This design approach is compatible with the modular resupply concept of replacing the pressurant module. The self-sealing disconnect is recommended in lieu of separable fittings because it serves as a back-up valve while reducing modular resupply time. Present technology does not indicate that repair will be performed on a high-pressure (3000 psi) vessel within the Space Station workshop. Therefore, half of the disconnect and valve could be permanently attached to the sphere by brazing or welding since the sphere will be returned to earth for servicing.

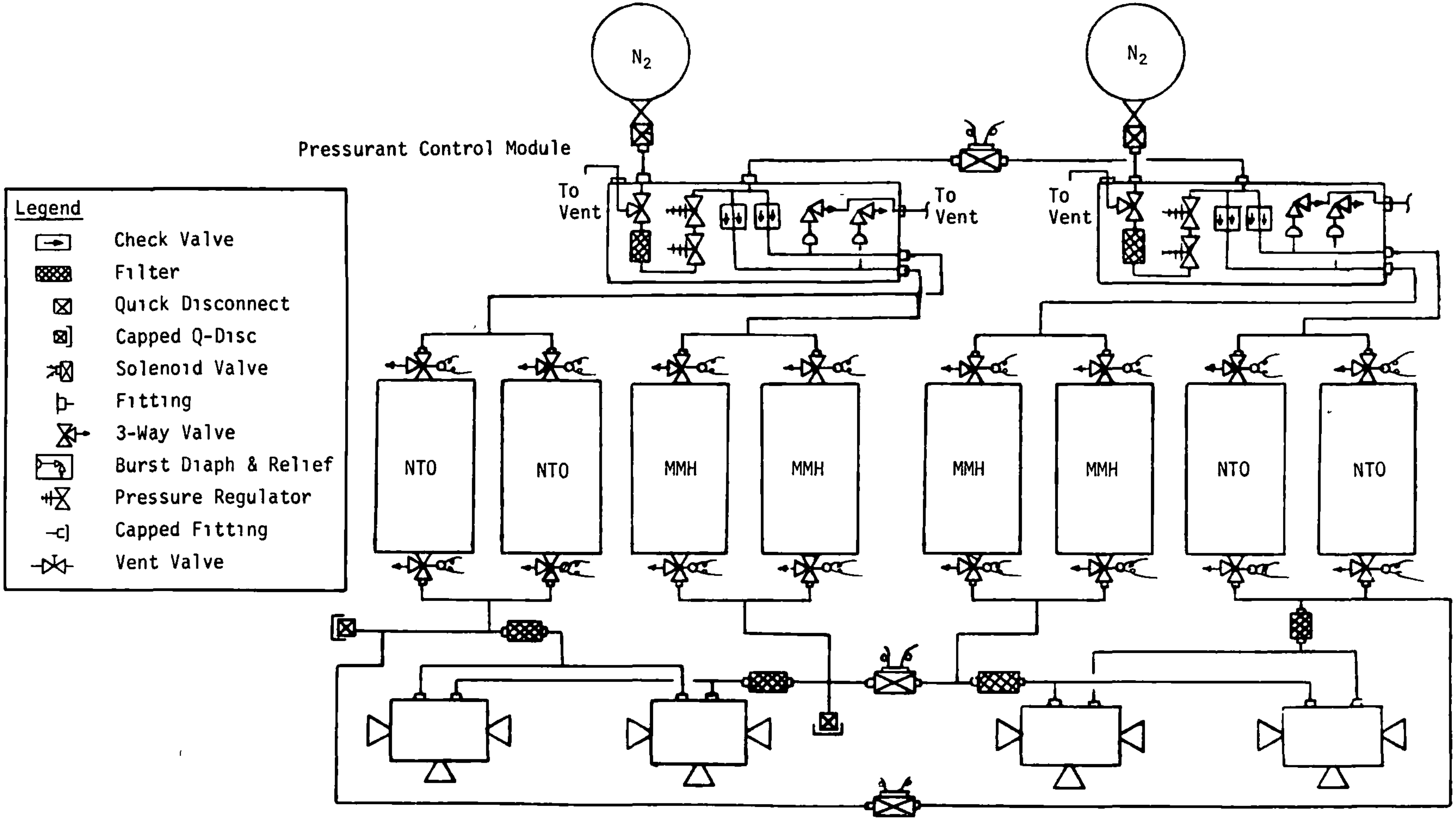


Fig. IV-10 Recommended APS Schematic

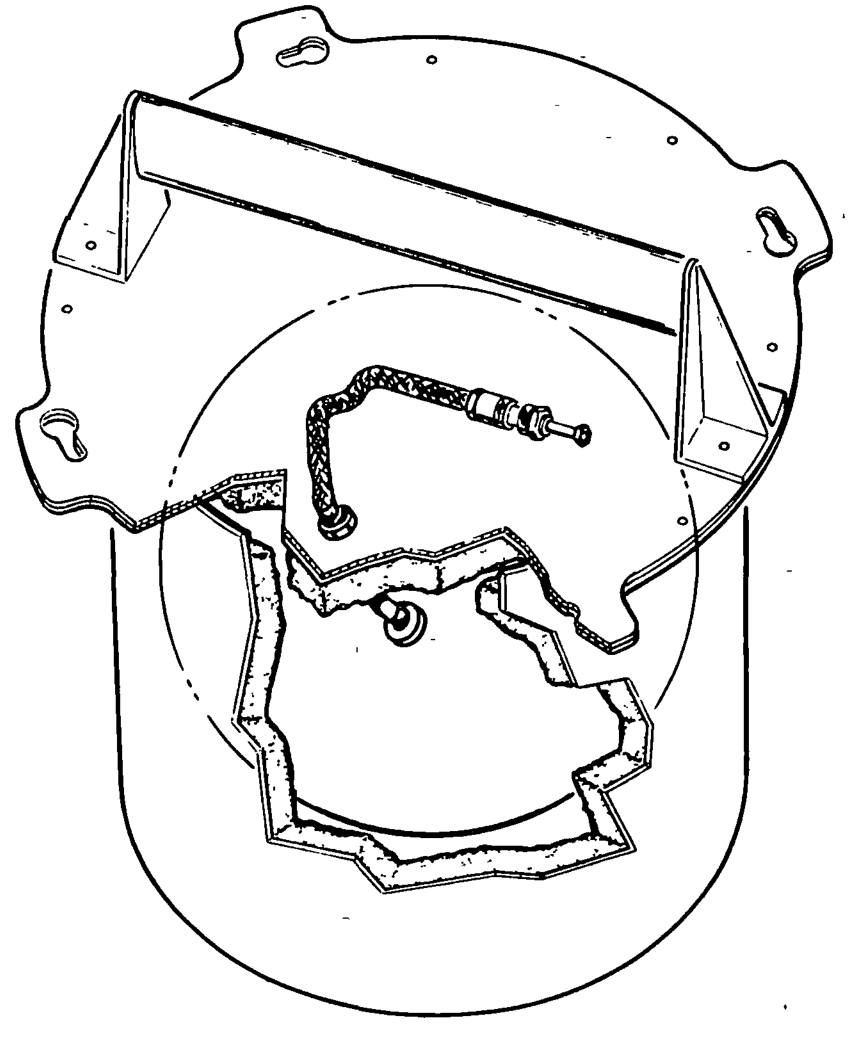


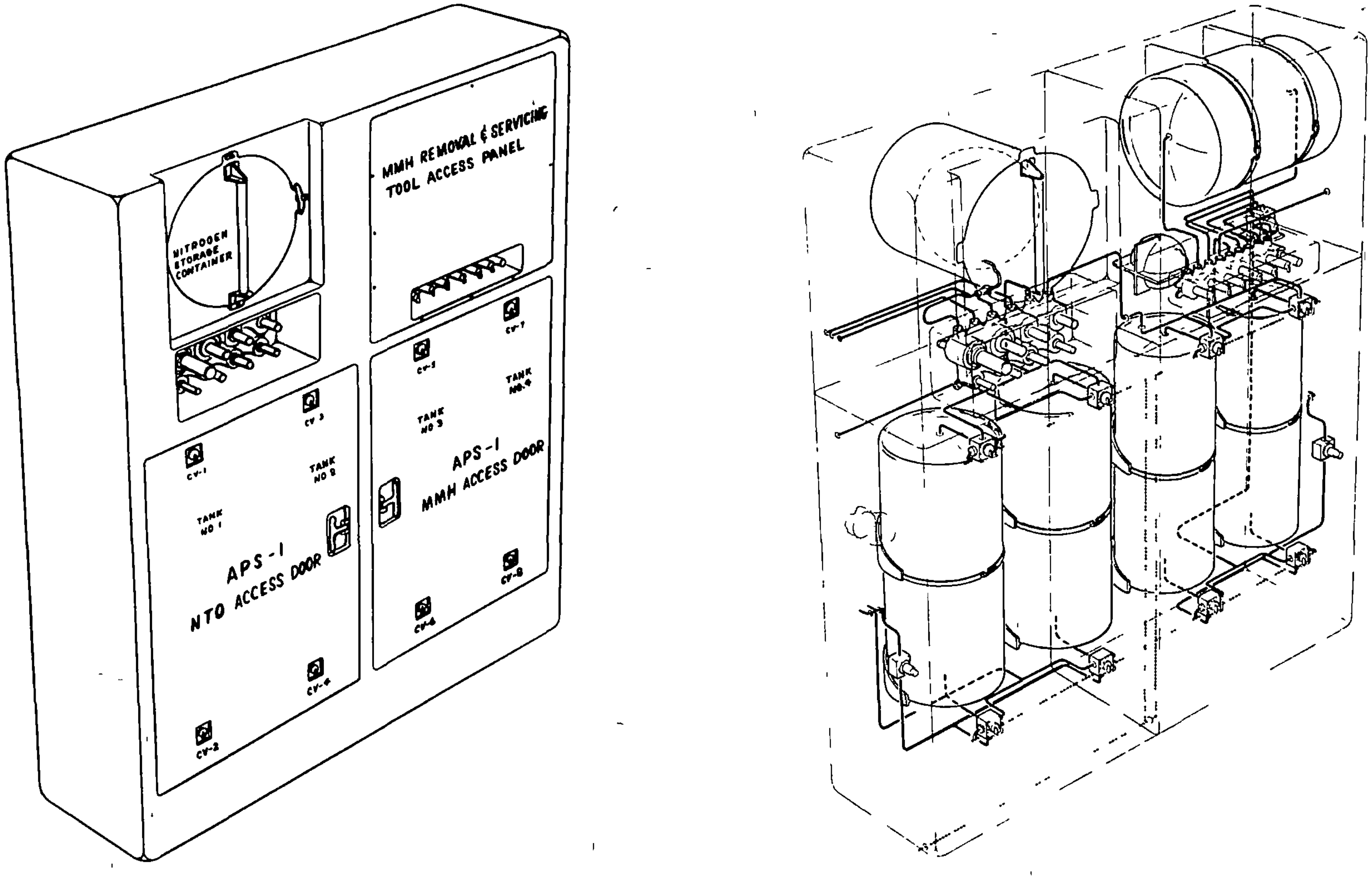
Fig. IV-11 Nitrogen Sphere

The Space Station constraints and guidelines specify that high-pressure pneumatic tanks and propellant tanks shall not be located in the crew quarters, and further, that a structural wall shall separate the tanks from the crew quarters. Figure IV-12 depicts a compartment configuration that satisfies the above constraint and still allows IVA maintenance. During replacement of the sphere, either for resupply or repair, the enclosed tankage area could be pressurized for a shirtsleeve environment. This would facilitate repair/replacement and still retain a high degree of safety. Special tools and protective packaging are not required to remove or replace the pressurant storage sphere or to provide protection during transportation to and from earth. The modular resupply method dictates that protection is required for the pressurant sphere and personnel handling the module. The depleted or failed nitrogen sphere can be depressurized completely, or to a relatively low pressure, for the return to earth. Limited quantities of residual nitrogen can be bled into the living quarters to make up the O_2/N_2 atmosphere, thus conserving the commodity within the Space Station.

2. Pressurant Control Module

The pressurant control module consists of the following components: shutoff and three-way bleed valve, filters, pressure regulators, check valves, burst diaphragm, and relief valve. These components could have a common module body with the various hold-down mechanisms attaching the components to the body as shown in Fig. IV-13.

This module lends iteself to the two maintenance concepts, (1) removing and replacing the entire module, and (2) replacing a module subassembly in place. This design offers the most flexible approach in that subassemblies can be replaced with the module in place in the event of a random failure, and still provide total modular replacement for scheduled replacement as determined from wearout data. The principal advantage of this design is that it offers a high degree of maintainability with relatively few spares and instructions. In keeping with this design objective, the components such as valves and regulators could be designed so that repair would consist of replacement of subassemblies instead of piece parts. Since failures for these components are usually the valve seat or poppet, these items can be designed to be removed and replaced as a slip-in/slip-out assembly as shown in Fig. IV-14.



(a) Exterior

(b) Interior

Fig IV-12 APS Compartment

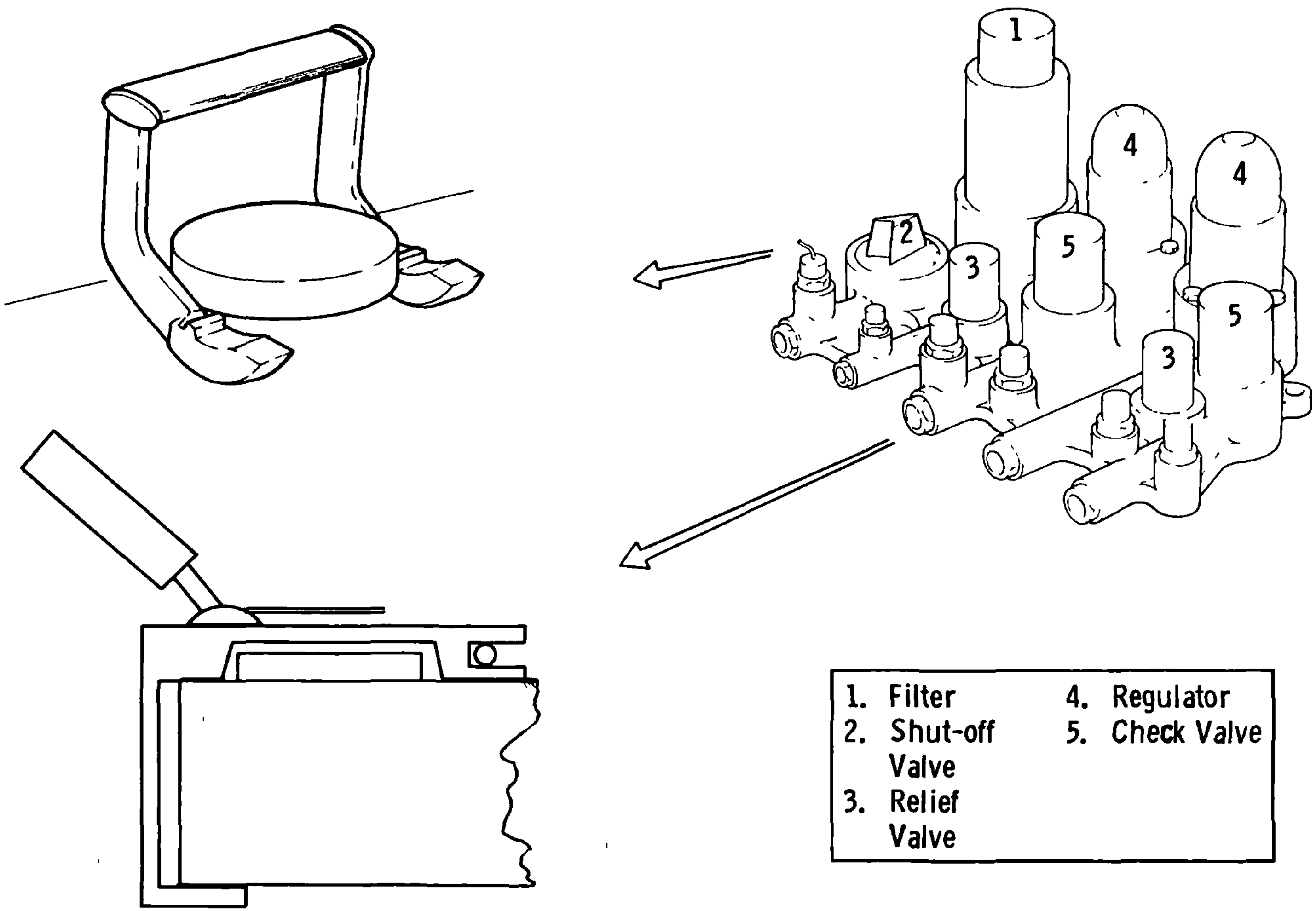


Fig. IV-13 Pressurant Control Module

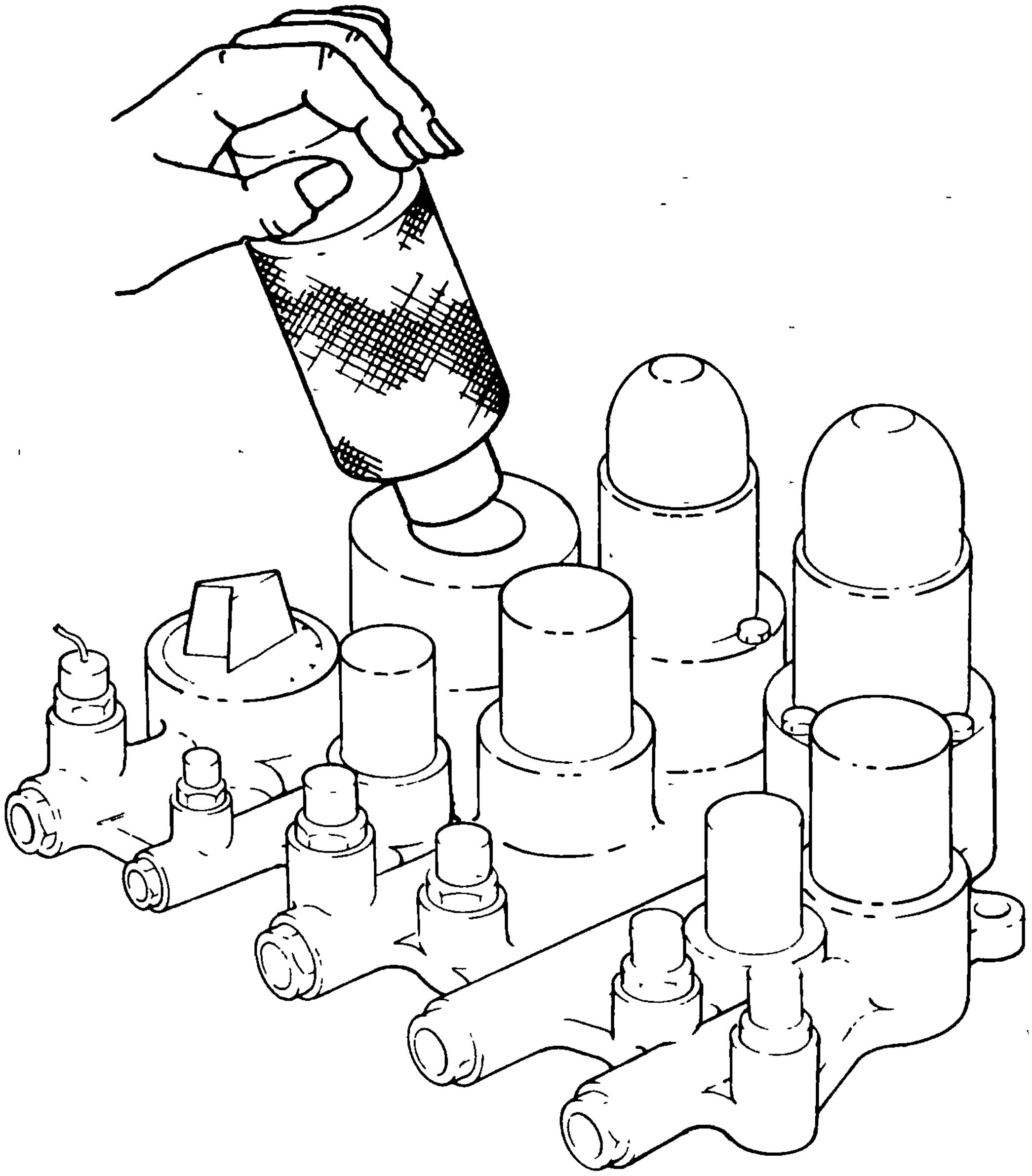


Fig. IV-14 Module Subassembly Removal

It is assumed with this concept that the pressurant control module would be located within a pressurized area during all operations. The spares could also be stored in the immediate vicinity for quick access and repair. Instrumentation and logic from the OCS will isolate the failed component to assist the crew in determining whether the failure can be bypassed for repair at a more convenient time, or if the repair should be made immediately. In either case the module design should require no tools or only simple hand tools to perform the repair task. The tubing is attached to the module through a separable fitting with reusable seals.

In summary of the options available to provide an IFM capability for the pressurant control module, the actual module/component design is the main controlling factor. However, the module/components configuration can be designed to enhance maintainability, and random failures can be remedied by module or module subassembly replacement. These tasks would fall in the category of corrective maintenance.

Preventive maintenance will consist of replacement of the module or individual subassemblies (such as filters) on a scheduled basis. The anticipated replacement schedule for each existing component and the impact on the logistic vehicle has been determined, and a tentative plan has been derived for replacement of components. This plan is provided in Chapter V, Maintainability.

As depicted in Fig. IV-15, packaging has a direct effect on all areas associated with providing an IFM capability. Therefore, the system and component designer must design with these objectives as a goal.

3. Propellant Storage Tank

The propellant storage tank will consist of a shell assembly, metal bellows assembly, two three-way solenoid valves, and a fluid gaging sensor, as shown in Fig. IV-16.

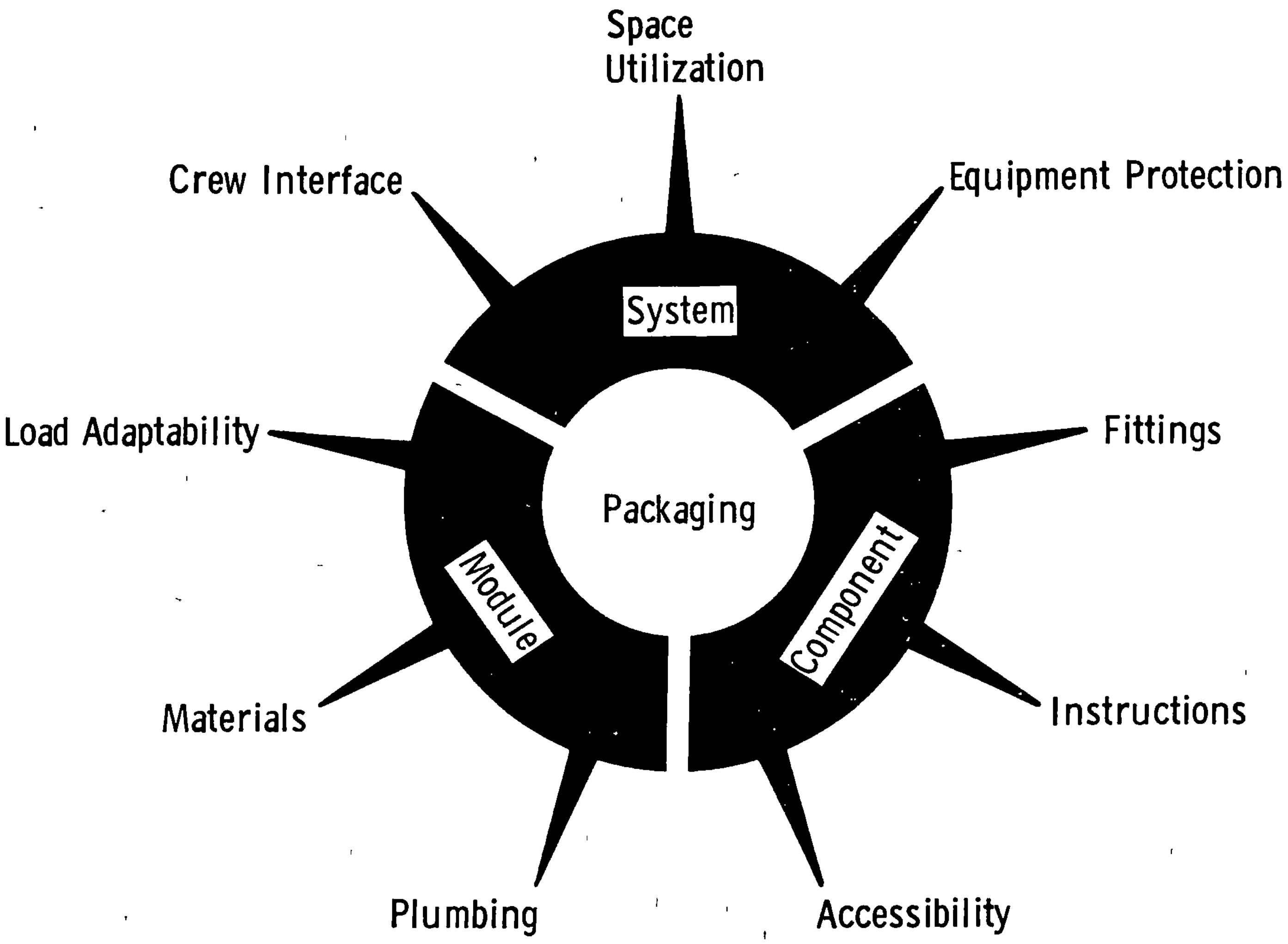


Fig. IV-15 IFM Packaging Considerations

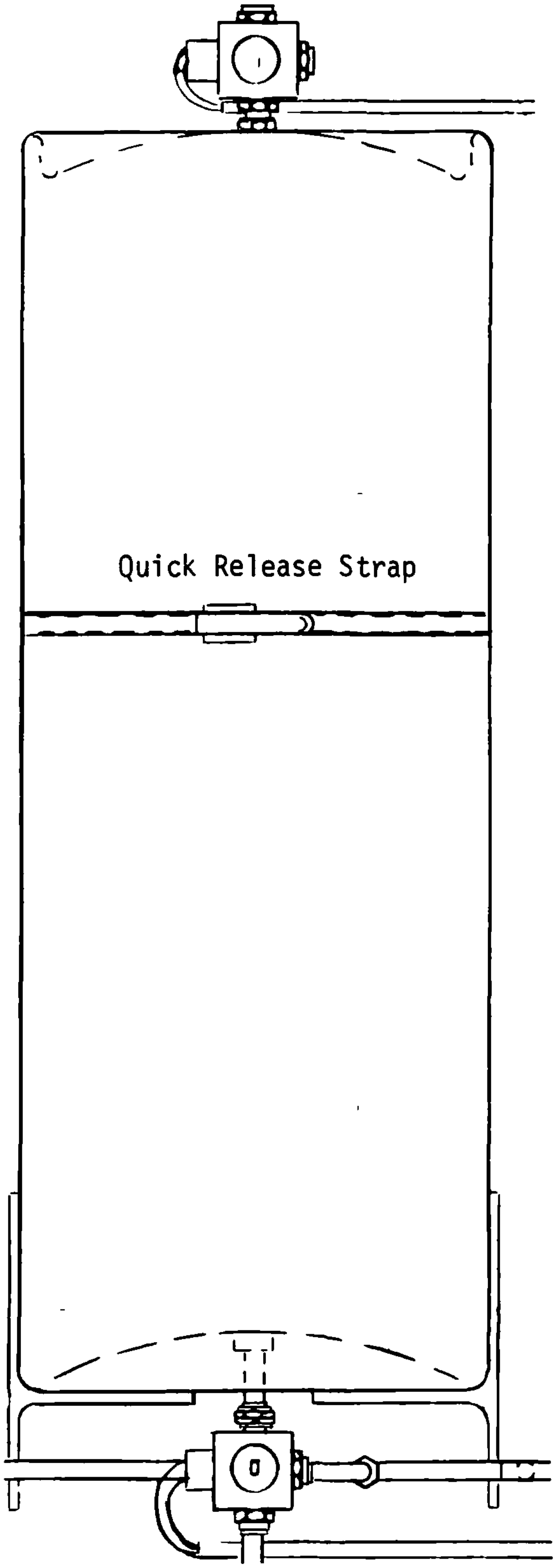


Fig. IV-16 Propellant Storage Tank

The shell assembly consists of the pressurant gas inlet head and a one-piece cylindrical shell welded together. The bellows assembly consists of the movable head, the bellows core, and propellant outlet head welded together. The three-way valves attached to each end of the tank by tubing are solenoid operated with manual backup and the vent or purge outlets directed to the fluid removal tools. The quantity gaging sensor is located on the outside and along the length of the tank. The propellant is expelled when the pressurizing gas enters a port in the head of the outer shell and collapses the bellows.

The propellant tank lends itself to the maintenance concept of removing and replacing the complete tank by using separable fittings at the tube connection to the valves. This concept is attractive because the most probable failure will occur in the bellows assembly, which would require a complete tank replacement with the present design. However, a tank could be designed that is reparable. The three-way valves provide a great deal of flexibility for both maintenance activities and during propellant resupply. During resupply the three-way valve on the gas head would be positioned to vent the ullage overboard while the tank is being filled through the propellant manifold. In case of a failure in the bellows assembly the tank could be isolated from the system and the contaminated propellant and ullage removed from the tank through the three-way valves. The contaminated propellant can be disposed of by several methods. One method is to dump the propellant overboard, however, this may interfere with experiments being conducted and because of the high corrosive nature of the propellant, this method is not recommended. Another method is to have portable sump tanks available to accept the contaminated propellant and return it to earth via the logistic vehicle. A minimum of two sump tanks would be required, one for fuel and one for oxidizer. Another consideration, adaptable to an internal leak, would be to relieve the ullage pressure on the tank, cap the tubing, and return the tank and valves to earth with the contaminated propellant. For certain failures, propellant could be transferred to the other partially filled tanks in the compartment, thus conserving propellant. Both of the above methods would eliminate the need for auxiliary sump tanks. The latter two methods appear to be the most feasible when the factors of time, weight, and safety are considered. The three-way valves also provide the capability to purge and test lines and components upstream and downstream from the propellant storage tank. The reasons for solenoid operated valves with manual backup are that in case of a major failure in the propellant side of the tank or any of the propellant components, the propellant from the tank and pressurant supply to the tank can be immediately and remotely shut off. The manual backup provides a redundancy to the solenoid and also provides the crew the capability to control the valve when working in the propellant compartment. A built-in glove box, as depicted in Fig. IV-17, could be used as an extra safety precaution when a leak is suspected in the propellant area. The glove openings would be normally plugged and sealed to provide a positive seal in the spacecraft skin.

4. Engine Module

The engine module would consist of the engines, two propellant manifold blocks, electrical bundle assembly, and the supporting structure. Each engine consists of a nozzle, combustion chamber, injector, quad-injector valves, and instrument sensors associated with the engine assembly. Breaking the propellant feed lines and one electrial connector would suffice to free the engine module for removal. Engine thrust is transmitted through thrust mounts on the module which are designed to hold the engine in place with quick release devices adapted to the mount to eliminate fasteners. Two propellant manifold blocks are required for each module to distribute the fuel and oxidizer to each engine. The electrical bundle assembly provides the necessary wiring for engine control and monitoring. The supporting structure would provide the support and protection as required for the various assemblies. A mounting flange provides the interface between the engine module and the Space Station. The actual design will be determined from engine size and the other related assemblies' design. Incorporated into the design should be the capability to remove or swing-in the complete module from within the Space Station. This eliminates the requirement for EVA and would facilitate maintenance tasks.

It is recommended that four engine modules, containing three or four engines, be located 90° apart on the Space Station rather than two modules containing six or eight engine assemblies located 180° apart. The four-module arrangement gives greater reliability and flexibility, not only in maintenance, but also in the operation of the system. For an operational consideration, two of the four engine modules could be operated from half of the pressurant and propellant supply for the first resupply interval, then be switched to the other two modules and the other half of the pressurant and propellant supply for the next resupply interval. By doing this, a complete system redundancy or built-in spares would be available at all times. The nonoperating half of the system, below the shutoff valve at the pressurant sphere would be in a static condition at a reduced pressure. This will add to component life and reduce leakage probabilities. The quad engine valves are recommended as they increase system reliability significantly and eliminate the need for redundant propellant feedline valves.

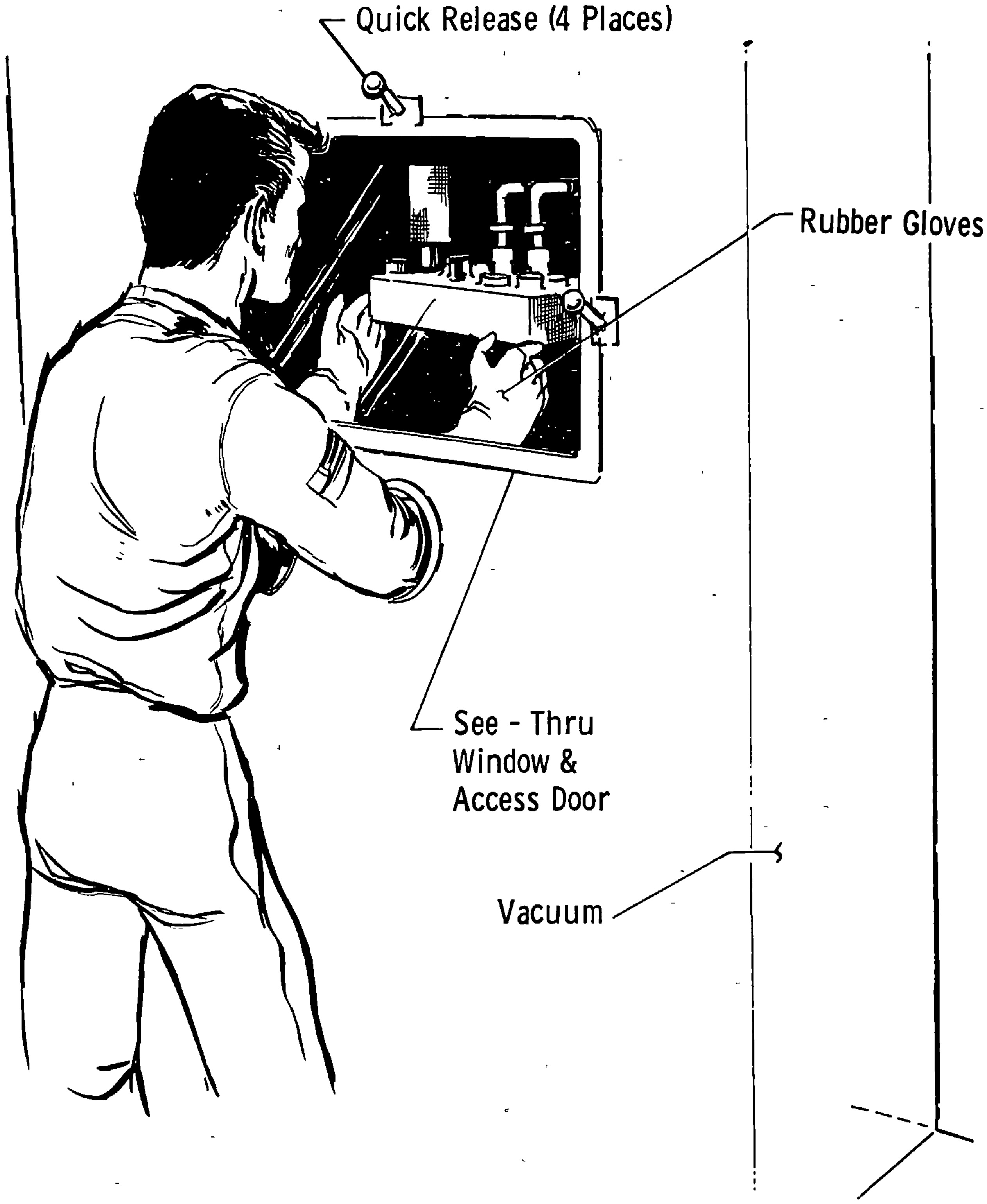


Fig. IV-17 Glove Box Maintenance Concept

This module lends itself to modular replacement in case of failure or scheduled replacement. However, after removal the module may be repaired by the replacement of a complete engine in a portable glove box or in the General Purpose Laboratory. The engine solenoid valves have the lowest reliability of all the components in the module, and thus are most likely to fail before engine module replacement because of the three-year engine and valve life.

In case of a failure or scheduled replacement of the engine module, the interconnecting tubing would be bled, purged, and electrical power interrupted before removing the module from the operational position. The bleed and purge operation would be performed with a fluid removal tool and the three-way valve on the tank. To prevent inadvertent contact of the fuel and oxidizer, two fluid removal tools are required for this system, which are physically incompatible with each other, to perform this task. Engine repair could be done in a pressurized area in a shirtsleeve environment after the engine module is removed. Conventional concepts of engine design and mounting have required donning a life support suit and EVA to remove engines.

One concept is presented in Fig. IV-18 that would not require the use of a pressurized suit. Space Station constraints require that EVA shall be minimized, and shall only be used for emergency situations. Donning and removing an EVA suit is a lengthy procedure, and working in the Apollo-type hard suit requires considerable exertion with the result of a high metabolic load. An element of safety is involved when the astronaut is in the suit, even during IVA conditions.

Figure IV-18 shows a configuration with a removable flange-type engine mount. The glove box approach could be used to permit engine removal without donning a pressurized suit. Each engine assembly could be designed so that it could be removed separately. Quick-release devices would be used on the engine mount flange and engine assemblies to permit removal with a minimum of effort and crew training. This approach is consistent with the anticipated Space Station design in that there will be a meteoroid shield surrounding the outer wall. This will require placing engine modules a short distance from the Space Station interior skin.

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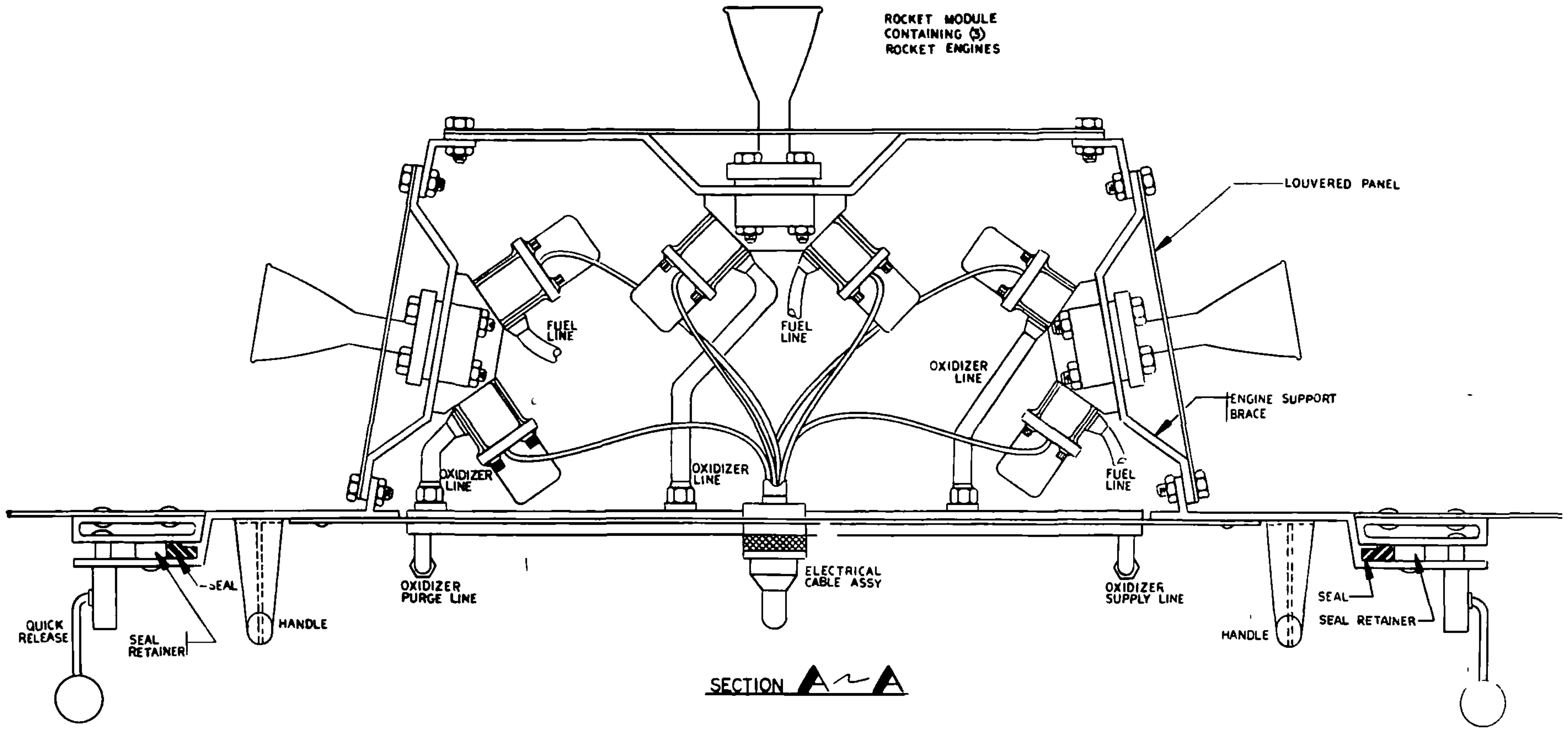
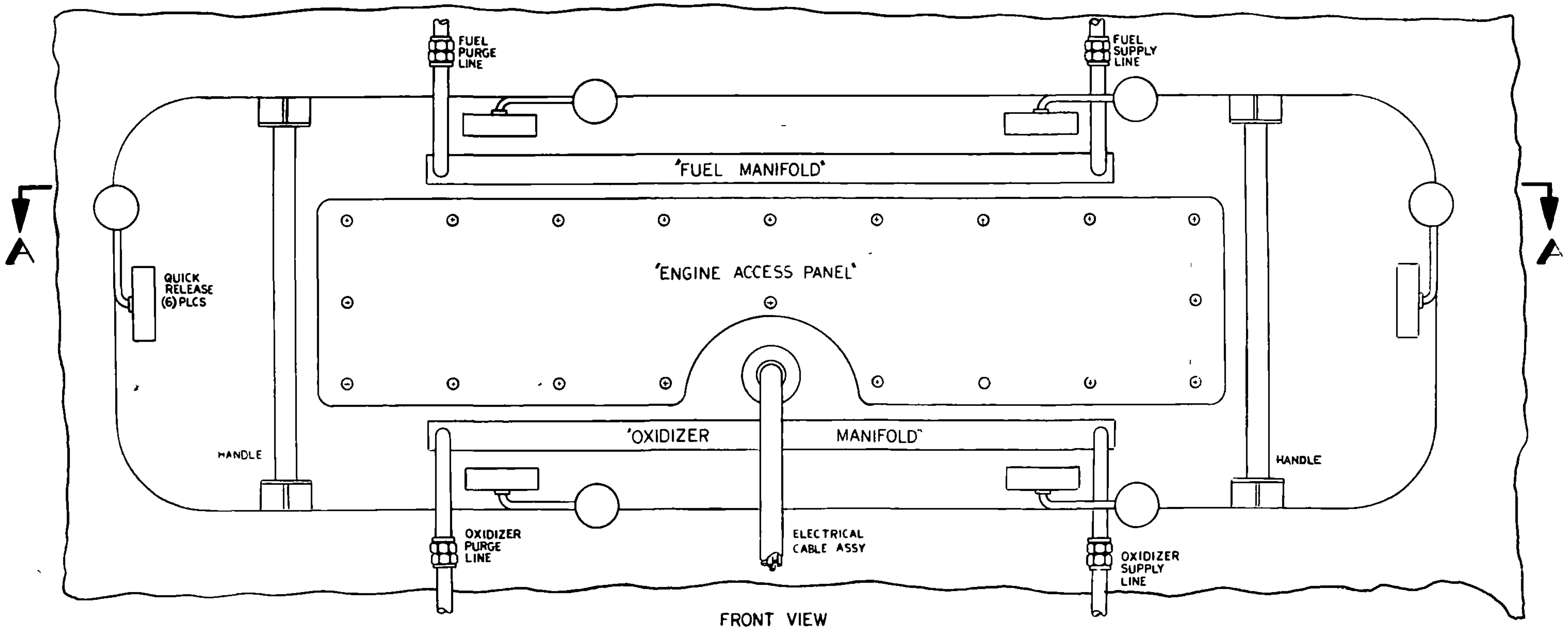
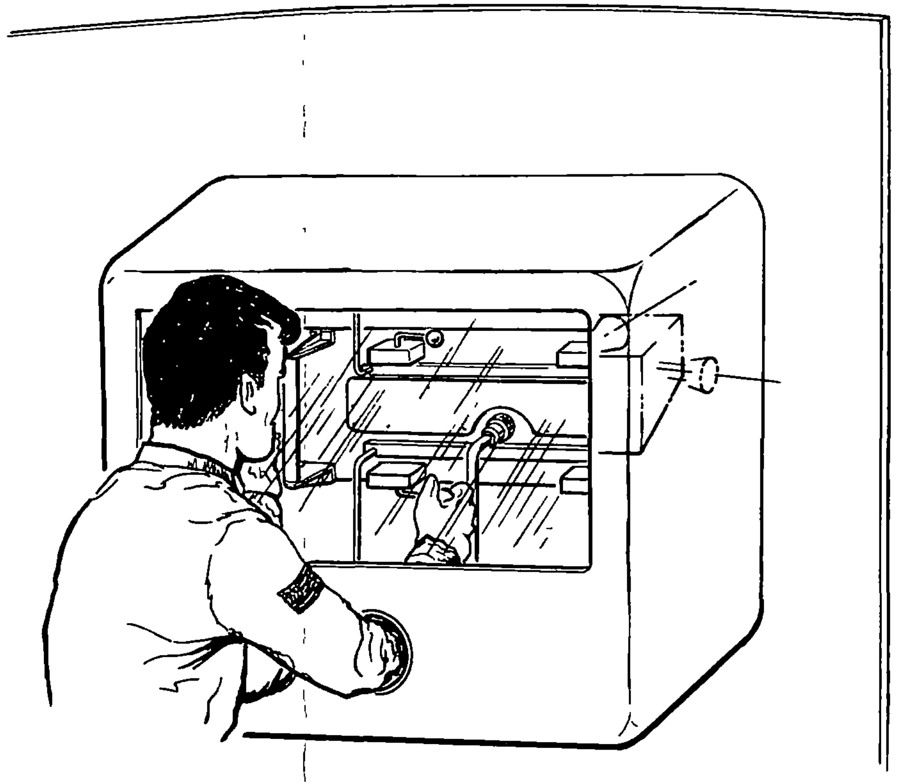


SECTION A-A



FRONT VIEW



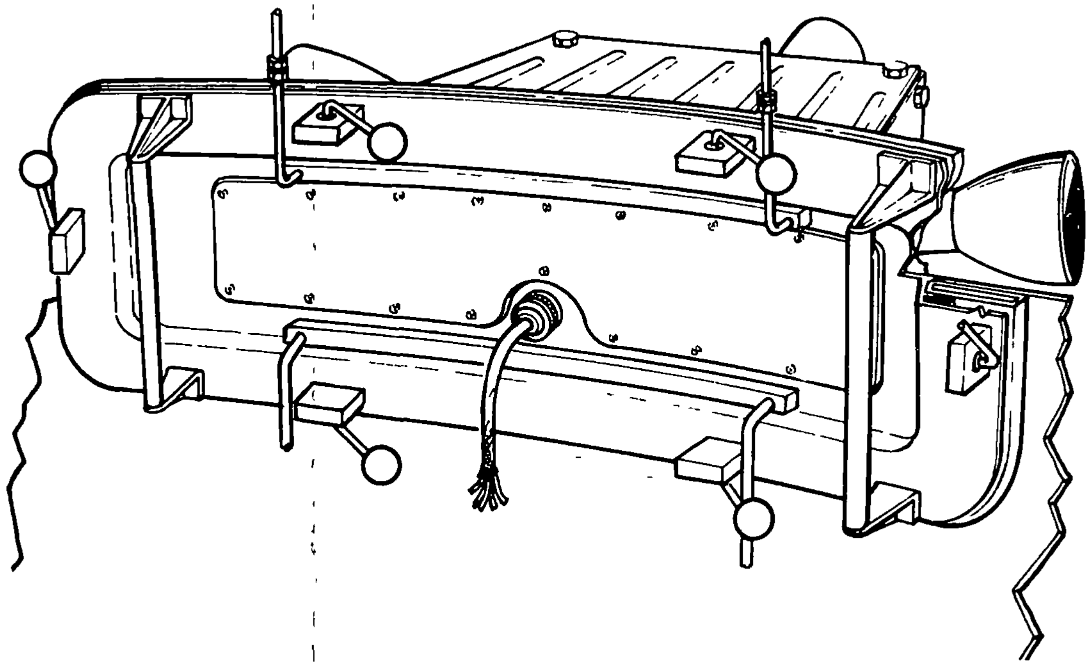


Fig IV-18 Flange Engine Mount

FOLDOUT FRAME

FOLDOUT FRAME 2

F. INDIVIDUAL COMPONENT CONCEPT

To facilitate maintenance on a bipropellant propulsion system using individual components in the system, several requirements must be acknowledged. As in the pod and modular concepts, packaging is a prime factor to achieve an IFM capability. Other considerations are the components' design and their retention in the system to facilitate maintenance tasks.

A system of individual components would be very similar to the system described in the modular concept and shown schematically by Fig. IV-10. The primary difference is in the pressurant control section of the system, where instead of the two pressurant control modules 12 components would take its place. The components are two three-way valves, two dual regulators with filter, four quad check valves, and four burst diaphragm and relief valves. The same maintenance concepts feasible for the modular concept would apply to a system of individual components except that separable tubing fittings are required at all components.

Some components such as valves and regulators may be repaired in place, depending on design and packaging configurations. One concept that takes advantage of this maintenance approach and increases system design flexibility is the common valve body approach depicted by Fig. IV-19. This commonality of valve bodies with slip-in and -out subassemblies allows the designer many options while retaining maintainability of the component. Another component that should be designed as a maintainable item is the propellant tanks. Due to their size and weight, a great savings could be realized if the tanks could be repaired in the Space Station. Therefore, since the most probable failures occur in the bellows, the tank could be designed so that the bellows assembly is removed from the exterior shell for either metal welding/brazing or an advanced epoxy sealant-type repair. Testing provisions are available after repair of the tank through the three-way valves and high-pressure (300 psi) nitrogen supply.

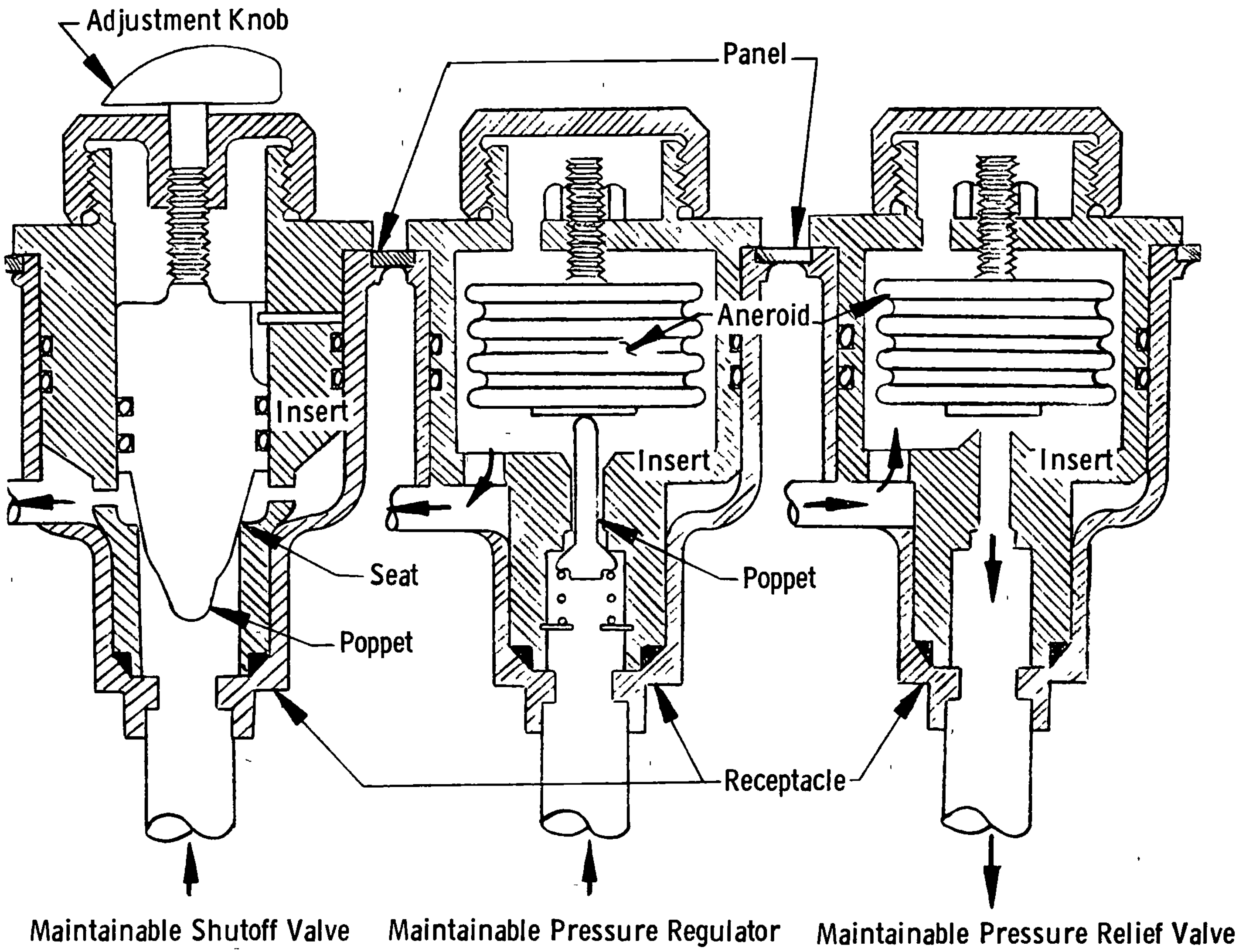


Fig. IV-19 Common Valve Body

In a system of individual components, packaging is a prime factor if any degree of optimization is achieved. It is evident that individual components will require more space and weight because of the physical size, individual mounting, and interconnecting tubing. The conventional packaging approach of putting components in a line with the tubing in a straight line between the components can be improved by having tubing ports in parallel and the tubing loop from one component to the next. Figure IV-20 depicts this packaging approach.

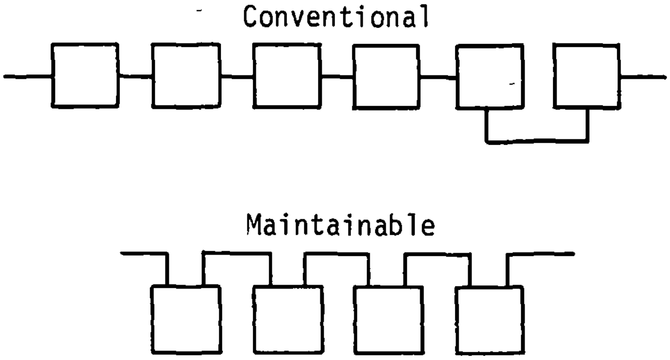


Figure IV-20 Conventional vs Maintainable Packaging

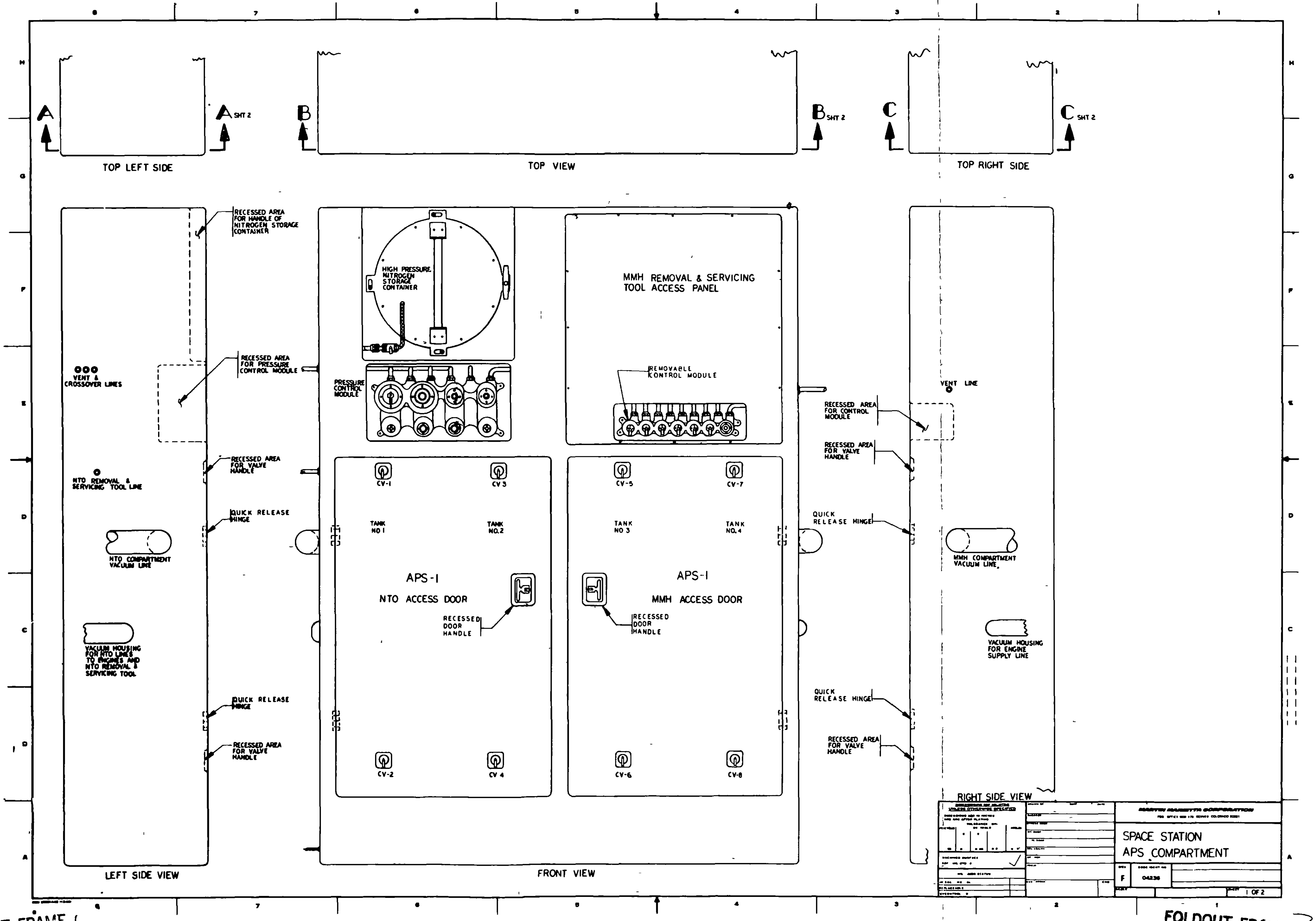
This packaging approach not only saves space but provides a more maintainable system. The components are easier to remove and replace without interfering with other components or tubing.

It is concluded that for a Space Station in the 1975 to 1980 time period, systems can be designed using individual components, although modularization is recommended as the optimum method of providing an IFM capability. For this reason, emphasis is placed on such factors as packaging for accessibility; standardization and commonality of components, fittings, and fasteners; fault detection and isolation; and crew training. These factors, if adhered to, will reduce space, weight, spares, logistics requirements, special tools, and maintenance repair time.

G. SPACE STATION APS CONFIGURATION SELECTION

To verify the conclusions made in regard to providing an IFM capability and satisfying the many constraints, conceptual designs and configuration drawings for the APS were prepared. Major emphasis was placed on packaging, accessibility, and crew safety. This aspect is very important because the packaging and design configuration enhances IFM, which may determine the success of the complete Space Station mission.

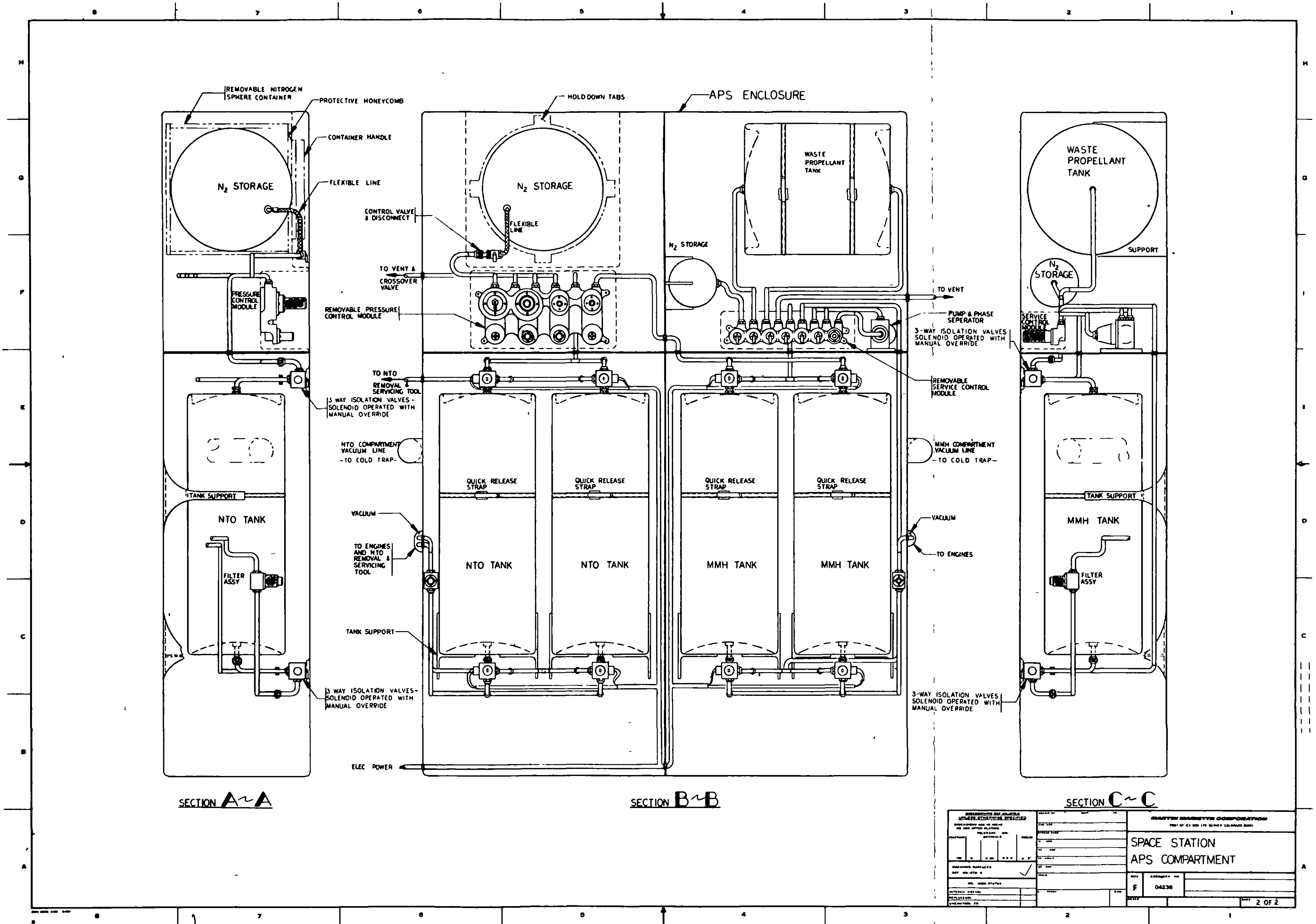
It was assumed that the APS would be located in a pressurized segment of the Space Station and housed in compartments that are normally vented to vacuum. The design considered all aspects of human engineering per MSFC-STD-267A and MIL-STD-1472 in the placement of equipment and operations required by the astronaut in performing maintenance functions. An example of human engineering and safety is depicted by the configuration of one of the APS compartments shown in Fig. IV-21 where all operating controls are placed between 34 and 70 in. from the floor. Also all removable fittings and components are placed between 17 and 72 in. from the floor. The fuel and oxidizer tanks are in separate compartments with separate access doors to preclude any chance of the two hypergolics coming in contact. The compartment is vented to vacuum to insure that no propellant vapors will migrate into the Space Station. Another desirable feature in the propellant compartments is to have manual control of the vent-to-vacuum valve to allow a small flow of air from the Space Station through the compartment to space during maintenance operations. This would provide an additional safety feature to preclude any change of toxic vapors getting into the habitable areas of the Space Station. The propellant storage access doors shall be operable with one hand with positive indication of locked and open, have all corners rounded, and be restrained in the open position completely free of and not obstructing any aisle space. The opening into the propellant storage shall have rounded corners and the depth to any fitting or fastener required to be worked on to remove and replace the tank or any component shall not exceed 17 in. The extra space in the bottom of the compartment is a convenient location to store APS spares, etc.



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Fig. IV-21 Space Station APS Compartment (1 of 2)



FOLDOUT FRAME 1

Fig. IV-21 (2 of 2)

FOLDOUT FRAME 2

The pressurant supply and controls are mounted above the propellant tanks in an adjoining compartment with the pressurant sphere contained in a protective mounting structure. This protective shield around the pressurant sphere will also complement the modular resupply concept by giving added protection to personnel handling the assembly. The pressurant control components are accessible from the front of the compartment since the control module will require the majority of the scheduled maintenance. Of prime importance in this area is the accessibility to the pressurant sphere and the filter since they must be changed every six months. Some leakage from these components into the Space Station will do no harm as long as the loss is not sufficient to jeopardize the propulsion function from a lack of APS pressurant. Also, all the pressurant module tubing connections shall be readily accessible with a standard wrench to complement easy removal and replacement of the module.

The Propellant Removal and Servicing Tool is located adjacent to the gaseous nitrogen storage area. The location of the operating controls, as with the nitrogen pressurant control module, place all of the operating controls at the optimum height above the floor. This compartment is also vented to vacuum to preclude any toxic vapors from migrating into the Space Station. The propellant removal and servicing tool shown is typical for each APS compartment. Two tools are needed because there are two hypergolic fluids and the built-in concept for the tool conserves space, weight, and provides a much safer operation than a portable tool.

Space Allocation - Space allocation layouts and tradeoff studies were made on the installation of the APS and spin-despin propellant and pressurant supply in the Space Station. This is an important aspect of the study because the physical location will enhance inflight maintenance, space utilization, and will complement the entire Space Station.

It was assumed that the propulsion systems would be located in the same pressurizable segment of the Space Station and housed in compartments that are normally vented to vacuum. The installation considered all aspects of human engineering per MSFC-STD-267A and MIL-STD-1472 and safety in the arrangement of equipment and operations required by the crew in performing maintenance functions.

The propellant and pressurant required for the spin-despin operation for the 30-day artificial-g experiment would be stored in the immediate area with the APS. The propellant requirements for the spin-despin operation are approximately ten times larger than the APS, or 10,000 lb propellant and 300 lb pressurant, and will be depleted in the first 75 days of the mission. For a system like this, it is not necessary to provide the full inflight maintenance capability as in the long-term APS to retain a high degree of reliability. However, to optimize space and equipment on the Space Station, some isolation and access to the spin-despin components within the Space Station are desirable features. It is also conceivable and feasible to cannibalize this short-term system to repair long-term systems. Another desirable feature would be to have the same propellants as the APS so the Propellant Removal and Servicing Tools connected to the APS could be used to purge and decontaminate the system. As in the APS, the fuel and oxidizer tanks should be in separate compartments that are normally vented to vacuum. The spin-despin compartments should be fitted with access panels instead of hinged doors.

The segment of the Space Station selected for installation of the propulsion systems has an inside diameter of 33 ft, a central transit and utility core with an outside diameter of 12 ft, and a floor-to-ceiling height of 80 in.

The location of the APS within the Space Station has not been fully resolved to date, but three alternatives are possible. The APS may be located on a level that has no docking ports, on a level that has four docking ports, or a level that has two docking ports located 180° apart. The main consideration when planning space allocation is the location and access required for the docking ports, because each docking port requires a 5-ft aisle free of permanent installations. This study considered all three alternatives, and design layouts were prepared showing the best space allocations for each configuration. The alternatives of either two or four docking ports were considered as one option, because for resupply the APS should be located near a docking port.

The location of the engine modules is assumed to be on the same level as the rest of the system for nearly all configurations, but this is not an absolute requirement as shown in one layout configuration.

The first two layouts, shown in Fig. IV-22 and IV-23, are those configurations adaptable to the level containing the docking ports. The APS is located adjacent to the transit and utility core and the spin-despin propellant is located on the outer wall of the Space Station. This configuration allows complete access to all propulsion components, but limited access for inspection of the Space Station inner wall. However, this configuration does give a redundant pressure wall in case of meteoroid penetration of the Space Station wall. Although both configurations are very similar, Fig. IV-23 provides more safety to personnel working on any area with quick access to the transit and utility core. Work areas in Fig. IV-23 could be illuminated better with fewer lights than in Fig. IV-22. Neither configuration interferes with the docking ports or the aisle to the transit and utility core. The weight distribution of these two configurations during launch is poor, but good for the long-term mission.

In Fig. IV-24 and IV-25 the scheme is just the reverse of Fig. IV-22 and IV-23 in that the APS is located on the outer wall and the spin-despin propellant is placed near the transit and utility core. The space allocation is approximately the same for all four configurations. Other equipment may be located in the free areas not occupied by the propulsion system or that designated as free aisleways. A 40-in. aisle is required in front of the APS control panels and a 30-in. minimum aisle is required in front of the spin-despin system. The configuration shown in Fig. IV-22 does use the docking port aisle for access to the APS operating panel, thus providing dual usage for space that is wasted except during resupply.

Layouts in Fig. IV-26 and IV-27 are similar in that all the commodities are located near the outer wall. However, Fig. IV-26 gives direct access to more of the outside wall than the other configurations. One poor feature of this layout is that the astronaut has only one escape route when working in the area between the propellant compartments. Fig. IV-27 depicts an installation with no engine in the segment with the propellant storage area. This layout does not have any particular advantages except good space use and accessibility to components.

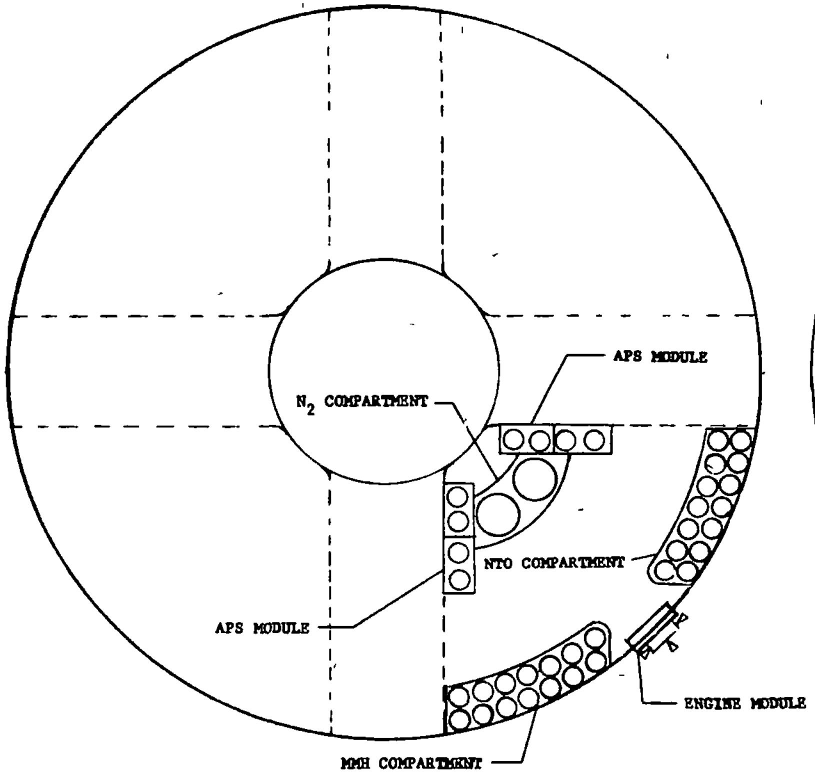


Fig IV-22 APS and Spin-Despin Installation

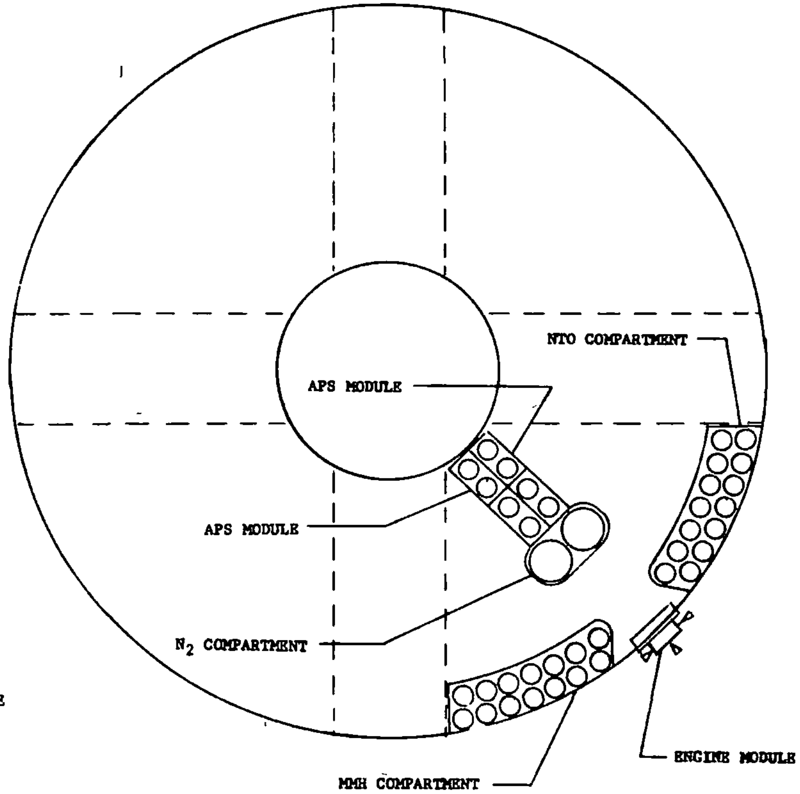


Fig IV-23, APS and Spin-Despin Installation

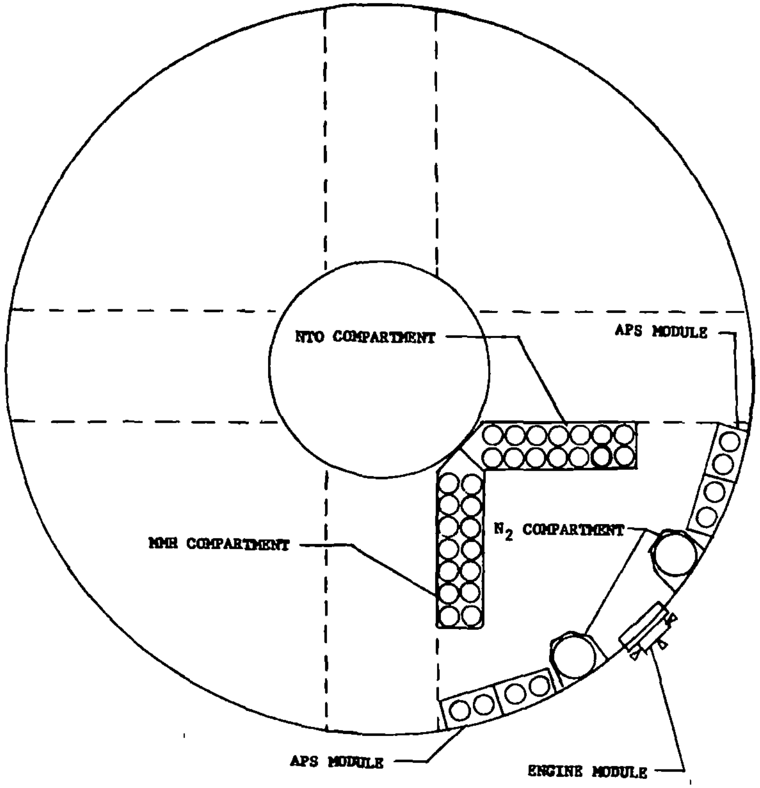


Fig IV-24 APS and Spin-Despin Installation

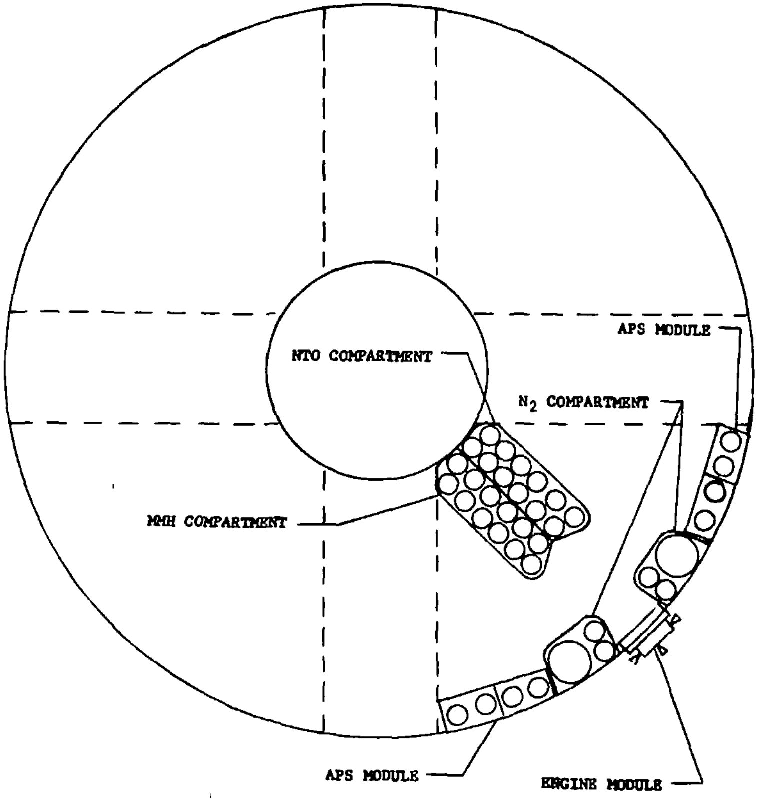


Fig IV-25 APS and Spin-Despin Installation

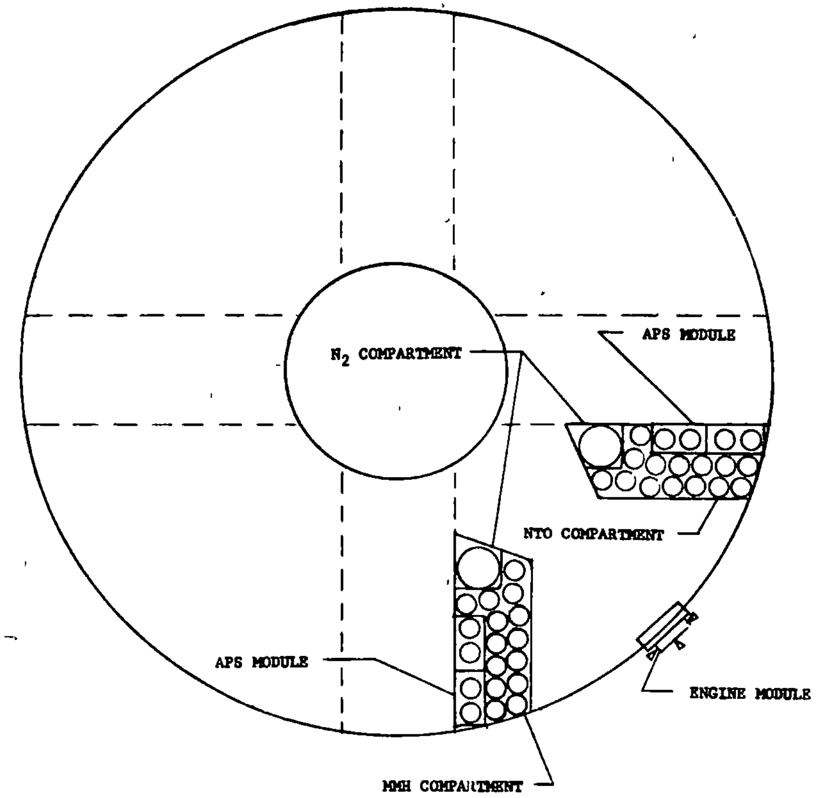


Fig IV-26 APS and Spin-Despin Installation

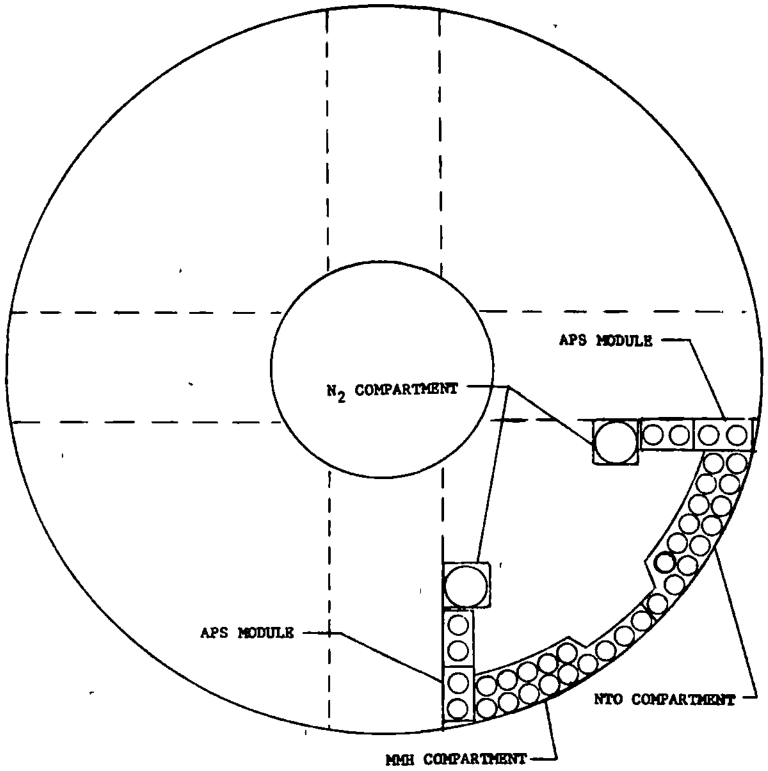


Fig IV-27 APS and Spin-Despin Installation

The remaining four layouts, Fig. IV-28 thru IV-31, depict the installation of a Space Station segment without docking ports and a minimum of two access doors to the transit and utility core. Of these four, Fig. IV-28 and IV-29 provide very good accessibility to components, and Fig. IV-29 has the optimum weight distribution and the most access to the Space Station wall. Figure IV-31 gives good single level access to the components and the Space Station wall. However, this configuration does not have a good escape route when performing tasks in between the propellant compartments. Figure IV-30 requires two-level access to the spin-despin propellant tanks, but there is ample room for this operation. Weight distribution is mostly near the outer wall, which places a penalty on the overall system for maneuvering the Space Station.

This study has concluded that the layout shown by Fig. IV-22 is the most attractive layout for a level with docking ports. The docking ports severely limit the free space available for permanent installations, but resupply is enhanced if the propulsion system is located adjacent to the docking ports.

The most optimum layout for the APS and the spin-despin propulsion system is shown in Fig. IV-29. It offers maximum use of space, single level access for maintenance activities, maximum escape routes for the astronauts, maximum access to the Space Station skin for inspection and repair, and optimum weight distribution for the entire mission. These two recommended configurations will remain the same even if the Space Station diameter is reduced from the 33 ft used in the layouts.

Since the installation may have the spin-despin propellant tanks packaged one behind the other (two levels) the design must accommodate the removal of two tanks at a time. Figure IV-32 depicts a design that will provide for the removal of two tanks. This concept shows separate access panels for each set of tanks, although one panel could be used for two sets of tanks. To reduce isolation valves, the propellant system could be manifolded into two groups (two or four) of tanks with a common manifold tied into the main manifold. It is not anticipated that maintenance would be required for the intended mission of the spin-despin system, but the system may be used for other systems on the Space Station. Some uses of the spin-despin components would be storage of contaminated fluid in the propellant tanks and cannibalization of components such as valves, regulators, etc.

In several of the layouts the pressurant storage for the spin-despin propulsion system is located in the area of the engine modules. This installation is depicted by Fig. IV-33, which shows a view of the installation from inside the Space Station.

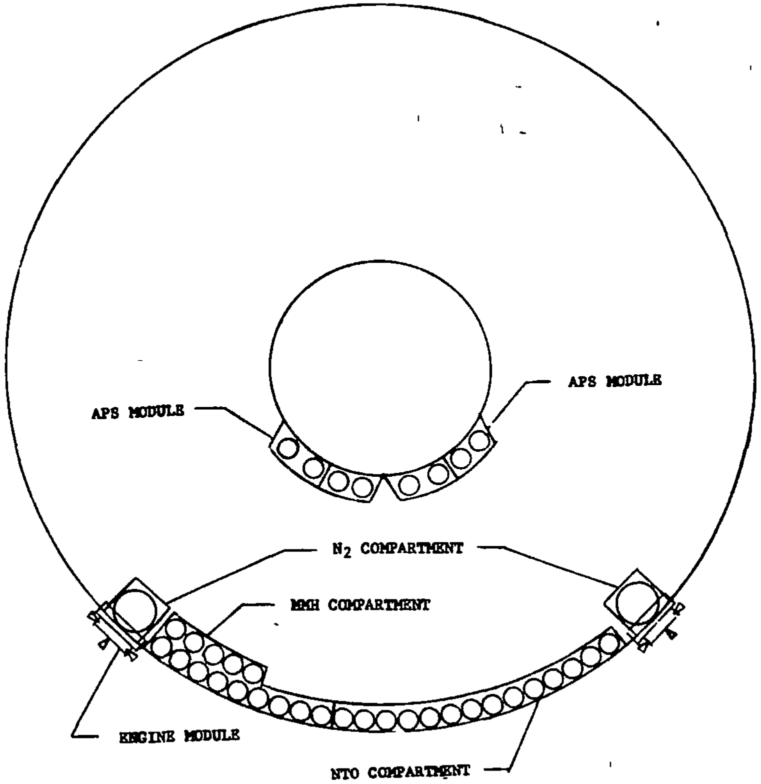


Fig IV-28 APS and Spin-Despin Installation

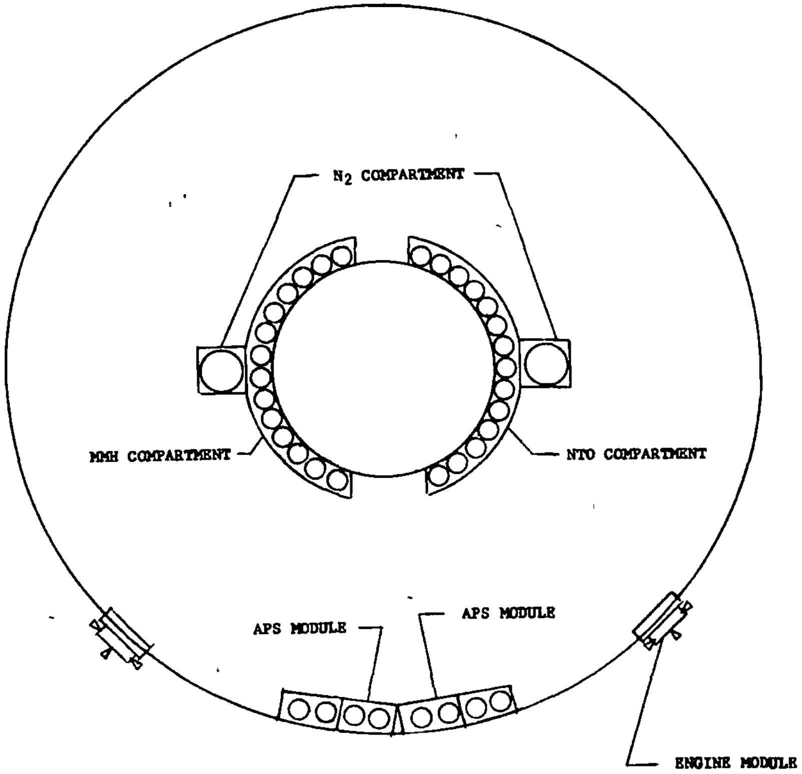


Fig IV-29 APS and Spin-Despin Installation

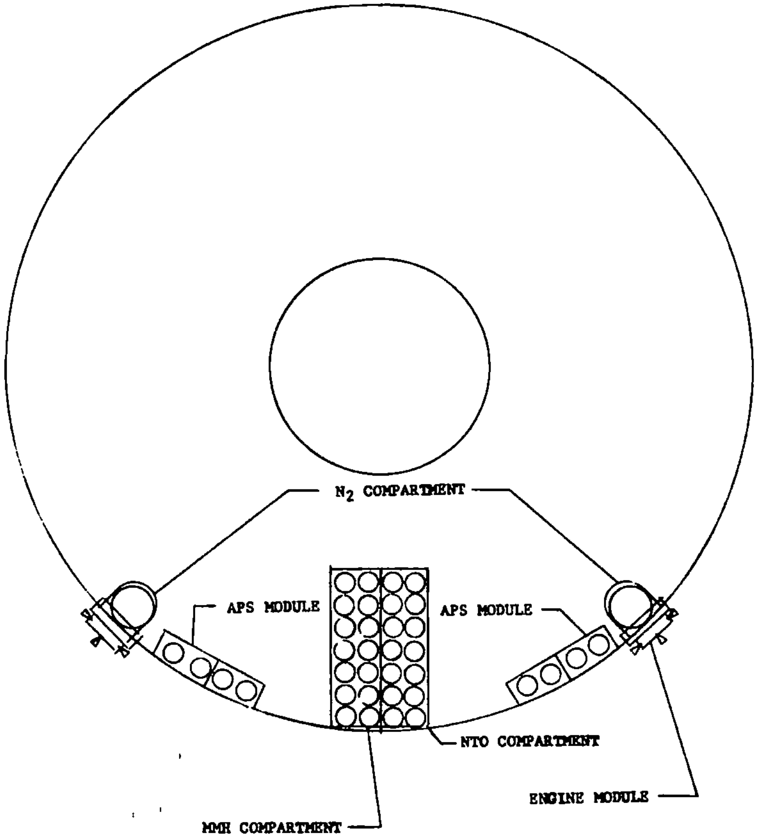


Fig IV-30 APS and Spin-Despin Installation

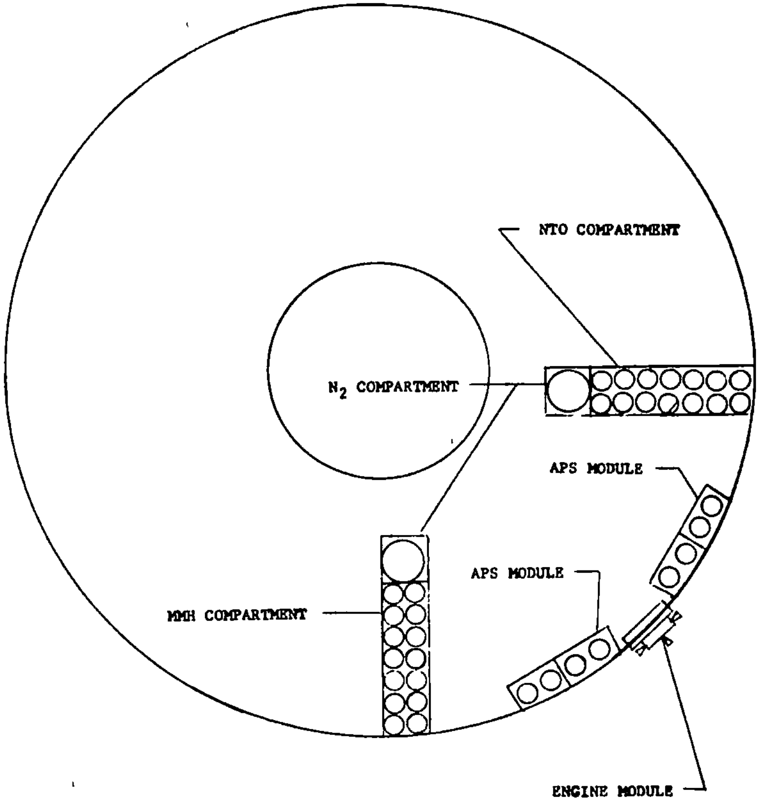


Fig IV-31 APS and Spin-Despin Installation

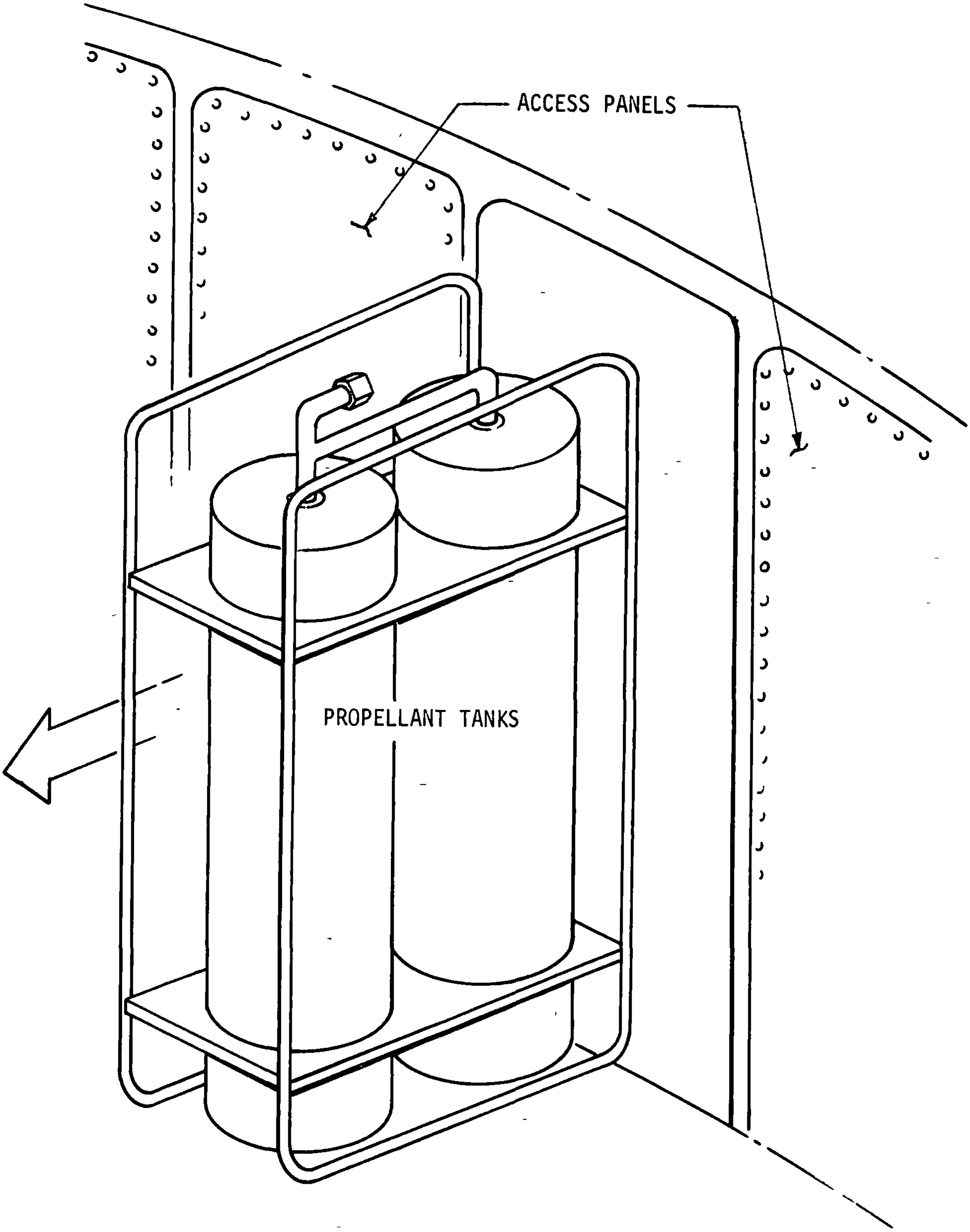


Fig. IV-32 Tank Removal Subpack

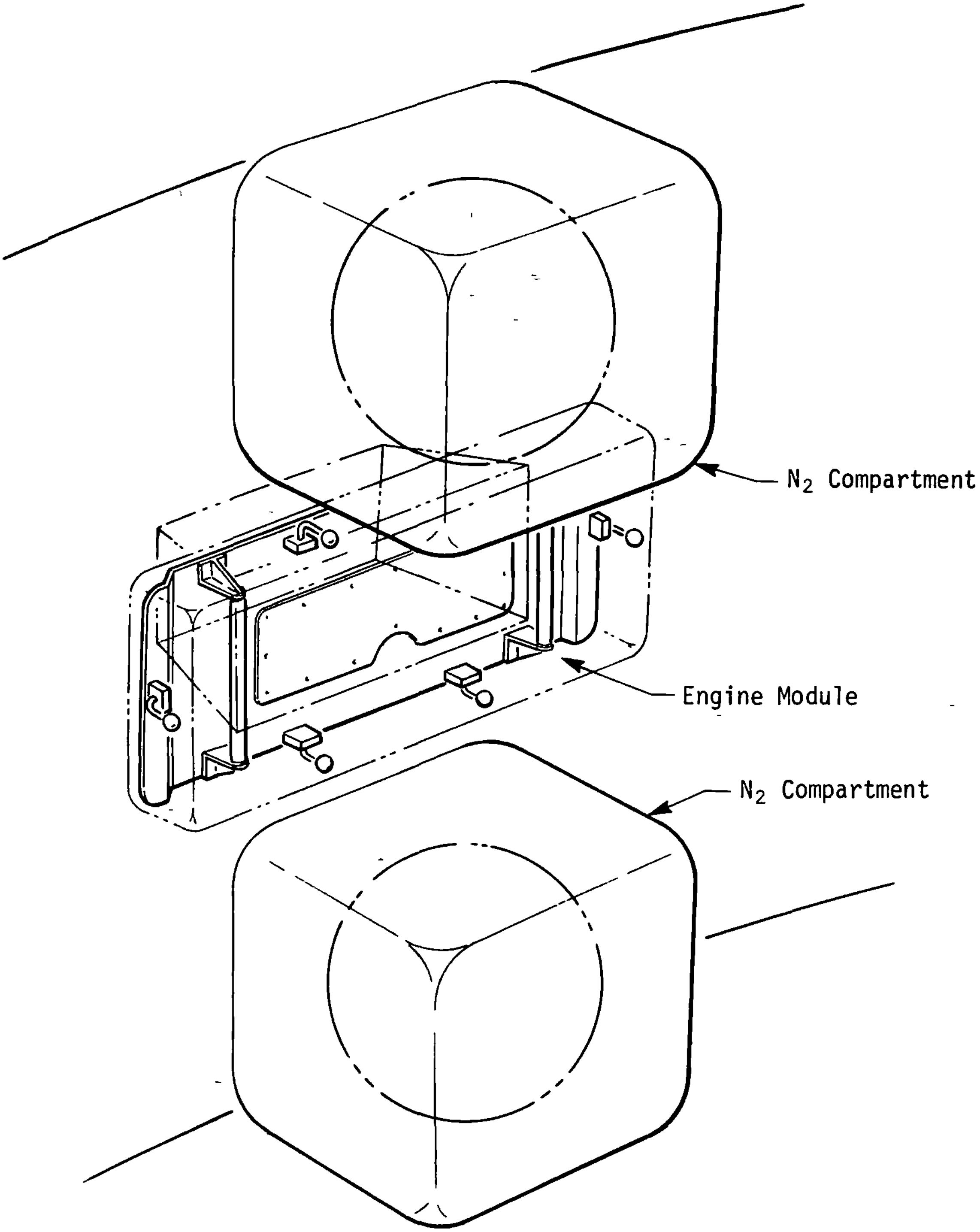


Fig. IV-33 N_2 Compartment and Engine Module Installation

H. LEAKAGE CRITERIA

The ability to remove components from a system is a very necessary element in inflight maintenance, but this requirement also increases the potential leakage paths in the system. In view of the potential leakage problem, an analysis was conducted to determine what leakage criteria were allowable for the bipropellant auxiliary propulsion system (APS) in the Space Station.

The analysis considered the number of external leakage paths in the propulsion system and the system commodity. Table IV-1 shows the number of leakage paths for each subsystem in the APS for both the module approach to component packaging and a system comprised of individual components.

Table IV-1 System Leakage Paths

Subsystem	Equivalent Leakage Paths	
	Module Approach	Components
High-Pressure Nitrogen (3000 psi)	16	20
Low-Pressure Nitrogen (220 psi)	60	66
Monomethylhydrazine	118	118
Nitrogen Tetroxide	118	118
Total	312	322

As indicated, the percentage of exterior leakage paths for the module configuration, as compared to individual components, is not substantially reduced. For the Space Station APS, the component module configuration only reduced leakage paths by 3%, or a reduction of ten fittings out of 322 exterior leakage paths. The reason for the low percentage reduction in the APS is due to the type of system in that the pressurant control area is the only portion of the system that lends itself to a modular configuration.

Parametric leakage data for the fuel, oxidizer, and nitrogen is presented graphically in Fig. IV-34, IV-35 and IV-36. Using these graphs, the pounds of commodity lost through external leakage can be quickly determined as a function of leakage criteria and the number of fittings in the system. The data assume that the leakage criteria (cc/sec) is based on a system that has been leak checked using nitrogen at the operating pressure of the system.

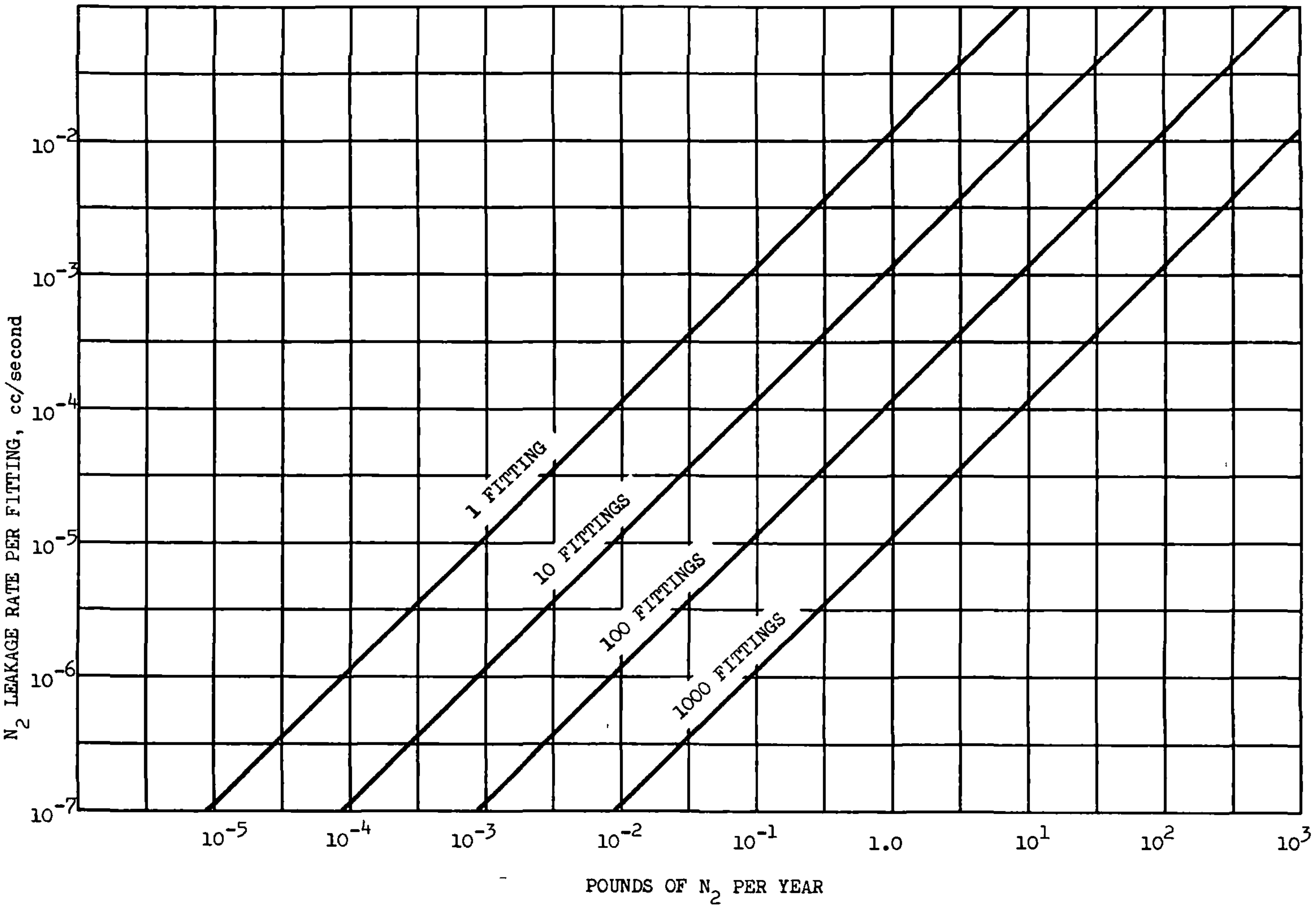


Fig. IV-34 Nitrogen Pressurization Subsystem Leakage

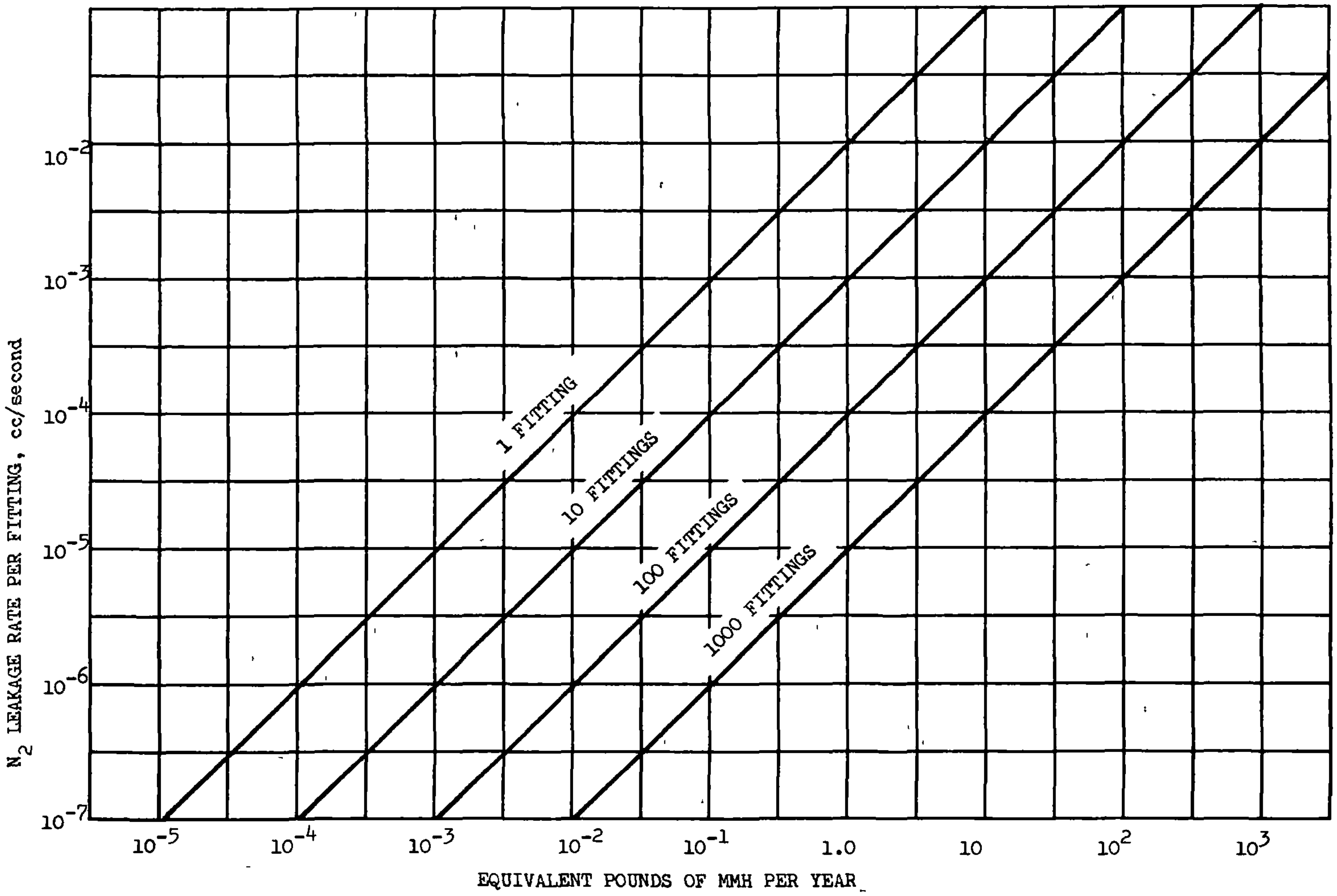


Fig. IV-35 MMH Subsystem Leakage

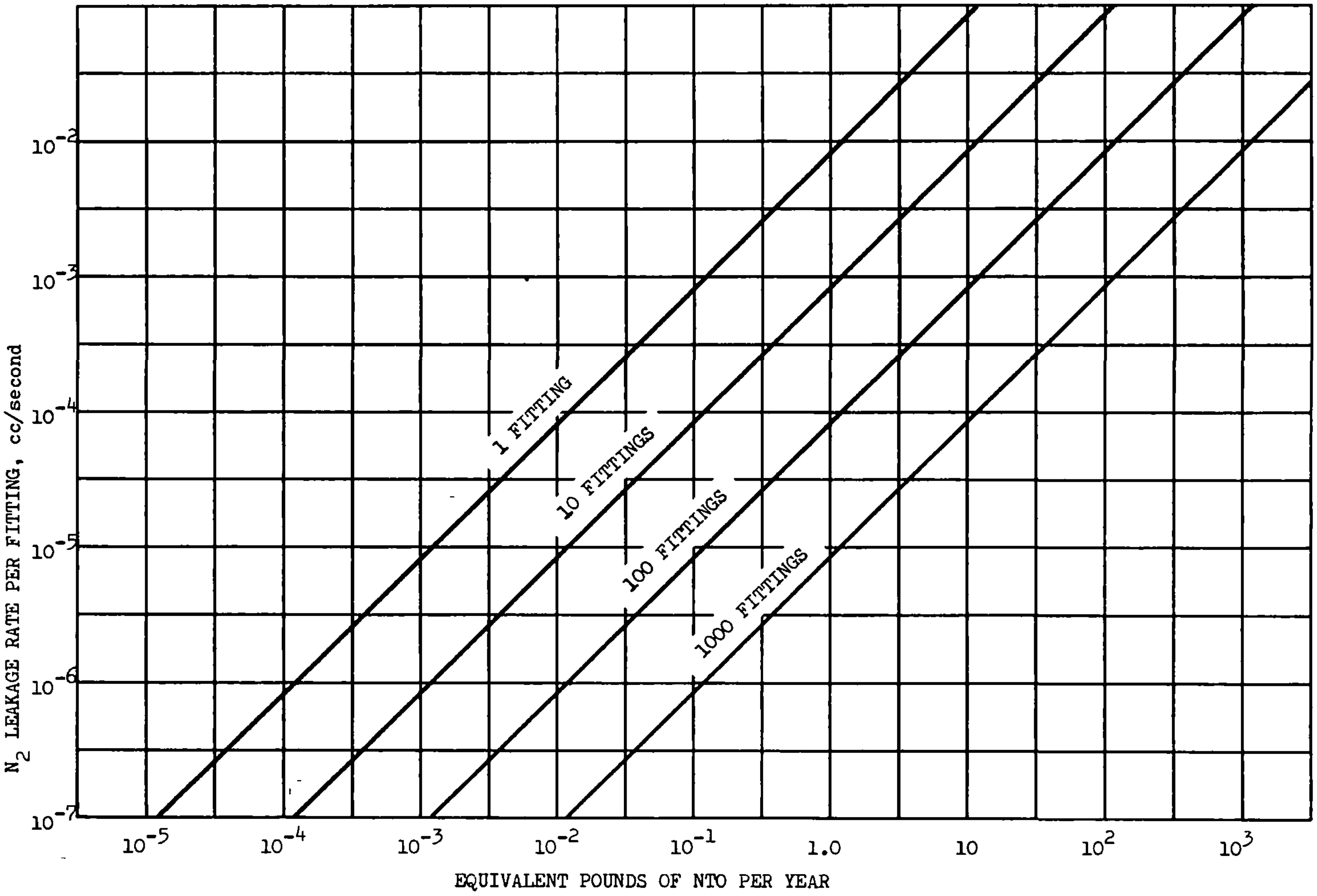


Fig. IV-36 NTO Subsystem Leakage

The system commodity loss is presented in Table IV-2. This table presents the commodity loss and percent of total commodity loss for the APS as a function of the leakage rate. The data are based on an APS configuration using individual components with 322 leakage paths and with all of the leakage paths leaking at the same leakage rate. This is a conservative estimate since the probability is small that all of the fittings will be leaking at the maximum rate at the same time.

Table IV-2 System Commodity Loss

Leakage Criteria (cc/sec N_2 per fitting)	System Loss (lb/year)			Percent of System Commodity* (loss per year)		
	N_2	MMH	NTO	N_2	MMH	NTO
1×10^{-7}	6.45×10^{-4}	1.18×10^{-3}	2.36×10^{-3}	0.00215%	0.000315%	0.000378%
1×10^{-6}	6.45×10^{-3}	1.18×10^{-2}	2.36×10^{-2}	0.0215%	0.00315%	0.00378%
1×10^{-5}	6.45×10^{-2}	1.18×10^{-1}	2.36×10^{-1}	0.215%	0.0315%	0.0378%
1×10^{-4}	0.645	1.18	2.36	2.15%	315%	0.378%
1×10^{-3}	6.45	11.8	23.6	21.5%	3.15%	3.78%
1×10^{-2}	64.5	118	236	215%	31.5%	37.8%

*Total commodities are: Nitrogen 30 lb, fuel 375 lb, oxidizer 625 lb.

Historically, leakage criteria for propulsion systems have been very stringent (10^{-7} cc/sec). These criteria were based on the high toxicity of the propellants, their hypergolic nature, the corrosive environment resulting from a propellant leak, and high penalty for commodity losses due to leakage over an extended period of time. One of the constraints on the Space Station is that high-pressure spheres and propellant tanks must be isolated from the crew quarters. In addition to this constraint, this study has concluded that the propellant enclosure should be vented to vacuum during normal operation, with the capability to be repressurized for maintenance activities.

With the enclosures vented to vacuum, many of the design problems related to toxicity and corrosion are greatly reduced. As indicated by the system commodity loss in Table IV-2, the loss is not significant until all fittings were leaking in excess of 10^{-4} cc/sec per fitting. Therefore, the conclusion of this aspect of the study is that the system should be designed and qualified (before launch) to a leakage rate of 10^{-6} cc/sec nitrogen per fitting, and actually meet a leakage rate of 10^{-4} atm cc/sec of nitrogen for the duration of the mission. This will allow for degradation due to the human element and seal materials. Present technology and hardware will more than meet these requirements because a leak rate of 10^{-4} cc/sec is approximately a bubbletight joint. This level of leakage will also allow the use of less stringent methods of determining leakage points in the system. Thus it is apparent, from all tradeoffs, that leakage criteria are to be considered, but more emphasis should be on fitting design criteria for inflight maintenance. Some of the more desirable features a fitting should possess are:

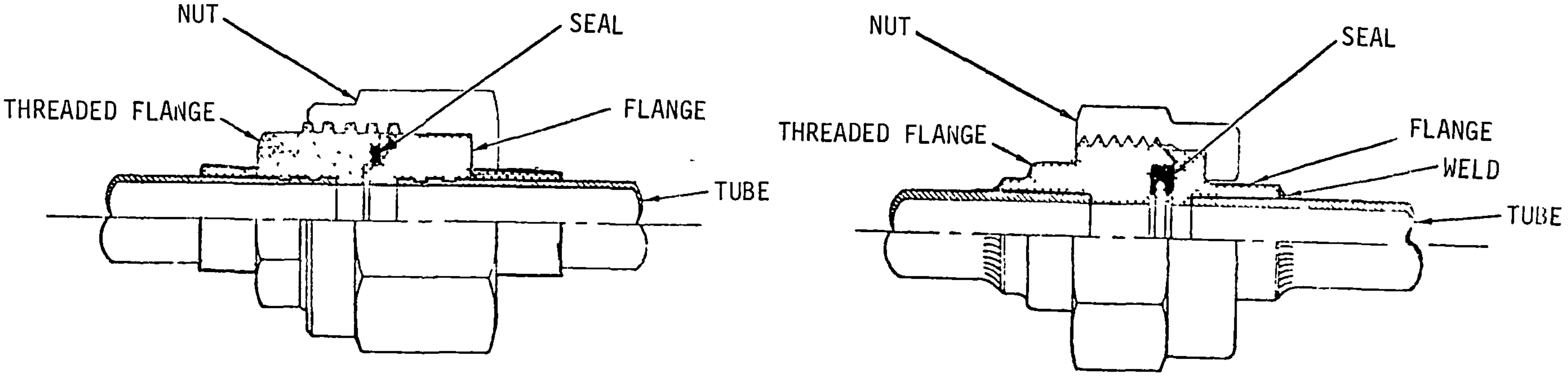
1) A fitting with a replaceable seal;
2) Repeated sealing integrity after numerous assembly and disassembly operations in zero gravity,
3) Compact design with simple and positive assembly;
4) A fitting that is foolproof in assembly and which can be easily repaired or replaced in zero gravity;
5) A fitting design which eliminates or reduces failure modes.

I. MAINTAINABLE FITTINGS

In the analysis of separable fittings, it was realized that to have an IFM capability for the APS, the system must have mechanical fluid fittings and replaceable instrumentation sensors. Separable fittings are required even though they are heavier and have a greater potential for leakage than brazed or welded joints.

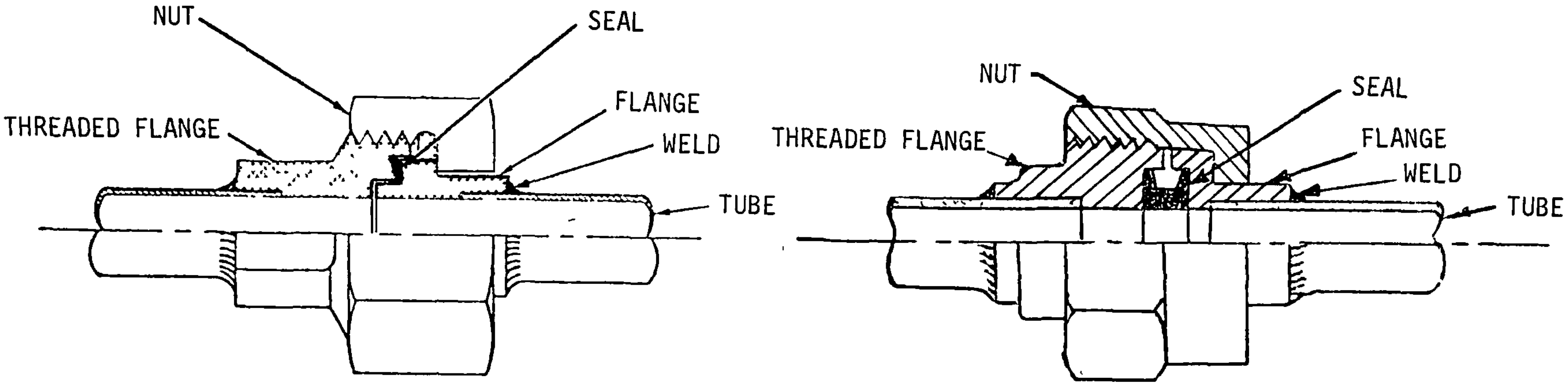
The evaluation of separable fittings resulted in selecting four candidate couplings and seals, each with certain features that are adaptable to IFM. These four couplings are the Bobbin seal developed under Air Force Contracts AF04(611)-8176, -9578, and -11204, and used in the Bob-N-Loc coupling; Astro-Weight couplings with metal K seals; Conoseal couplings with metal seals; and Gamah couplings with metal seals. Each of these couplings consist of a threaded flange, a nut, a flange and seal as shown in Fig. IV-37. The primary difference in the various separable joints is the seal configuration. Also, one manufacturer uses the stub ACME thread, rather than the straight thread, and a reusable seal. Of the four mentioned above, the Bobbin seal and the Gamah seal have given the better results in test of high-pressure (over 2000 psi) systems for extreme environmental conditions and long duration. The major advantages of couplings and fittings of the types described above are that seals are separate from the coupling, there are no closely machined surfaces that must be mated, and an unskilled person can easily make a joint that will meet the 10^{-4} atm cc/sec leakage rate. Therefore, since leakage is no longer the predominant criterion, more emphasis should be placed on the accessibility to the fitting, the ease of assembly/disassembly of the fitting and repeated high reliability with each assembly.

The two most common failures of a separable coupling or fitting is a failure of the seal or threads, which results in excessive leakage. The seal problem can be easily remedied by replacing the seal if separate seals are employed. The thread failure, due to stripping or galling, can be a very serious problem if a backout solution is not available. A coupling configuration as depicted in Fig. IV-38 has one major advantage over the conventional couplings in that it provides a backout solution to thread failures. The design includes a replaceable nut and split retainer ring for disassembly purposes. To be assured that the thread failure occurs in the replaceable nut, the threaded female flange would be made of a harder material. To remove a faulty nut, the nut would be moved back over the male flange until the split retainer ring is exposed and removed, the faulty nut will then pass over the male flange for removal. Replacement of a spare nut would be the reverse of this procedure.



GAMAH

ASTRO-WEIGHT



CONOSEAL

BOB-N-LOC

Fig. IV-37 Reusable Tube Couplings

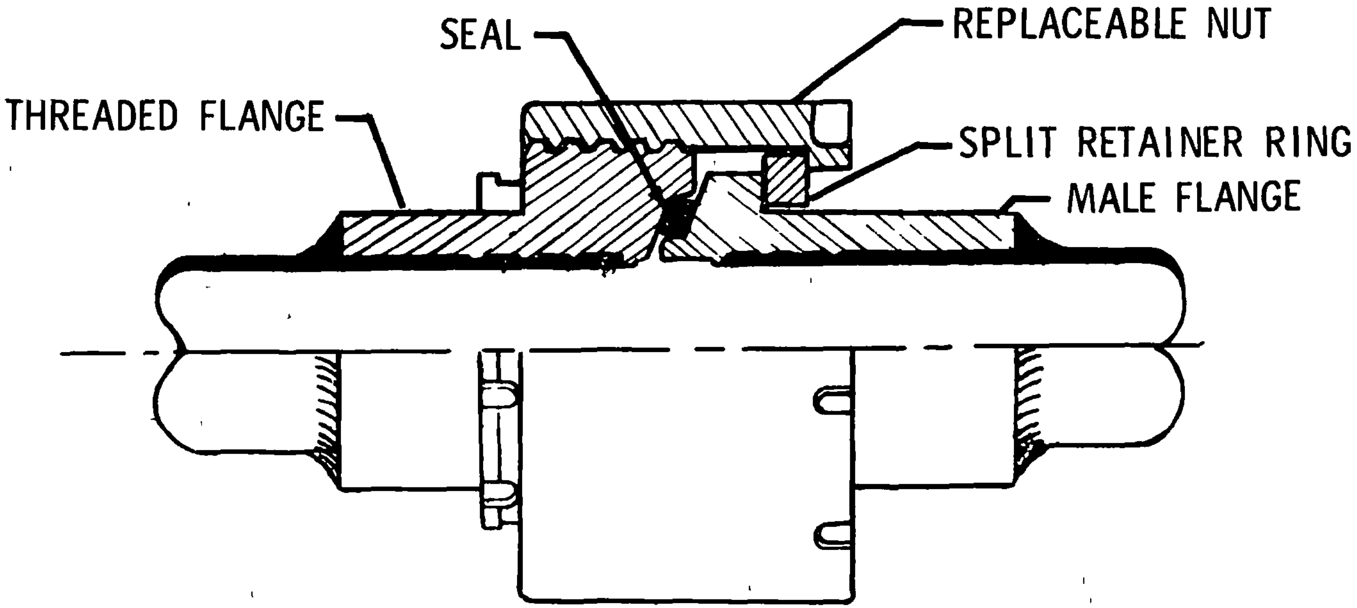


Fig. IV-38 Reusable Tube Coupling with Replaceable Nut

The stub ACME thread is recommended as one way to reduce thread failures because it is almost impossible to cross thread and is easy to start even if not visible to the operator. Another consideration in fitting design is to have the seal material made of a softer material than the seal cavities to preclude damage to the welded-in flanges. The slight radial clearance in the seal cavity establishes a rapport between seal and cavity by allowing the cavity to support the seal in the event the modulus of elasticity of the seal material is reduced by time or temperature. A circular nut is shown in Fig. IV-38 to achieve a minimum envelope and weight, although hex nuts could be used. With the circular nut a spanner wrench is required for tightening. Another concept would be to have a backup O-ring as a redundant seal to the metal seal. The O-ring would be made of Teflon or other compatible material.

An inflight solution to the replacement of an entire fitting is shown in Fig. IV-39. This Gamah coupling does not require any welding or brazing processes to complete the fitting and tube repair. To provide the tube coupling repair capability, the initial tube coupling would have short flanges with the tube swaged and welded to the flanges. If a coupling requires replacement, the tube would be cut off immediately behind the coupling. A coupling with extra length flanges could then have the tubing swaged to the flanges.

The only flared tube type fittings that have been tested and gave satisfactory results are the modified AN fittings. A modified AN fitting is identical to a standard AN fitting with the exception of a groove machined on the nose of the fitting and a Teflon ring inserted. This forms a composite metal-to-Teflon and metal-to-metal seal when in contact with a flared tube. Extensive development tests have been conducted on this fitting. The tests concluded that the fittings do require more support for external loads and for vibration loads than similar joints with AN fittings without modification. The torque relaxation problem is also greater with the Teflon seals than the nonmodified fittings. The test indicated that the modified fittings gave good sealing characteristics even when manufacturing specifications were not met. The use of damaged (by handling or use) fittings and extensive torque relaxation did not alter the sealing properties significantly. The Teflon seals do tend to lose slight sealing properties when reused but this was not great enough to require changes of seals more often than approximately once per 50 reassembly times. These tests were conducted by Brown Engineering Company, Inc., per NASA Contract NAS10-1360.

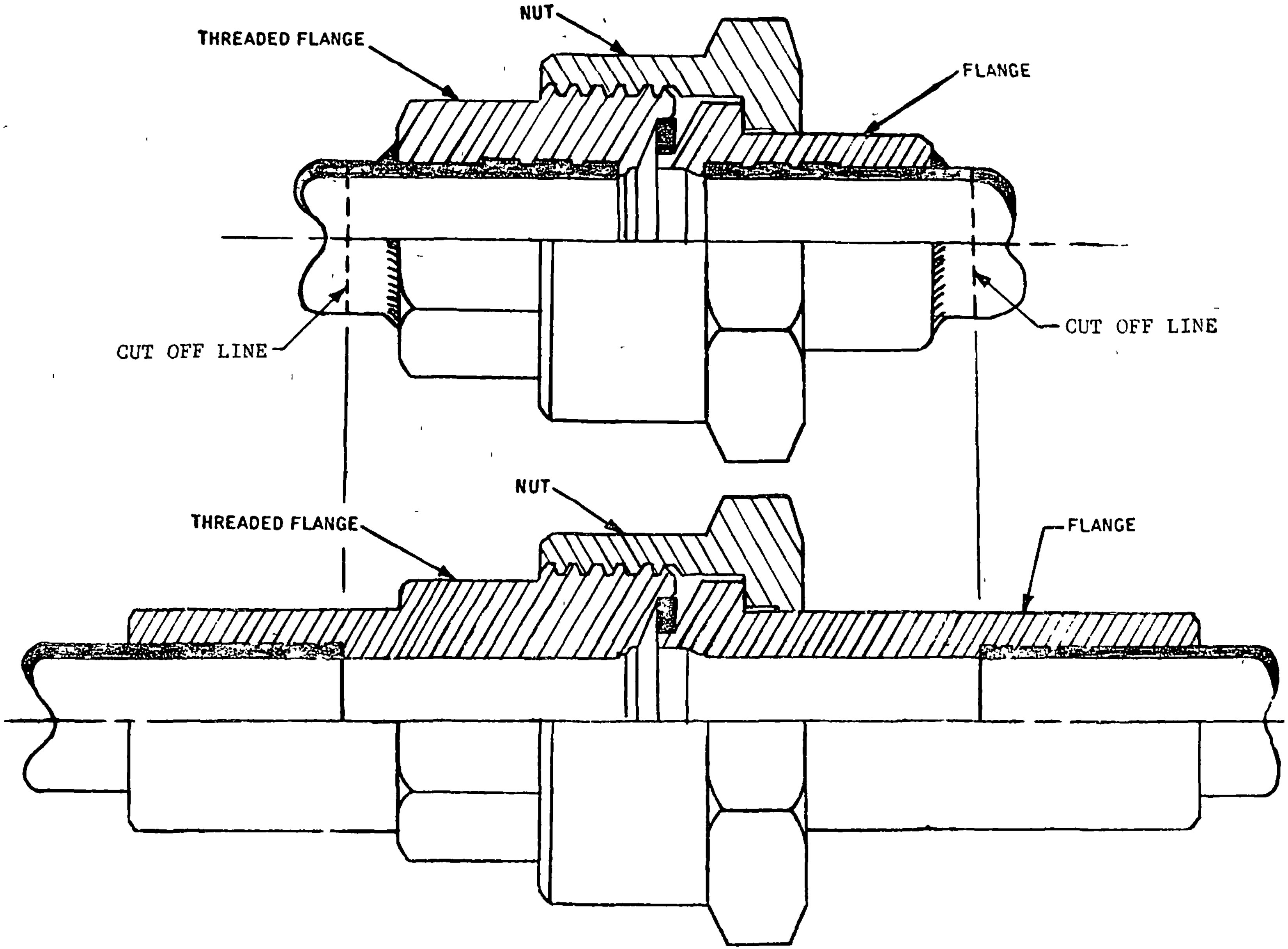


Fig. IV-39 Gamah Coupling Replacement with Long Flanges

The tools required to assemble or disassemble these fittings are standard open-end wrenches, spanner wrenches, and/or tubing wrenches that are nonsparking and adaptable to being restrained in zero gravity.

J. PROPELLANT TOXICITY ANALYSIS

An analysis was conducted to determine contamination levels in the Space Station due to spillage or leakage of the APS propellants, nitrogen tetroxide (NTO) and monomethylhydrazine (MMH). Basic data and conditions in the Space Station were taken from the NASA RFP statement of work, dated 28 April 1969.

The two basic situations treated in this study are contaminant buildup versus:

1) Spillage of assumed volumes of contaminants;
2) Constant leakage of contaminants at assumed rates.

Each of these categories are investigated separately for NTO and MMH in both a single floor case and the total Space Station.

Statement of work parameters describing the Space Station internal environment are as follows:

Single floor volume = 5987 ft^3;

Total Space Station Volume = 29,935 ft^3;

Environment:

$T = 68°F = 528°R$,

Relative humidity = 40%,

$p = 10$ psia,

$P_{O_2} = 2.7$ psia (constant O_2 partial pressure);

Cabin atmosphere leakage = 1170 lb_m in 90 days or 1.5×10^{-4} lb_m/sec.

1. Contaminant Buildup vs Spillage

The problem investigated in this portion of the analysis predicts the contamination levels resulting from spillage of liquid propellants. It was assumed that, upon spillage, the volume of contaminant would be instantaneously and uniformly distributed throughout the volume in question. Spilled volumes of liquid, v_c, were assumed and the mass of spilled fluid, w_c, was found by

$$w_c = \rho_c v_c \left(lb_m\right) \tag{1}$$

with v_c in cm^3, ρ_c (liquid density) in lb_m/cc

To find the number of moles, n_c, of contaminant

$$n_c = \frac{w_c}{M_c} \left(lb_m \text{ moles}\right) \tag{2}$$

where M_c is the molecular weight of the contaminant. Assuming perfect gas behavior, to determine the number of moles, n_a, of cabin atmosphere gas:

$$n_a = \frac{p V}{R T} \left(lb_m \text{ moles}\right) \tag{3}$$

where

$p = 5$, 10 or 15 psia or 720, 1440, 2160 lb_f/ft^2,

$V = 5,987\ ft^3$ or $29,935\ ft^3$,

$R = 1545 \dfrac{ft - lb_f}{lb_m\text{-mole } °R}$,

$T = 528°R$.

Since ideal gas behavior is assumed, the number of molecules of atmosphere gas and contaminant are

$$N_A = N_o n_a \tag{4a}$$

and

$$N_C = N_o n_c \tag{4b}$$

respectively, where N_o is Avogadros number, a constant. The contamination level, C_1, is found by

$$C_1 = \frac{N_o\ n_c\ (10^6)}{N_o\ n_a} = \frac{n_c\ (10^6)}{n_a}\ \text{ppm} \qquad [5]$$

or, substituting Eq [2] and [3] into [5]:

$$C_1 = \frac{\rho_c\ v_c}{M_c}\ \frac{\bar{R}\ T}{pV}\ (10^6)\ \text{ppm} \qquad [6]$$

Now:

$\rho_{MMH} = 1.92 \times 10^{-3}\ \text{lb}_m/\text{cc} = 54.5\ \text{lb}_m/\text{ft}^3$ (liquid density),

$\rho_{NTO} = 3.21 \times 10^{-3}\ \text{lb}_m/\text{cc} = 91.0\ \text{lb}_m/\text{ft}^3$ (liquid density),

$M_{MMH} = 46.08\ \text{lb}_m/\text{lb}_m\text{-mole}$

$M_{NTO} = 92.02\ \text{lb}_m/\text{lb}_m\text{-mole}$

Curves plotted from Eq [6] are shown in Fig. IV-40 and IV-41. They reflect the two contaminants each plotted for one segment and the total Space Station at three pressures.

Two toxicity levels are indicated in Fig. IV-40 and IV-41. The emergency tolerance level is the maximum amount allowable for a ten-minute unprotected exposure. The maximum acceptable concentration is the maximum amount that can safely be endured for an 8-hr workday. The values indicated in Fig. IV-40 and IV-41 reflect contamination levels for the presence of a single contaminant. If more than one toxic substance is present, the maximum concentrations must be proportioned between the constituents.

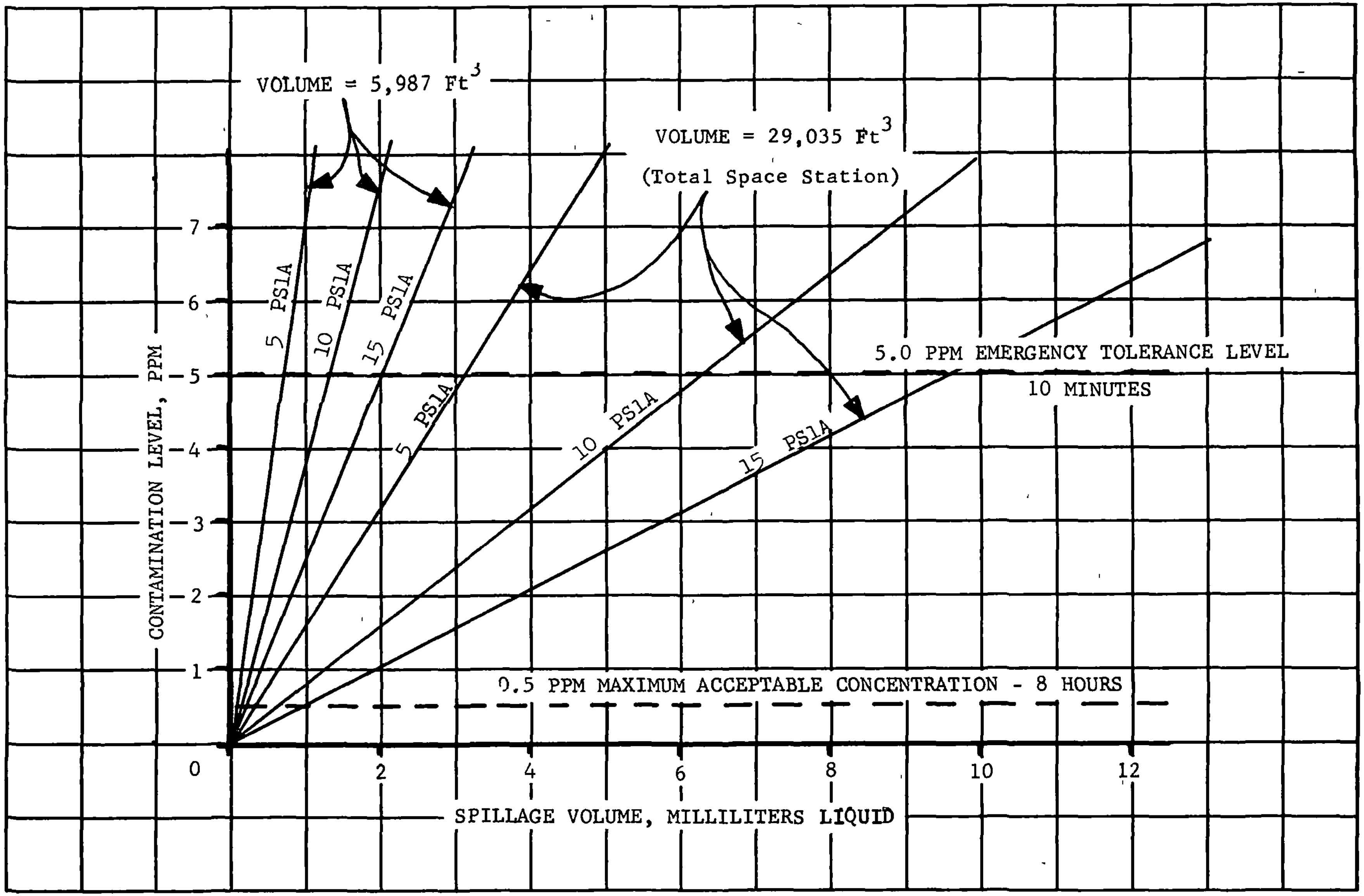


Fig. IV-40 MMH Contamination vs Spillage Volume

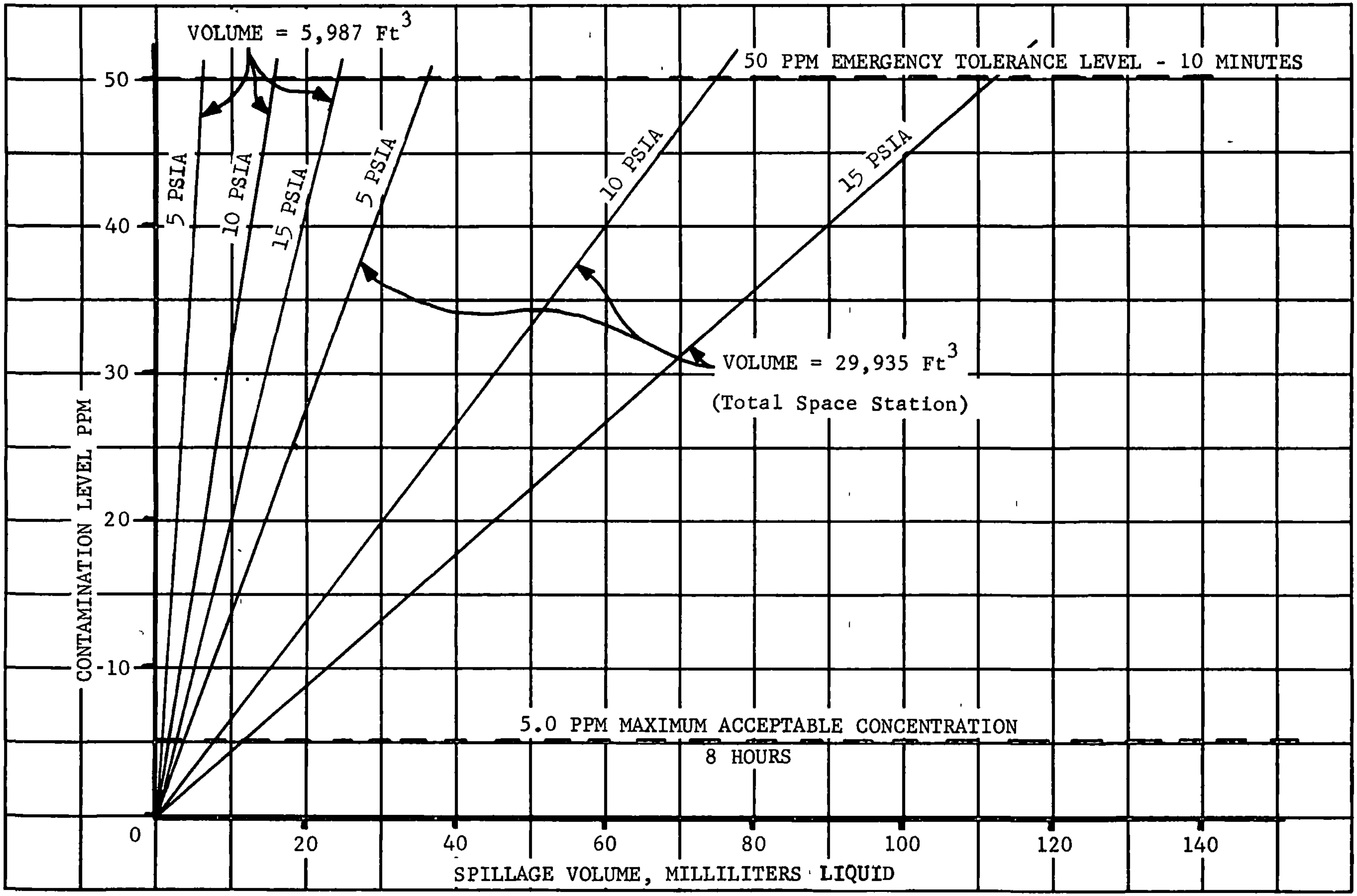


Fig. IV-41 NTO Contamination vs Spillage Volume

The following conclusions were arrived at for propellant spillage in the Space Station:

1) Emergency tolerance levels will be reached when (0.7 to 110 milliliters) of spillage occurs. The amount of critical spillage is highly dependent upon the propellant, Space Station atmospheric pressure, and volume;
2) Maximum toxicity levels occur at reduced Space Station pressures and volume;
3) Propellant systems must be thoroughly decontaminated before breaking open the system;
4) Toxicity levels within the system must be verified safe before opening the system;
5) Astronauts should wear protective flexible clothing when performing repair on a propulsion system;
6) Emergency breathing apparatus should be provided within easy reach, and the Space Station design should include emergency isolation of one segment (floor) in the Space Station;
7) Fuel spills (MMH) present the highest toxicity levels for comparable volumes;
8) Sufficient time is available to take emergency measures for small spills;
9) Components should be designed with no trapped volumes, minimum seal material exposed to the propellant, and minimum internal volume.

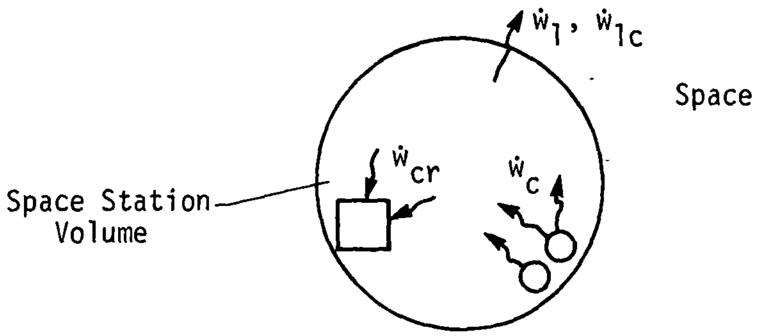


Fig. IV-42 Propellant Leakage Diagram

2. Contamination Buildup vs Constant Leakage Rates

The dynamics of this problem are illustrated in Fig. IV-42 where,

$\dot{w}_c$ = flow rate of contaminant leakage into the Space Station $\left(lb_m/sec\right)$,

$\dot{w}_{cr}$ = mass flow rate of contaminant removal from cabin atmosphere by the environmental control system $\left(lb_m/sec\right)$,

$\dot{w}_l$ = mass flow rate leakage of atmosphere from cabin to space $\left(lb_m/sec\right)$,

$\dot{w}_{lc}$ = the contaminant leakage rate out of the Space Station $\left(lb_m/sec\right)$,

$\dot{w}_c'$ = the effective instantaneous mass flowrate of contaminant accumulating within the Space Station $\left(lb_m/sec\right)$.

Summating the mass flowrates of contaminant,

$$\dot{w}_c' = \dot{w}_c - \dot{w}_{lc} - \dot{w}_{cr} \qquad [7]$$

Now if n_c is the number of moles of contaminant, and $\dot{n}_c$ is the rate of change:

$$\dot{n}_c = \frac{\dot{w}_c'}{M_c} \qquad [8]$$

where M_c is the molecular weight of the contaminant. The number of moles of Space Station atmosphere n_a $\left(lb_m\text{-moles}\right)$,

$$n_a = n_{H_2O} + n_{O_2} + n_{N_2} = f\ (p\ V) \qquad [9]$$

For 40% humidity, the partial pressure of H_2O is

$$p_{H_2O} = (0.40)(\text{vapor pressure of } H_2O \text{ at } 68°F)$$

$$= (0.40)(0.34) = 0.136 \text{ psia} = 19.584 \text{ lb}_f/\text{ft}^2 \qquad [10]$$

and,

$$n_{H_2O} = \frac{p_{H_2O} V}{\bar{R} T} \qquad [11]$$

The partial pressure of O_2, P_{O_2} is constant at 2.7 psia.

$$n_{O_2} = \frac{P_{O_2} V}{\bar{R} T} \qquad [12]$$

The partial pressure of N_2 is

$$P_{N_2} = p - P_{O_2} - p_{H_2O} \qquad [13]$$

where p is the cabin pressure. Again, the number of moles of N_2 is given by

$$n_{N_2} = \frac{p_{N_2} V}{\bar{R} T} \qquad [14]$$

Equation [9] then gave the number of moles of Space Station atmosphere gas for the different conditions of the study.

The numbers of molecules of contaminant and atmosphere are respectively,

$$N_c = n_c N_o \qquad [15]$$

$$N_a = n_a N_o \qquad [16]$$

also,

$$\dot{N}_c = \dot{n}_c N_o \tag{17}$$

The rate of contamination buildup, $\dot{C}_2$, in ppm/second is therefore

$$\dot{C}_2 = \frac{\dot{n}_c N_o (10^6)}{n_a N_o} = \frac{\dot{n}_c}{n_a} (10^6) \text{ ppm/sec} \tag{18}$$

The amount of contamination at any time, t, is given by

$$C_2 = \int_o^t \dot{C}_2 \, dt \tag{19}$$

$\dot{C}2$ is a function of time as shown below:

$$\dot{w}_c' = \dot{w}_c - \dot{w}_{1c} - \dot{w}_{cr} \tag{7}$$

however,

$$\dot{w}_{1c} = \frac{\left(\dot{w}_c \; t\right)}{W_a} w_1 \tag{20}$$

or

$$\dot{w}_c' = \dot{w}_c - \frac{\left(\dot{w}_c' \; t\right)}{W_a} \dot{w}_1 - \dot{w}_{cr} \tag{21a}$$

where W_a = the mass of cabin atmosphere gas

and

$$\dot{w}_c' = \frac{\dot{w}_c - \dot{w}_{cr}}{1 + \frac{w_1 t}{W_a}} \tag{21b}$$

Substituting the various parameters into Eq [18]:

$$\dot{C}_2 = \frac{\left(\dot{w}_c - \dot{w}_{cr}\right)(10^6)}{\left[1 + \frac{\dot{w}_1 t}{W_a}\right] n_a M_c} \qquad [22]$$

Substituting Eq [22] into [19] and integrating:

$$C_2 = \frac{\left(\dot{w}_c - \dot{w}_{cr}\right)(10^6) \ln\left[1 + \frac{\dot{w}_1 t}{W_a}\right] W_a}{n_a M_c \dot{w}_1} \text{ ppm} \qquad [23]$$

The values assumed for $\dot{w}_c$ are the mass flowrates based on contaminant vapor leakage volumes of 10^{-2}, 10^{-4} and 10^{-6} cc/sec. The density of the contaminant vapors at p = 10 psia are calculated by

$$\rho_c = \frac{pM_c}{\bar{R}\,T} \qquad [24]$$

Resulting in:

$$\rho_{NTO} = 0.1625 \frac{lb_m}{ft^3}, \qquad \rho_{MMH} = 0.0815 \frac{lb_m}{ft^3}$$

Then

$$\dot{w}_c = \dot{v}_c \rho_c. \qquad [25]$$

Therefore

$$C_2 = \frac{W_a \left(\dot{v}_c \rho_c - \dot{w}_{cr}\right) 10^6 \ln\left[1 + \frac{\dot{w}_1 t}{W_a}\right]}{n_a M_c \dot{w}_1} \text{ ppm} \qquad [26]$$

Figures IV-43 thru IV-46 show contaminant levels versus elapsed time for three values of total propellant system leakage. The data were calculated at a Space Station pressure of 10 psia, and assumed uniform distribution of the vapor with specification atmosphere leakage from the Space Station. The toxicity levels will increase, for a given value of propellant system leakage, as Space Station atmosphere leakage to space decreases. The following conclusions resulted from this analysis:

1) Nominal system leakage (10^{-4} cc/sec) into the Space Station will reach MAC levels in approximately two weeks. Therefore, adequate time is available to effect repairs;
2) Leakage failures (10^{-2} cc/sec or higher) will reach MAC levels in approximately 3 hr, which will necessitate emergency action to be taken;
3) The propellant system and its inherent leakage must be isolated from the normal crew occupied areas of the Space Station;
4) No failure mode should allow leakage into the Space Station crew quarters (i.e., leakage shown is to vacuum);
5) The design of the Cataylic burner in the Space Station environmental control system should consider the requirement to remove propellant contaminants in the event of a spill. A small toxic removal unit should be located in the same level of the Space Station as the propellant system to remove local vapors in the event of a spill or emergency.

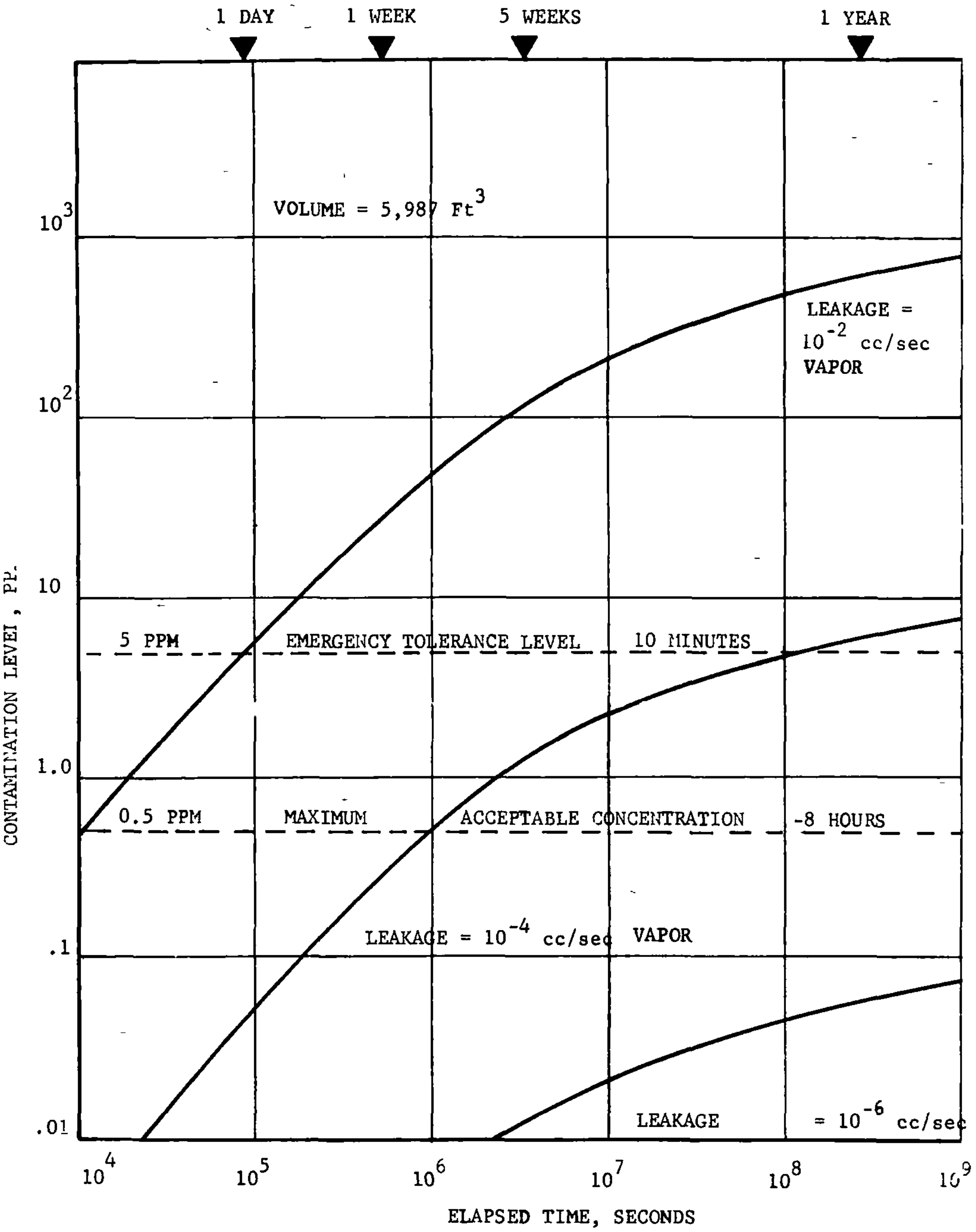


Fig IV-43 MMH System Leakage vs Toxicity Level

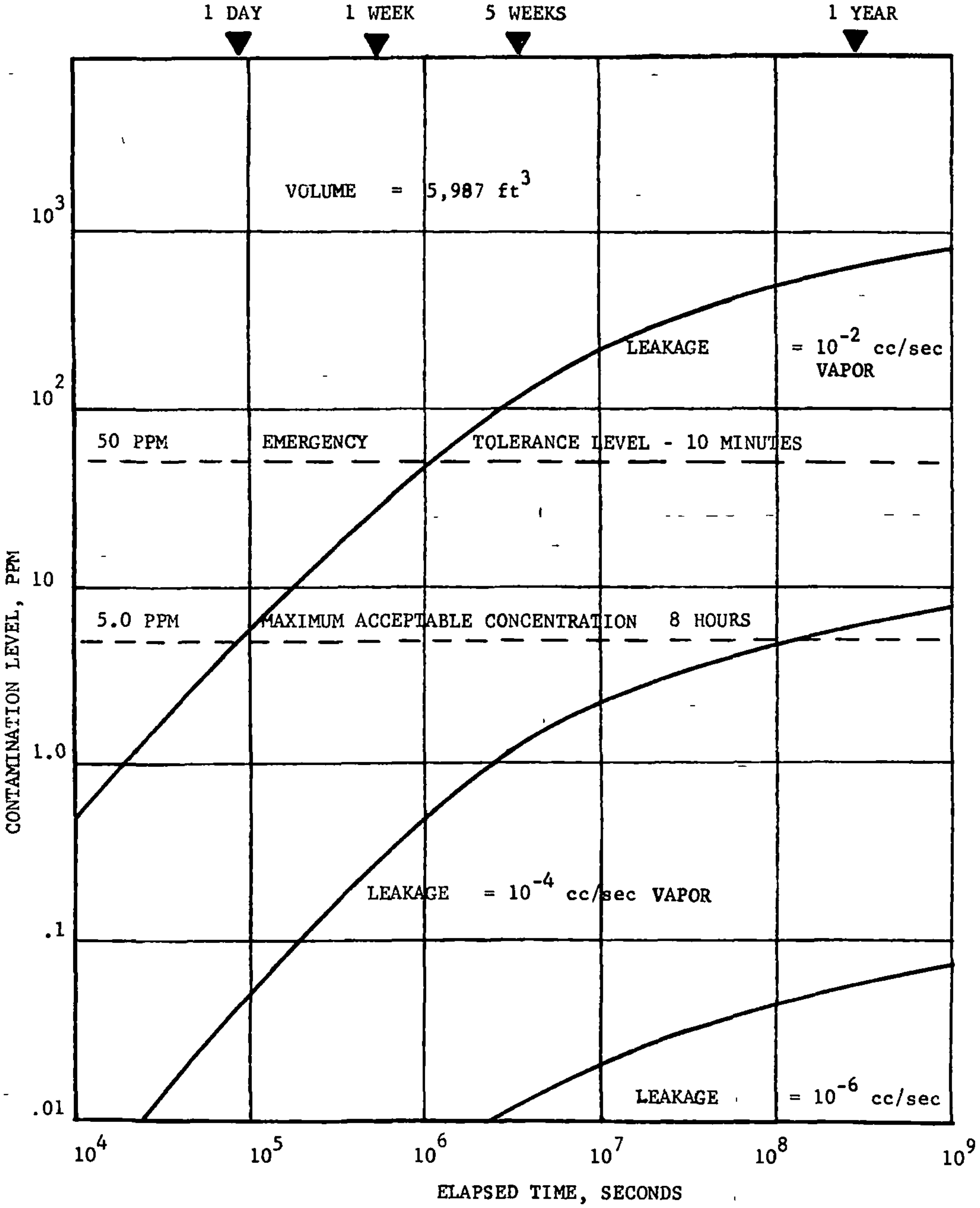


Fig IV-44 NTO System Leakage vs Toxicity Level

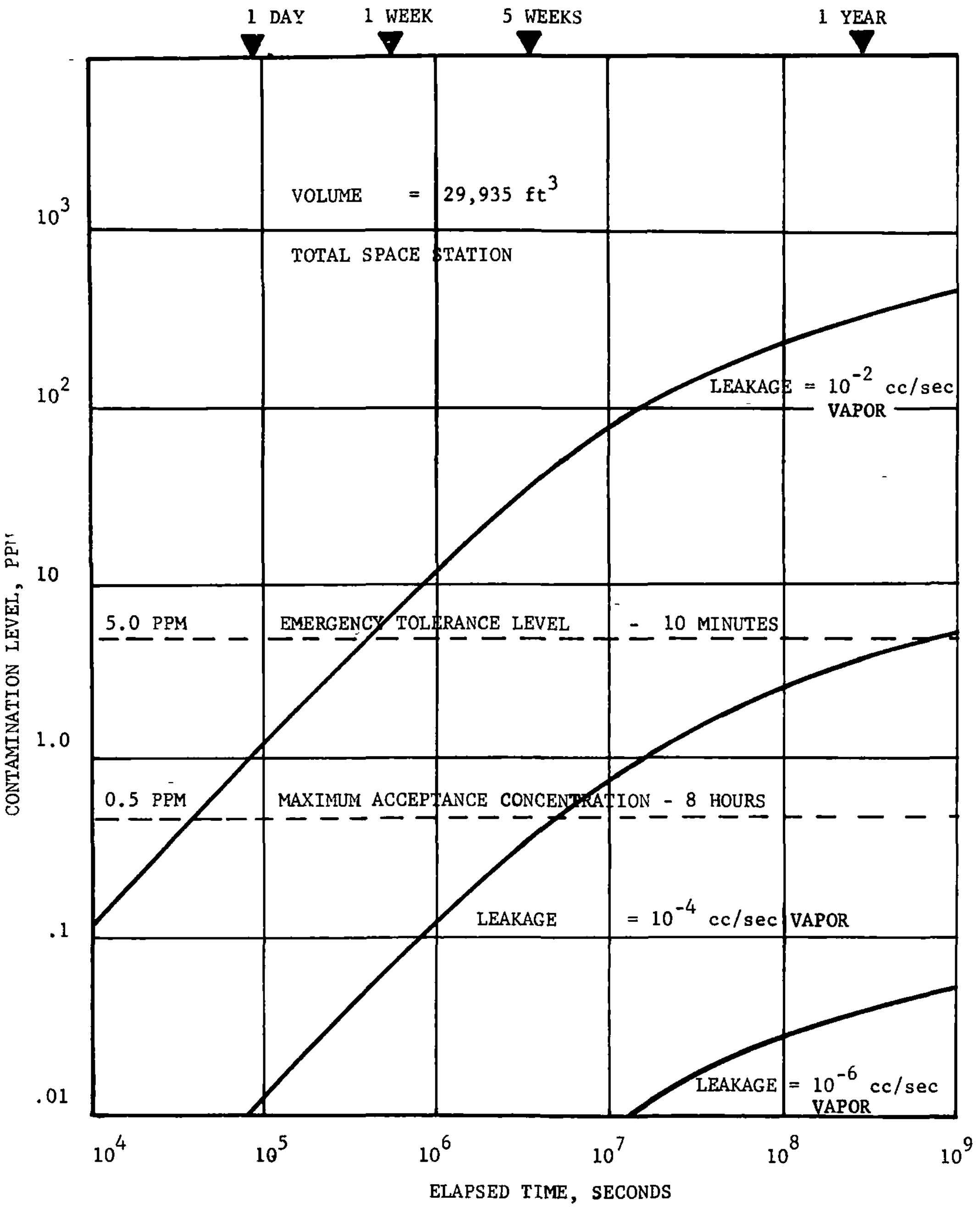


Fig. IV-45 MMH System Leakage vs Toxicity Level

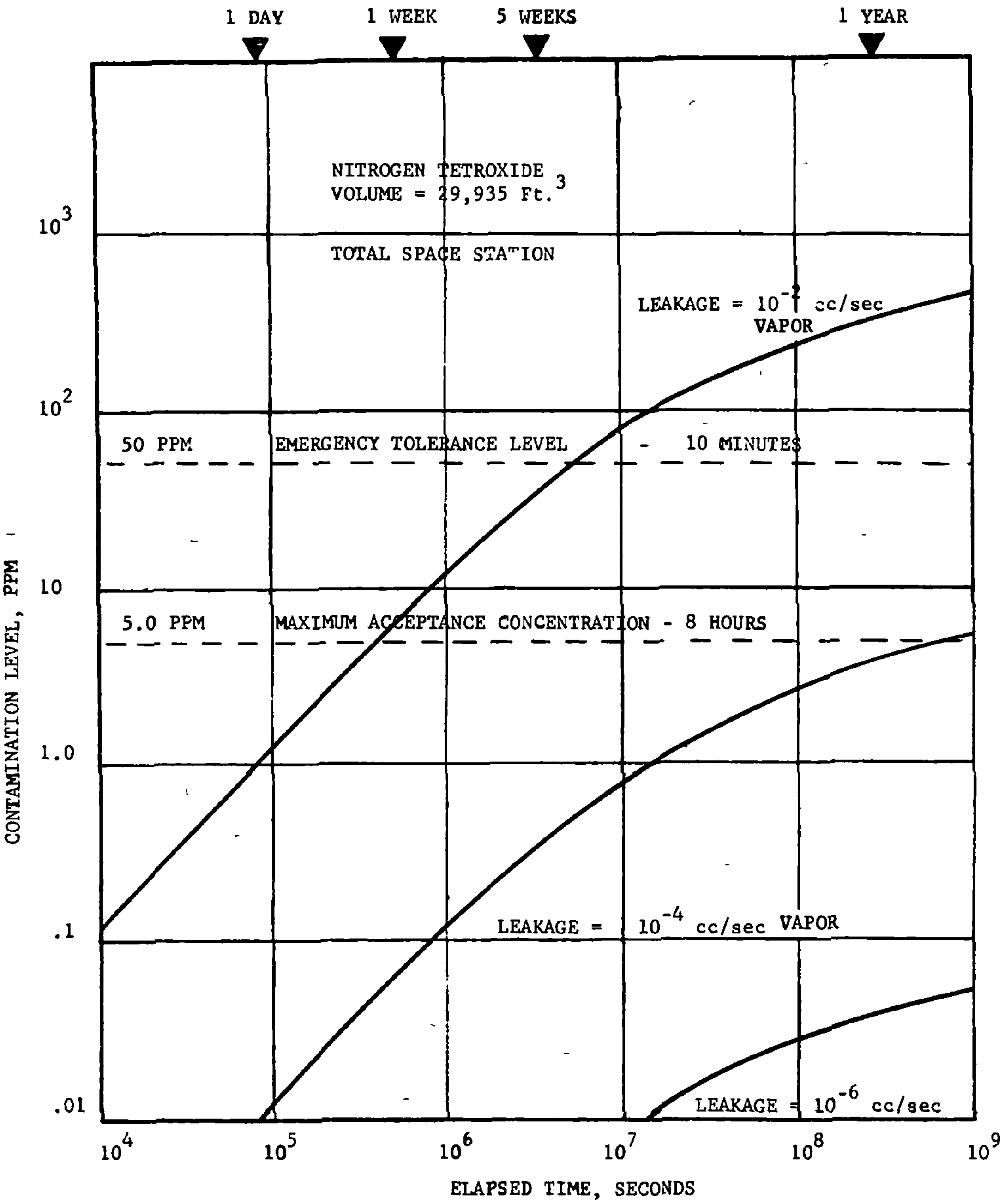


Fig. IV-46 NTO System Leakage vs Toxicity Level

3. Theoretical Contaminant Removal Requirements

When contaminant is being removed from the atmosphere by the environmental control system, i.e., $\dot{w}_{cr} > 0$, it is desirable to know how much must be removed to theoretically restrain the contamination level below a given value at a given time. Figure IV-47 illustrates the contamination buildup versus $\dot{w}_{cr}$ plotted from Eq [26]. Careful attention should be given to the parameters which are indicated as fixed on Fig. IV-47.

Summarizing the results of this curve for $t = 10^9$ sec:

1) To keep below 0.5 ppm of MMH, 6.8×10^{-4} lb_m of MMH must be removed per month;
2) To retain a level of 5.0 ppm of MMH, 7.5×10^{-5} lb of MMH must be removed per month;
3) To remain below 5.0 ppm of NTO, 1.5×10^{-4} lb_m of NTO must be removed per month;
4) If $\dot{w}_{cr} = 0$ the contamination level for NTO will not exceed 50 ppm at the conditions given at 10^9 sec.

K. FLUID HANDLING AND SPECIAL TOOLS

One of the most critical and necessary maintenance tasks in providing an IFM capability is propellant removal and handling. Because of all the potential hazards associated with both NTO and MMH, special care and tools are required when maintenance tasks require working with lines or components containing these fluids. The hazards involved have been explained in the toxicity analysis; therefore, in this section we will discuss the special tools and procedures required for the removal and replacement of modules or components containing NTO and MMH. The procedures also include the sequence of tasks to remove and replace components of the pressurization system.

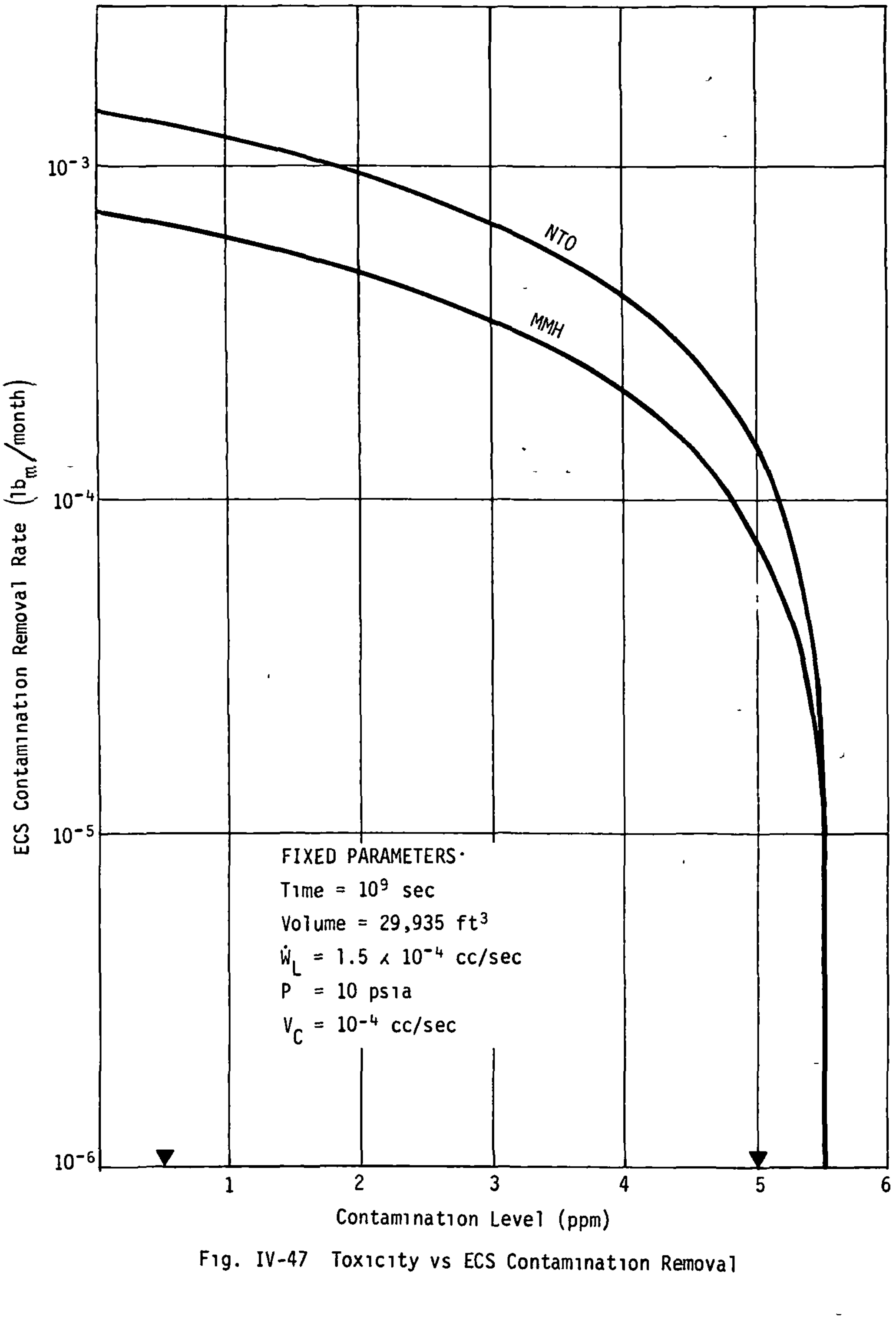


Fig. IV-47 Toxicity vs ECS Contamination Removal

The minimum number of special tools required to handle and perform maintenance tasks on components or modules containing NTO or MMH are the Propellant Removal and Servicing Tool, portable propellant leak detectors, and propellant leakage monitoring devices for each fluid. In addition, a portable N_2 leak detector is recommended for testing the system for leaks before introducing the propellant fluid to a repaired section of the system. The N_2 leak detector would also be used to check for leaks after repairs in the pressurization section of the system.

Two Propellant Removal and Servicing Tools, such as the one schematically illustrated in Fig. IV-48, are required to safely remove and store contaminated propellants from the APS. Each tool would consist of a pump, a liquid-gas separator to prevent venting propellant to the atmosphere, a positive expulsion tank to store contaminated propellants that can be returned to earth via the logistic vehicle, gaseous nitrogen supply for purging and testing the affected sections of the APS, and the necessary interconnecting tubing, control valves, check valves, and instructions. The pump is required in case propellants cannot be pressure transferred, due to a tank ullage failure. The tools could also employ some of the same components as the APS, thus cannibalization could be employed, if necessary, to reduce the spares requirements. The N_2 supply for the propellant removal and servicing tools is self-contained or it could be obtained from the Space Station ECS for purging requirements and from the APS pressurant supply for leak testing requirements. The low pressure from the ECS would be sufficient for the purging operations, and since the quantity required for testing requirements is relatively low, 0.1 lb per test, there is ample N_2 to satisfy the APS and leak testing requirements.

It is recommended that the propellant removal and servicing tools be built into the Space Station as an integral part of the APS. The reasons for a built-in tool, rather than a portable tool, is that since two are required, one for each propellant, and they would only be used for the APS, a built-in unit would take less volume and weight. Also, the use of this tool in any other system would present a potential hazard due to residual propellant or contamination (oxidizer, organic, water) remaining in the tool after use. Safety constraints would not allow any other usage of a tool used in a propellant system, even considering cleaning after use. This concept is depicted in the conceptual design of the APS compartment. This configuration uses the available space that is adjacent to propellant storage tanks and thereby reduces interconnecting tubing, monitoring and detection devices, and provides the crew the capability of controlling all phases of maintenance tasks on the APS compartment from the immediate area.

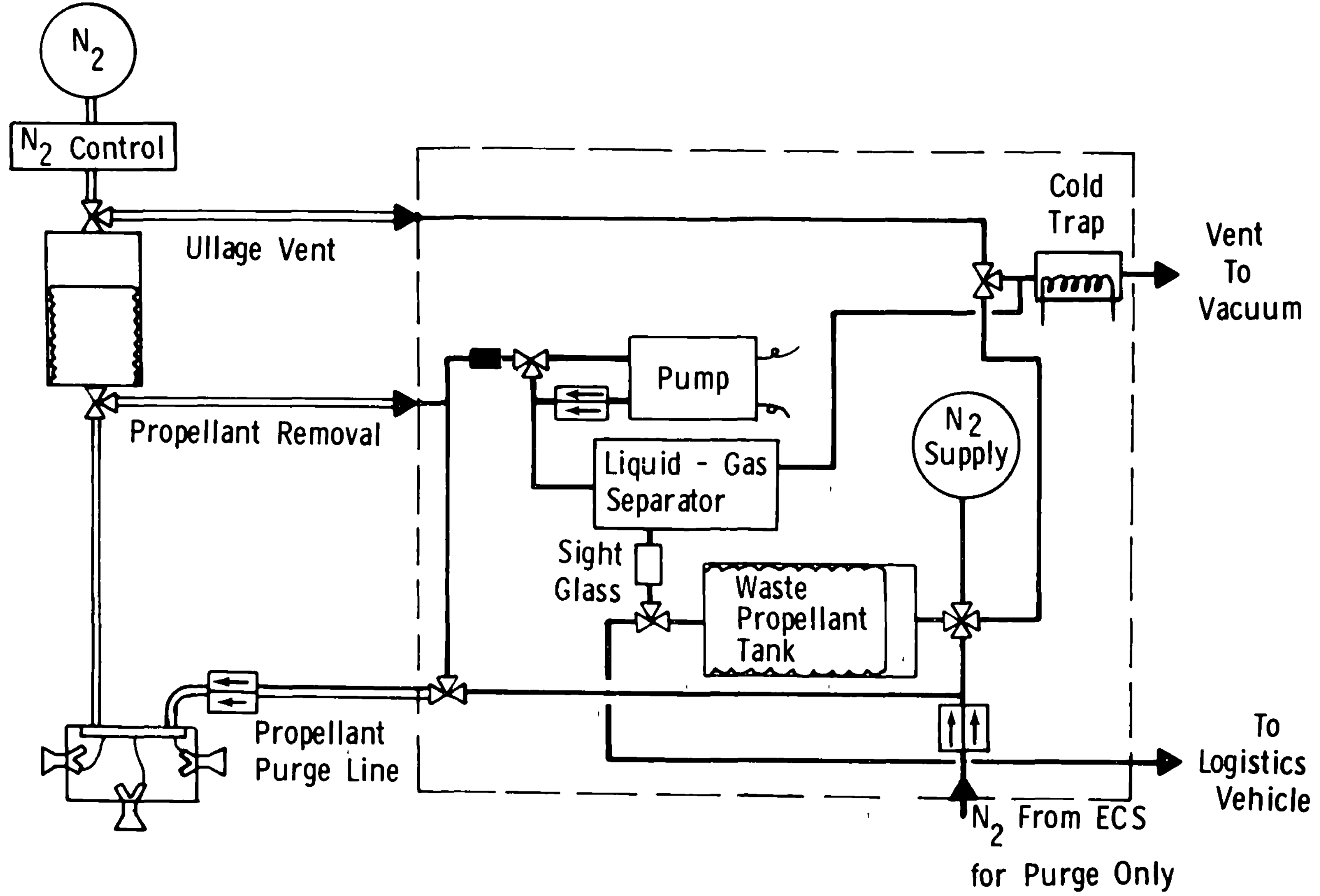


Fig. IV-48 Propellant Removal and Servicing Tool Schematic

It should be noted that the checkout and decontamination equipment, once considered to be ground equipment, now becomes a piece of flight hardware. The purge lines are an appendage in the propulsion system. Even though the equipment is in a standby mode the majority of the time, the equipment must be considered in the overall propulsion system integrated design and reliability predictions.

Since one of the primary safety constraints is that the APS propellant lines shall not be opened until there is a positive indication of safe toxic levels, it is evident that purge ports are required at the engine module to provide a loop for the purging commodity, gaseous nitrogen. It would be desirable to have a purging port at each engine solenoid valve; however, this is not very practical. A more feasible location for the purging ports would be in the fuel and oxidizer manifolds on each of the four engine modules. This would require a total of eight purging ports to purge all the components between the propellant tanks and the engines.

The propellant tanks would not be purged, but would be decontaminated by removing the remaining fluid with the propellant removal and servicing tool, and then a controlled sequence venting of the ullage and the propellant storage volume to vacuum through a cold trap.

The detection and monitoring of the storable propellants and their residues in the storage compartment and on the surface of the components is essential for two reasons: (1) to protect personnel who are required to work in the compartment with the components, and (2) to prevent damage to the components.

The term detection is used to designate noncontinuous quantitative test for propellants or their residues. A separate sample is examined each time and in each area that is suspected of containing propellant or propellant vapor.

The term monitoring is used for the process in which sampling is continuous. Monitoring equipment also can incorporate alarms or provisions for reducing or eliminating the detected material from the area being sampled.

Two portable detection devices, one for fuel and the other for oxidizer, are required for isolating propellant leaks and for a verification of system integrity after the removal and replacement of propellant components. The preferred portable detection kit for fuel uses a ppm meter specifically for MMH. The test, which is extremely sensitive, can be applied to wet or dry surfaces, solutions, and air samples. The nitrogen tetroxide portable detector, suitable only for air sampling, indicates the presence of NO_2 on a ppm meter. Surfaces can be tested for NO_2 with pH-indicating paper since NO_2 diluted with water produces nitric acid. Reference to a color chart indicates the level of acidity and the corresponding level of dissolved NO_2. It may also be feasible to coat fittings and other potential leakage paths with a substance which would give a visual indication of a propellant leak.

The monitoring system to detect propellants in their compartments would consist of gas analyzers. It is recommended that the monitoring devices be compatible with the Onboard Checkout System (OCS) to give rapid indications that a failure has occurred. The location of the sensors will be determined by the actual design configuration of the propellant compartments.

In keeping with the primary maintenance philosophy of removal and replacement of components or modules, Table IV-3 lists the sequence of events required to rectify failures or to perform planned maintenance activities. The Propellant Removal and Servicing Tool schematic and recommended APS schematic were used as a functional guide to determine the necessary operations to remove and replace the APS components or module and put the system back in service. The procedures in Table IV-3 do not include the detail step-by-step procedures to perform the maintenance task. This can be done only after the actual system is designed. Also, such items as donning protective clothing, pressurizing and depressurizing compartments, pulling circuit breakers, etc, are not included in the table. The time to accomplish these tasks was used in the maintainability analysis in determining the time to effect repair.

The engine solenoid valve replacement was included since it is a high failure item. If the solenoid valves were located away from the injector, it may be feasible to repair the valves. This is possible for long burn maneuvering functions. For an engine design such as the baseline engines, the solenoid valves would not be a replaceable component except in a clean room environment. If quad solenoid valves are used, the engine failure probability is so near the failure probability of the quad solenoid valves that it is more feasible to replace a complete engine assembly.

Table IV-3 Sequence of Component/Module Replacement Tasks

Repair Procedure	Component or Module						
	N_2 Sphere	N_2 Filter	Pressurant Module or Component	Propellant Filter	Propellant Tank	Engine Module	Engine Solenoid Valve
I Isolate Faulty Item and Bleed--							
A Position Valve on N_2 Sphere to OFF		1	1	1	1	1	1
B Position Three-Way Pressurant Control Valve to Vent N_2 Sphere	1	2	2				
C Position Three-Way Pressurant Control Valve to Vent N_2 Module	2	3	3				
D Position Three-Way Pressurant Valve(s) on Propellant Tank to Vent Control Module and Lines			4		2		
E Position Three-Way Pressurant Valve(s) on Propellant Tank to Vent Ullage				2	3	2	2
F Position Three-Way Propellant Valve(s) on Tank to Bleed/Purge to Remove Propellant					4	3	3
II Propellant Purge							
A Position Control Valves on Propellant Removal Tool(s) to Circulate N_2 thru Engine Manifold(s) and Lines					5	4	4
B Vent Propellant Components and Lines thru Propellant Removal Tool to Vacuum					6	5	5
III Component/Module Removal							
A Remove Item	3	4	5	3	7	6	6
B Cap Ports on Component or Module	4	5	6	4	8	7	7
IV Component/Module Installation							
A Install Spare Component or Module	5	6	7	5	9	8	8
B Package Removed Item for Transport to GPL or Return to Earth for Repair	6	7	8	6	10	9	9
C Store Removed Item		8	9	7		10	10
V Leak Check							
A Position Valve on N_2 Sphere to ON	7	9	10	8	11	11	11
B Position Three-Way Pressurant Control Valve to Operating Position	8	10	11				
C Charge Propellant Lines and Components with N_2 from the Propellant Removal Tool					12	12	12
D Check for Leaks with N_2 Leak Detector Tool	9	11	12		13	13	13
E Vent Propellant Components and Lines thru Propellant Removal Tool(s) to Vacuum					14	14	14
F Position Three-Way Pressurant Valve(s) on Propellant Tank to Operating Position			13	9	15	15	15
G Position Three-Way Propellant Valve(s) on Tank to Operating Position					16*	16	16
H Check for Leaks with MMH and/or NTO Leak Detector Tools				10	17	17	17
VI Checkout System							
A Perform Standby Test with OCS	10	12	14	11	18	18	18
B Perform Dynamic Test with OCS						19	19
VII Return System to Service or Standby	11	13	15	12	19	20	20

*Follow Resupply Procedure

L. IFM BIBLIOGRAPHY

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V. MAINTAINABILITY

The maintainability analysis of the APS resulted in analyzing four areas of concern that are necessary to provide an IFM capability. These analyses were based upon the recommended modified APS shown schematically in Fig. IV-10 (Chapter IV). The areas studied were:

1) Mean-time-to-repair (MTTR) of the various components;
2) Estimated scheduled and unscheduled maintenance times;
3) Crew-time profile to accomplish APS maintenance, repair, and resupply;
4) Recommended list of onboard spares.

In addition to the above analyses, a brief study was conducted to evaluate engine life as a function of Space Station mission requirements; including spin, despin, sun track, and gravity gradients. The design aspects of maintainability have been discussed in Chapter IV.

It is apparent that the achievement of a ten-year mission requires the combined use of high reliability components, redundancy, and an in-space maintenance and repair capability. Maintenance can be defined as all the activities necessary to keep the APS in, or restore it to, a satisfactory operating condition. Maintenance may be either scheduled or unscheduled.

Unscheduled maintenance is defined as any corrective maintenance required as a result of equipment failure or damage. Maintenance actions conducted as a result of conditions found during scheduled inspections including OCS are also classified as unscheduled maintenance.

Scheduled maintenance is any planned maintenance action deemed necessary to enhance the functional success of the equipment and/or preclude operational failure.

A. UNSCHEDULED MAINTENANCE

Tables V-1, V-2, and V-3 present the estimated unscheduled maintenance time per year for the APS subsystems and their components. The estimates assume that complete failed components, such as valves (level 7), were removed and replaced. Lower tier items such as valve poppets would not be replaced with the component installed in the APS. The times required for each maintenance task were estimated for the modular internally mounted concept that requires no EVA.

The average unscheduled maintenance times per year were calculated as follows:

1) The times 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 nitrogen sphere is 81 minutes (Table V-2);
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 Chapter VII. The failure probabilities include environmental and application adjustment factors. For example, the probability of a nitrogen sphere random failure is 406 ppm/year;
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. Thus the probable unscheduled maintenance time for the two nitrogen spheres is 0.07 minutes per year;
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 requirements for the pressurization system is about 6.9 minutes per year. Obviously no maintenance can be performed in 6.9 minutes; however, over a period of years, the average maintenance time prorated over the mission years will be 6.9 minutes for the pressurization subsystem.

Table V-1 Estimated Unscheduled Maintenance Time to Correct Random Failures, Propellant Storage and Transfer Subsystem

Task	Estimated Task Times (minutes)						
	3-Way Valve	Tank	Filter	Solenoid Valve	Lines & Joints	Trans-ducers	Q. D. Valve
Fault Isolation	3	5	3	5	20	5	5
Review Maintenance Procedure	5	10	5	5	10	5	5
Obtain Spare	5	10	5	5	10	5	5
Don Protective Clothing	10	10	10	10	10	10	10
Travel to Subsystem	5	7	5	5	5	5	5
Decontamination	60	60	0	40	40	40	40
Pressurize Compartment	5	5	5	5	5	5	5
Remove Access Cover(s)	5	5	5	5	5	5	5
Disconnect Instrumentation	0	4	0	0	4	4	0
Remove Part & Store in Bag	9	20	3	6	15	2	5
Install New Part	9	20	2	6	15	2	5
Connect Instrumentation	0	4	0	0	4	2	0
N_2 Checkout & Leak Check	10	10	10	10	10	10	10
Propellant Fill	45	45	0	20	20	20	20
Propellant Checkout & Leak Test	10	10	10	10	10	10	10
Replace Access Door(s)	5	5	5	5	5	5	5
Actuate System & OCS Checkout	5	5	5	5	5	5	5
Depressurize Compartment	5	5	5	5	5	5	5
Travel to Station & Stow Gear	10	10	10	10	10	10	10
Perform Administrative Functions	5	5	5	5	5	5	5
Total Task Times (T)	211	255	93	162	213	160	160
Number of Parts Required (n)	16	8	4	2	1	12	2
Probability Part Failure, ppm/yr ea (Q)	2,460	3,210	194	2520	150	172	44
Probability Part Type Failure (n) (Q)	39,360	25,680	776	5040	150	2064	88
Maintenance Time per Year (n) (Q) (T)	8.30	6.55	0.07	0.82	0.03	0.33	0.01

Note: Total subsystem unscheduled maintenance time = $\Sigma n\,QT$ = 16.11 minutes/yr.

Table V-2 Estimated Unscheduled Maintenance Time to Correct Random Failures, Pressurization Subsystem

Task	Estimated Task Times (minutes)									
	N_2 Sphere	Q. D.	3-Way Valve	Press. Reg	Check Valve	Relief Valve & Burst Disc	Filter	Lines & Joints	Solenoid Valves	Trans-ducer
Fault Isolation	3	3	3	3	3	10	3	20	5	5
Review Maintenance Procedure	5	5	5	15	10	10	5	10	5	5
Obtain Spare	5	5	5	5	5	5	5	10	5	5
Travel to Subsystem	5	5	5	5	5	5	5	5	5	5
Bleed Down Pressure	5	2	5	5	5	5	0	5	5	5
Pressurize Compartment	5	5	5	0	0	0	0	10	0	0
Remove Access Cover(s)	3	3	3	3	3	3	3	12	3	3
Disconnect Instrumentation	2	0	0	0	0	0	0	0	0	2
Remove Part & Store in Bag	5	5	9	5	5	5	3	15	6	3
Install New Part	5	5	9	2	2	2	2	15	6	3
Connect Instrumentation	2	0	0	0	0	0	0	0	0	2
N_2 Checkout & Leak Check	10	10	10	10	10	10	10	10	10	10
Replace Access Door(s)	3	3	3	3	3	3	3	12	3	3
Actuate System & OCS Checkout	5	5	5	5	5	5	5	5	5	5
Depressurize Compartment	3	3	3	0	0	0	0	0	0	0
Travel to Station & Stow Gear	10	10	10	10	10	10	10	10	10	10
Perform Administrative Functions	5	5	5	5	5	5	5	5	5	5
Total Task Times (T)	81	74	85	76	71	78	59	144	73	71
Number of Parts Required (n)	2	2	2	4	8	4	2	1	1	10
Probability Part Failure, ppm/yr ea (Q)	406	71	4000	10,300	1,470	5,150	315	278	4060	278
Probability Part Type Failure (n) (Q)	812	142	8000	41,200	11,760	20,600	630	278	4060	2780
Maintenance Time per Year (n) (Q) (T)	0.07	0.01	0.68	3.13	0.83	1.61	0.04	0.04	0.30	0.20

Note: Total subsystem unscheduled maintenance time = $\Sigma n\ QT$ = 6.9 minutes/yr.

Table V-3 Estimated Unscheduled Maintenance Time to Correct Random Failures, Engine Subsystem

Task	Estimated Task Times (minutes)				
	Transducer	Engine Solenoid Valve	Engine* Less Valves	Lines & Joints	Engine Module (Ref)
Fault Isolation	5	5	5	10	5
Review Maintenance Procedure	5	10	10	10	10
Obtain Spare	5	5	5	5	5
Don Protective Clothing	10	10	10	10	10
Travel to Subsystem	5	5	5	5	5
Decontamination	40	40	40	40	40
Pressurize Compartment	5	5	5	10	10
Remove Access Cover(s)	5	5	10	10	10
Disconnect Instrumentation	2	2	4	4	2
Remove Part & Store in Bag	3	10	20	15	25
Install New Part	3	10	20	15	25
Connect Instrumentation	2	2	4	4	2
N_2 Checkout & Leak Check	10	10	10	10	10
Propellant Fill	20	20	20	20	20
Propellant Checkout & Leak Test	10	10	10	10	10
Replace Access Door(s)	5	5	10	10	10
Actuate System & OCS Checkout	5	5	5	5	5
Depressurize Compartment	5	5	5	5	5
Travel to Station & Stow Gear	10	10	10	10	10
Perform Administrative Functions	5	5	5	5	5
Total Task Times (T)	160	179	213	213	224
Number of Parts Required (n)	24	24	12	1	4
Probability Part Failure, ppm/yr ea (Q)	191	7,282	7,233	12	16,634
Probability Part Type Failure (n) (Q)	4584	174,768	86,796	12	
Probability Part Maintenance Time per Year (n) (Q) (T)	0.73	31.28	18.49	0.01	14.90 (Ref)

Note: Total subsystem unscheduled maintenance time = Σn QT = 50.5 minutes/yr.

*Includes thermal control, but not solenoid valves.

The average unscheduled maintenance time per year for the APS is about 74 minutes. As might be suspected, the engine solenoid valves require the most unscheduled maintenance time, 31 minutes per year average (Table V-3).

The maintenance times in Tables V-1, V-2, and V-3 are average values. Assuming a log normal distribution, multiply the average value by 0.5 and 3.2 to obtain the low and high values respectively at the 95th percentile distribution level. Thus the low, average, and high unscheduled maintenance times per year are approximately 36, 74, and 235 minutes, respectively.

Should it become necessary to employ either EVA or suited IVA, the estimated unscheduled maintenance times 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. EVA and suited IVA conditions require a buddy system, or two men. Also the task times in Tables V-1, V-2, and V-3 must be multiplied by 2.5 to account for the lack of mobility in a pressure suit.

B. SCHEDULED MAINTENANCE

The maintenance planned for any system depends in part upon the basic philosophies adopted. The most prevalent philosophy is to replace components either before they wear out or before their calendar lives are exceeded. This philosophy ensures continued high system reliability normally required for primary systems. These analyses assume component replacement before life limits are exceeded.

The APS system for the Space Station has been designated as a secondary system and some degradation of system reliability may be acceptable to reduce maintenance and spare requirements. The philosophy adapted for component replacement can be at or anywhere between the two "extremes" of replace components long before their lives are exceeded and replace components after they have failed. Allowing components to fail could provide life information useful to future programs. Substantiated data on mechanical component lives under spatial environments for long durations is not readily available. Allowing components in a secondary system to function until failure and then analyzing the failures would provide much needed information. This approach could be considered as a secondary experiment for the space station.

A compromise approach would be to replace the components in one-half of the APS before failure and allow the components in the other one-half to function until failure. Although having less statistical significance than replacing all components after life expiration, useful failure information would be gained, but system reliability would not be degraded as much. Should a component fail because of life limitations, the corresponding components in the other one-half system could be replaced before their lives are exceeded since they are newer components.

The conservative and more conventional approach of replacing components before their lives are exceeded was employed in estimating scheduled maintenance. However, if the final APS functions are secondary and some reliability degradation is acceptable, serious consideration should be given to allowing some components to function until failure to gain useful failure information.

Table V-4 presents the estimated life limitations of the APS baseline components. Most of the estimated component lives in Table V-4 are from "Workshop Attitude Control System (WACS), Propulsion Module Component Description Document," S&E-ASTN-PAS, dated March 25, 1969.

It is believed that the estimated two-year calendar lives of valves in the foregoing document are conservative. A study of mechanical component lives and reliability problems under spatial environments has been conducted by Martin Marietta Corporation, and the results are contained in the "Handbook of Long-Life Space Vehicle Investigations (1967 and 1968)," M-68-21, dated December 1968. This document, based upon literature and industry surveys, indicates that high reliability valves are capable of 3 to 5 year calendar lives, depending on seal material and valve type. Cyclic lives in excess of one million cycles can be obtained upon specification. Therefore, it is believed that if all valves are replaced either shortly after three years in space or after a total ground and space environment life of 5 years, the calendar lives of properly designed valves will not be exceeded. Analysis of system requirements indicates that the cyclic lives of the valves will not be exceeded if the valves are replaced on the calendar basis recommended.

Table V-4 Estimated Lives of APS Components

	Spatial Life Limitations			
Component	Cycles	Ref	Years	Ref
A. Valves				
1. Engine Solenoids	100,000	a	3	b
2. Feedline	100,000	a	2	a
3. Check Valve	5,000	a	3	b
4. Pressure Relief & Burst Disc	3,000 (valve)	a	3	b
5. Pressure Regulator	5,000	a	2	a
6. Three Way	5,000 Min	c	3	b
7. Quick Disconnect	400	a	2	a
B. Nitrogen Sphere (0-3200 psig - 0 = 1 cycle) and ½ Quick Disconnect	400	a	2	a
C. Filter Bodies (change filter element once a year)	--	--	10	c
D. Propellant Tanks				
1. Bellows (1 complete expulsion = 1 cycle)	100	a	10	c
2. Shell (0-219 psig - 9 psig = 1 cycle)	2,000	a	10	c
E. Transducers	--	--	3	d
F. Engine Assembly				
1. Engine	100,000 Starts	a	10,000 Sec Burn	a
2. Valve	100,000	a	3	b
3. Thermal Control System	100,000	c	3	c

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," Martin Marietta Corporation, M-68-21, 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 years, assumed terrestrial life is two years.

It may be possible to design and develop valves with a full ten-year life. However, since the valves will be required before 1975, real-time life tests of these valves would not be possible. To date no accelerated life tests of valves have been developed that are acceptable according to a Martin Marietta Corporation shelf-life study conducted for NASA-MSFC. (Reference *A Study of Programs for Evaluation of Component Life*, MCR-69-366, August 1968, Contract NAS8-21296.)

The transducer useful lives are five years total (terrestrial and spatial) per NASA-MSC specification MSC-KA-6D-68-1. Assuming a two-year life before launch, the spatial life of a transducer is three years. Martin Marietta Corporation experience indicates that these life estimates are essentially correct.

Combining the task times data of Tables V-1 thru V-3 with the estimated component lives of Table V-4, the scheduled maintenance time requirements can be calculated. To minimize the total maintenance time, identical components/module requiring replacement at the same time were assumed replaced during one maintenance operation, saving preparation and travel time. Since the engine solenoid valves, thermal control system, and transducers all have three-year lives, complete engine modules should be replaced, rather than replacing the components separately because the time to replace one engine module is less than the total replacement time of individual components. It was assumed one-half of the filters are replaced after each pressurant and propellant resupply that occurs every six months.

If all the components with three-year lives were replaced during one maintenance period, available crew time might be exceeded. Therefore, it is suggested that only half the valves, engine modules, and transducers be replaced at one period. The components in the system half that was active immediately after orbit insertion should be replaced first after three, six, and nine years. The initially redundant standby half of the APS should have the subject components replaced at 3½ and 6½ years.

About 3 hr will be required every six months to replace filters. It will require approximately 23 hr to replace and check out half of the valves, transducers, and engine modules (see Table V-5).

Table V-5 Approximate Ten-Year Scheduled Maintenance Task Times

Replacement Interval	Component Module Replaced	Average Replacement Time (minutes)	Total Time in Ten Years (hr)
I. Every ½ year	One-half of total filter elements (3)	175	
	Total I	175	55.4
II. Every 3 years	Pressurant control module	124	
	Two engine modules	448	
	One-half three-way solenoid valves (8)	434	
	Transducers not on replaced modules (6), and propellant quick disconnect (1)	385	
	Total II	1391	69.5
III. Every 3½ years	Same as II above except the replaced items are from other half of the system	1391	
	Total III	1391	69.5
	Totals I, II, III		194.4

Note:
1. Tasks combined to decrease maintenance times below are sum of individual task times in Tables V-1 thru V-3.
2. Maintenance is performed in shirtsleeve environment.
3. Maximum continuous maintenance period is 8 hr.
4. Feedline cross-over valves not replaced until failure occurs. Only fail open of normally closed valves or leakage through solenoid seals can negate APS redundancy, a low probability of occurrence.
5. Tasks are performed by one man.

C. PROPELLANT AND PRESSURANT RESUPPLY

Estimated time for propellant and pressurant resupply is 10 hr; 9 hr preparation, checkout, and configuration restoration plus 1 hr actual transfer time. Three men may be required for the resupply operation. Hence, a total of about 30 man-hours will be required every six months.

Total Time Profile - The preceding data provide the estimated maintenance repair and servicing times for the mission. The maximum requirements of 57 man-hours occurs at 3, 3½, 6, 6½, and 9 years. Any replacements at 9½ years are deemed superfluous because of the ten-year mission duration. About 33 man-hours are required for each consumable resupply, which includes replacing three filters.

D. ONBOARD SPARES

The recommended onboard spares were selected because they fell within one or more of the following three categories:

1) Components whose failure would adversely affect crew safety. No components met this criterion;
2) A component whose failure (single point) would seriously degrade the probability of mission success. An engine detonation could inundate its standby counterpart; sufficient spacing, if applicable, could materially reduce the probability of this occurrence. The crossover solenoid valves on the storage and transfer propellant and nitrogen systems could be single point failures for the failure modes of: (a) failed closed or (b) leakage through the solenoid seals, but the failure probabilities are small for these normally closed valves;

3) Either a component with a high failure probability or a number of identical components whose collective failure probabilities are high. Because of redundant usage, a component with a high random failure rate may not necessarily seriously degrade the probability of mission success; but may require relatively frequent replacement. Thus onboard spares should be carried for those components that may require frequent replacement.

Tables V-1 thru V-3 present the estimated random failure probability per year for the various components by subsystem. The total estimated failure probability, in ppm per year, for identical or very similar components is given in descending order in the following tabulation. The failure probability decreases rapidly below component grouping 4, the pressure regulator package. This suggests that, as a minimum, component groupings 1 thru 4 should be spared.

Component Grouping	Random Failure Probability (ppm/year)
1. Engine Solenoid Valves	0.1748
2. Engines Less Solenoid Valves Plus Thermal Control	0.0868
3. Three-Way Valves	0.0474
4. Pressure Regulator Package (Redundant Regulators in Package)	0.0412
5. Propellant Tanks	0.0257
6. Pressure Relief Valves & Burst Discs	0.0206
7. Check Valves	0.0118
8. Transducers	0.0094
9. Lines & Fittings	0.0004

The weights and volumes of onboard spares for the APS must be integrated with other systems in the Space Station for overall Space Station optimization. The Space Station Phase B Study is not being worked at the level of detail that will permit allocation of spares for each subsystem.

It is suggested that, as a minimum, the following major spares be carried onboard if weight and volume constraints permit:

1) One complete engine module. The solenoid valves could be cannibalized for separate valve replacement if design allows;
2) Two solenoid three-way valves -- one oxidizer and one fuel compatible type (either one should be nitrogen compatible);
3) One nitrogen pressure regulator assembly.

Spare transducers are not identified in the minimum spare parts list because of the variety of types and ranges required. Leakage or rupture were the only failure modes germane to system failure because the loss of one transducer would not preclude ascertaining the system condition using other transducer data and simple logic. Commonality can be achieved in transducers by standardizing sizes, range, fittings, material compatibility, etc. This will reduce the number of spares that must be stored onboard the Space Station.

E. ENGINE LIFE ADEQUACY

This section discusses the life adequacy of the baseline engines for the APS maneuvering functions and additional functions that include spin up, despin, gravity gradient, and sun track. Engine assembly life may be limited by either burn life or calendar life constraints. Engine assembly calendar life is limited by the estimated three-year life of the solenoid valves as discussed previously. Better definition of the Space Station control requirements are needed to determine if the burn lives of the engines can meet APS requirements and constraints. Table V-6 presents the total impulses required for the various APS functions and the total burn times per engine for these functions.

The baseline engine has a nominal thrust of 22 lb, a 10,000 sec burn life, and a start life of 100,000 times. If the 200,000 lb-sec impulse required per year for maneuvering functions (Table V-6) is divided evenly among the 12 engines, the engine burn life exceeds the ten-year mission requirements (7575 sec/engine). Thus the "basic" engines need not be replaced during a ten-year mission if only maneuvering functions are required. However, since the engine solenoid valves, transducers, and thermal control system should be replaced every three years as discussed previously, the engine module will also be replaced in the process.

Table V-6 Estimated Engine Burn Times

Occurrence (days after launch)	Function	Impulse Required (lb-sec x 10^6)	No. of Engines Used	Average Burn Time/ Engine (sec)*	
				22-lb Thrust	100-lb Thrust
1 - 3650	Maneuvering	2.000	12	7,575	1666
45	Spin-Up	0.493	2	11,200	2465
45 - 70	Gravity Gradient	1.275	4	14,500	3180
75 - 90	Sun Track	0.142	6	1,070	237
75	Despin	0.493	2	11,200	2465

*Not all engines required for all functions.

Should the spin-despin and associated functions be included as part of the basic attitude propulsion system, the burn life of the baseline engine (22 lb) will be exceeded before the first 75 days of the mission. This is a particularly undesirable situation because onboard replacement engines must be available before the first resupply, which occurs at 90 days. This situation can be corrected/alleviated by employing (1) separate engines for spin/despin; (2) baseline engines with longer burn lives; or (3) higher thrust engines with burn lives sufficiently long to permit the total impulse required before burnout.

Table V-6 also shows the burn times required for 100-lb thrust engines to accomplish the denoted functions. Some engines will perform more than one function, such as maneuvering, sun track, and gravity gradient functions. A 100-lb thrust engine could require as much as 5083 sec (1666 + 237 + 3180) of burn, per Table V-6. This figure is well within the present performance of these engines.

Other burn life-thrust combinations could satisfy mission requirements. An engine with a ten-year mission burn life is not required since the engine solenoid valves and engine instrumentation calendar lives are about three years. Therefore, it is more desirable to replace entire engine modules rather than replace individual components because the time required to replace an engine module is less than the time to replace engine valves and instrumentation transducers separately. However, spares weight and volume constraints and actual design may dictate replacing components and not the entire engine module.

Because of the present indefinite nature of the functional requirements of the various Space Station systems including APS, definite recommendations regarding the lives and thrusts of APS engines are not now possible. It may be desirable to use a separate set of engines for the spin-despin functions to allow thrust level optimization. One conclusion is possible: the baseline engines with 22 lb of thrust and a burn life of 10,000 sec will not meet the total burn time engine requirements of 23,145 seconds for the combined functions of gravity gradient, sun track, and maneuvering. These three combined functions will be imposed on some of the engines.

VI. ORBITAL RESUPPLY

A capability for orbital resupply of consumables to the Space Station APS will be necessary to economically satisfy the ten-year life requirements of the Space Station program. The major results of the resupply study reported in this chapter are:

1) The feasibility of the orbital resupply of consumables to the Space Station APS has been established;
2) An integrated resupply system has been identified and recommended for application to the advanced logistics system;
3) An alternative system has been identified and recommended for application to an accelerated program schedule;
4) Independent of other Space Station systems considerations, a resupply interval of 90 days has been identified as optimum from the standpoint of minimizing launch costs chargeable to the APS;
5) When considering all of the program integration requirements, shuttle schedules, and Space Station constraints; a six-month resupply interval is recommended.

A. STUDY SUMMARY

The study itself was conducted in four phases:

1) Phase I - Identification and Evaluation of Potential Fluid Transfer Techniques;
2) Phase II - Determination of an Optimum Resupply Interval;
3) Phase III - Definition of Candidate Resupply Systems;
4) Phase IV - Evaluation of Candidate Resupply Systems.

The results of each of these study phases are summarized in this section and discussed in more detail in subsequent sections.

1. Concepts

Approximately 50 fluid handling concepts were identified and evaluated for their applicability to the resupply of propellants and pressurant for the Space Station APS. Results of the evaluations are summarized below and appear in more detail as Appendix A. The majority of the discussion in this chapter centers around five resupply systems that were the most promising candidates from among the 50 approaches considered.

a. Propellant Resupply - Three fundamental approaches to the resupply of propellants were considered; fluid transfer, module replacement of the propellant storage tanks, and integrated consumable resupply systems. Module replacement was rejected primarily because the requirement for extensive commitment of crew members, extensive fluid removal and decontamination, access facilities, and cargo handling equipment. Integrated resupply concepts, such as replacement of the propulsion modules, or continuous supply from a docked logistics vehicle or attached consumables module, were found to be very attractive strictly from a resupply and maintenance point of view. However, no detailed investigation of these approaches was made during the study, because determination of their overall suitability requires consideration and further definition of major aspects of the program such as the logistic vehicle configuration.

Several pressurized fluid transfer techniques were found to be applicable to the propellant resupply function. These include the use of residual pressurant from the pressurant resupply operation, a separate high-pressure source, a conventional blowdown pressurization system, and a modified blowdown system using residual ullage from the expended propellant storage tanks.

Several suitable expulsion devices were also identified, including capillary screens, nonmetallic bladders and diaphragms, metal bellows, and several versions of metallic diaphragms and bladders. Selection of the most appropriate of these devices depends on the relative importance placed on system weight, development status, growth potential, and cost. All of these devices, however, are considered feasible at this time for the application being considered.

b. Pressurant Resupply - For application to the baseline APS both a simple blowdown system and modular replacement of the gas storage spheres are considered feasible. In addition several modifications to the baseline propulsion system were also investigated to determine whether they would materially reduce the resupply requirements.

Volatile liquid systems afford an attractive potential in that resupply of pressurant can be entirely avoided, barring malfunction or damage to the tankage. However, the possibility of development and operational problems should be recognized because of the early development status, sensitivity to certain duty cycles, and thermal conditioning required for these systems.

Use of a blowdown bipropellant system for the Space Station APS represents another means of eliminating the pressurant resupply requirement. This is accomplished by allowing recompression rather than venting of the ullage during propellant resupply. Disadvantages result from the lack of experience in bipropellant applications.

Integrated APS/ECLSS nitrogen sypply systems were also considered. However, since this approach is highly sensitive to duty cycle requirements, detailed evaluation requires further definition of both the ECLSS and APS operating duty cycles, and consequently was not attempted during this study.

2. Determination of an Optimum Resupply Interval

For the APS propellant load and impulse requirements specified for the baseline design, a resupply interval of 180 days is necessary to satisfy reliability and inflight maintenance requirements. Space Station Phase B Definition Studies have also specified 180 days as the optimum interval for resupply of the total consumables requirement. Independent of other systems, however, a resupply interval of 90 days is optimum for the APS from the standpoint of minimizing total launch costs chargeable to the system.

3. Definition of Candidate Systems

Based on the subsystem evaluations summarized above, five integrated resupply systems were fully defined in the detailed evaluation and analysis phase. The five candidate systems are presented schematically in Fig. VI-1 thru VI-5.

Figures VI-1 thru VI-3 illustrate systems that are suitable for resupply of the baseline APS. Figures VI-4 and VI-5 illustrate systems suitable for resupply of a hypergolic bipropellant APS, but which require major modification of the baseline APS.

System VI-1 - Pressurant is resupplied by equalizing pressures between a high-pressure storage bottle onboard the logistics craft and the expended storage spheres onboard the Space Staion. Propellant resupply is by pressurized transfer using residuals from the pressurant resupply operation as the energy source.

System VI-2 - Pressurant is resupplied by modular replacement of the gas storage spheres; propellant by blowdown of the propellant transfer tanks.

System VI-3 - This system is similar to System VI-2, except that ullage gases from the expended APS propellant storage tanks are used for pressurization of the transfer tanks.

System VI-4 - This system uses a permanent volatile liquid pressurization system, thus avoiding the necessity of routine pressurant resupply by recondensing the pressurant during propellant servicing. Propellants are resupplied by pressurized transfer using a separate regulated gas as the energy source.

System VI-5 - This system uses a blowdown pressurization system for the APS. Pressurant is recompressed during propellant servicing. Propellants are resupplied by pressurized transfer using a separate regulated gas as the energy source.

4. Evaluation of Candidate Systems

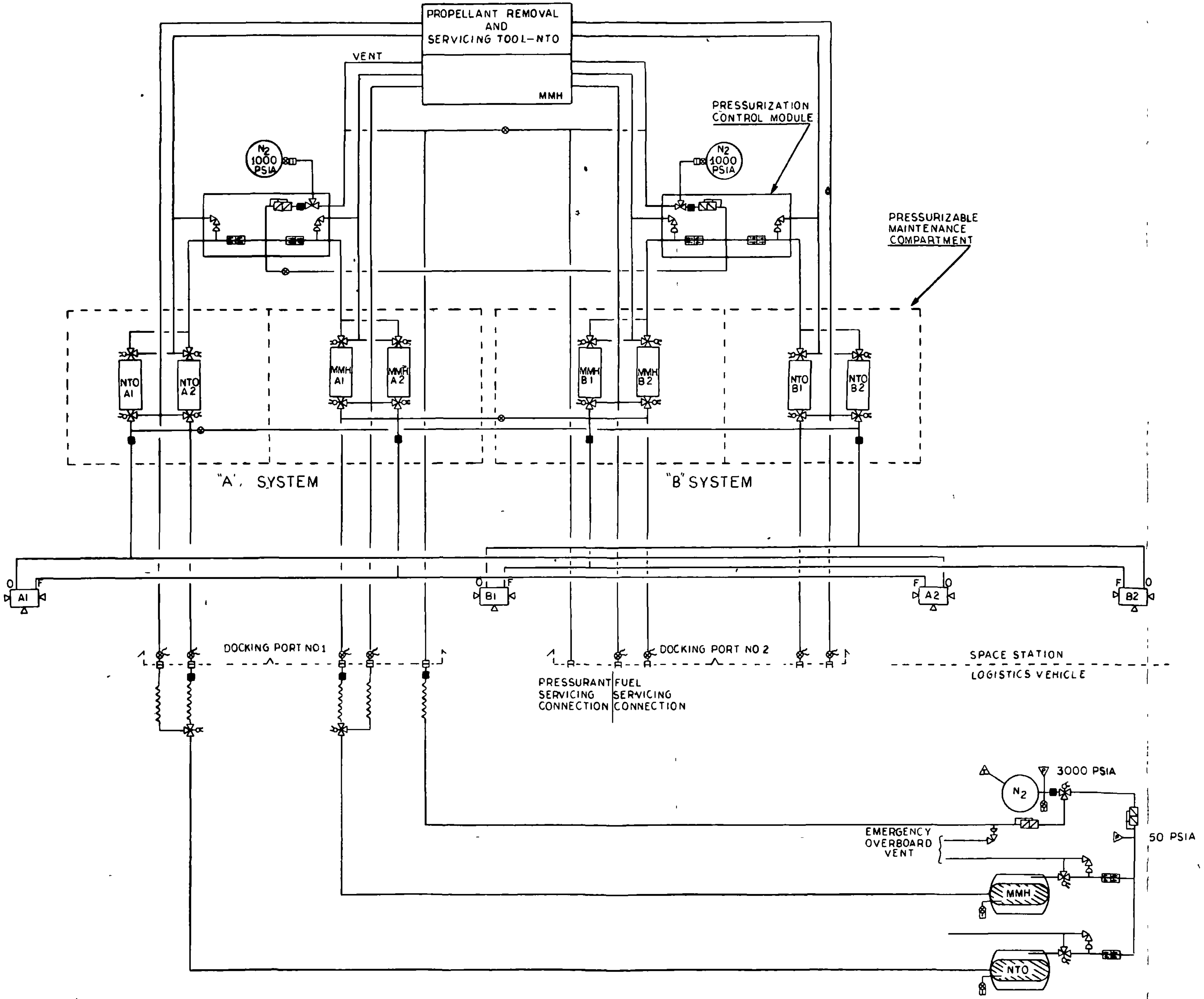
Comparative evaluations were made of the five candidate systems described above. Of the systems evaluated, System VI-2 is the recommended resupply system. However, all of the systems evaluated were found to be feasible approaches and System VI-1, which requires minimum development of new techniques, might also be considered if immediate application is required.

The major characteristics of each of the candidate resupply systems are summarized below.

System VI-1 - This system requires a minimum of new technology development and is well suited for immediate design and development. However, this is the heaviest system considered, both with respect to the Space Station launch weight and the shuttle resupply weights.

System VI-2 - This system is recommended as the best resupply system for resupply of the Space Station APS. This system is very nearly the lightest weight and requires only minor development of new technology, namely the packaging, handling, and installation of the pressurant spheres.

System VI-3 - This system was rejected as being slightly heavier and less reliable than System VI-2, without providing any additional capability.



LEGEND:

▨	PRESSURE REGULATOR
	BURST DISC & RELIEF VALVE
▬	QUAD CHECK VALVE
■	FILTER
⊗	TWO WAY ISOLATION VALVE, MANUAL
	REMOTE WITH MANUAL BACKUP
	THREE WAY VALVE, MANUAL
	REMOTE WITH MANUAL BACKUP
	CAPPED LINE
	MANUAL DISCONNECT
▽	PRESSURE TRANSDUCER
▽	TEMPERATURE SENSOR
~~	FLEX HOSE

Fig. VI-1

REGULATED PRESSURANT TRANSFER USING RESIDUALS FOR PROPELLANT TRANSFER

D 04236 APS VI-1

FOLDOUT FRAME

FOLDOUT FRAME

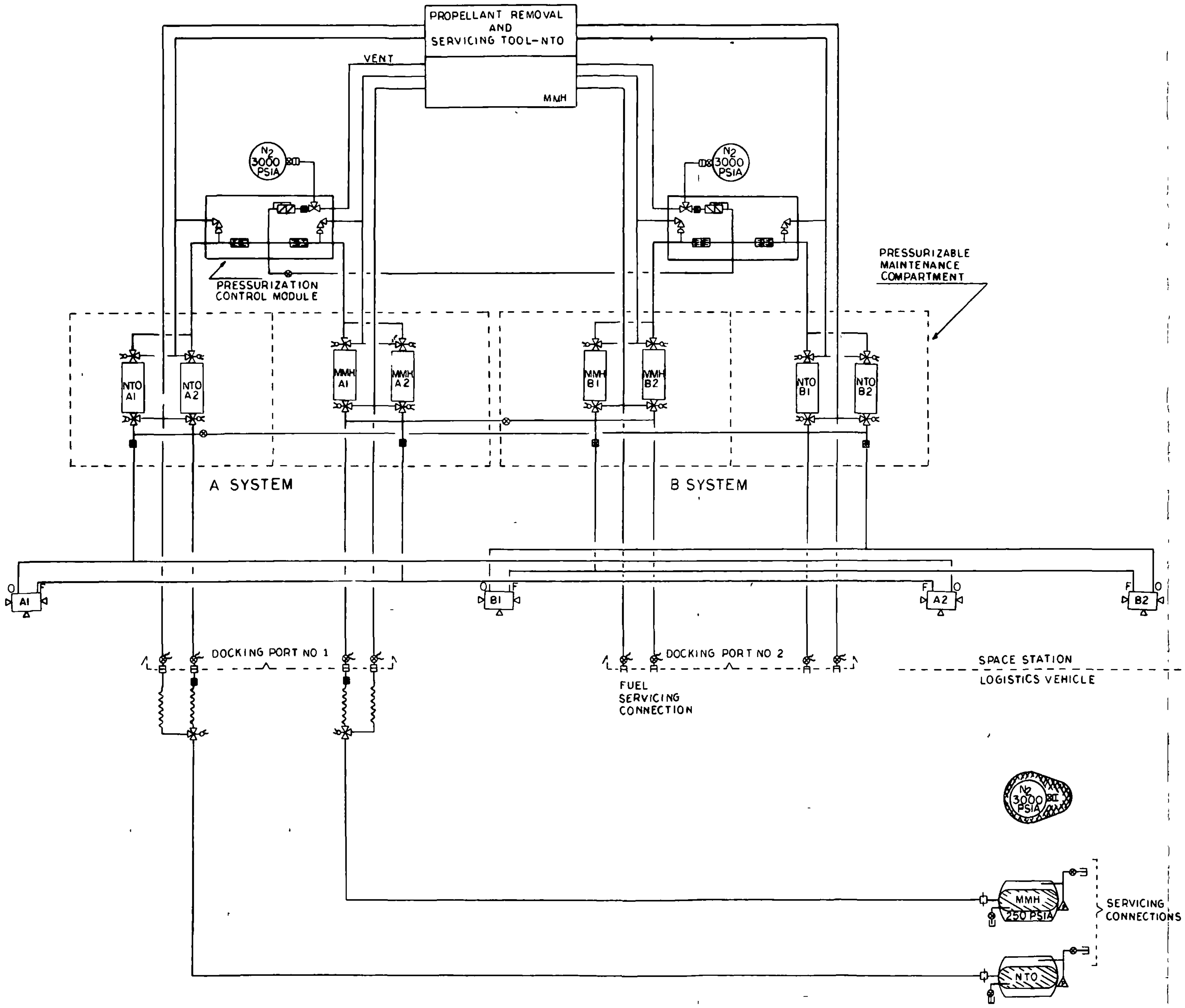


Fig. VI-2

BLOWDOWN PROPELLANT TRANSFER WITH MODULAR PRESSURANT TRANSFER

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FOLDOUT FRAME

FOLDOUT FRAME 2

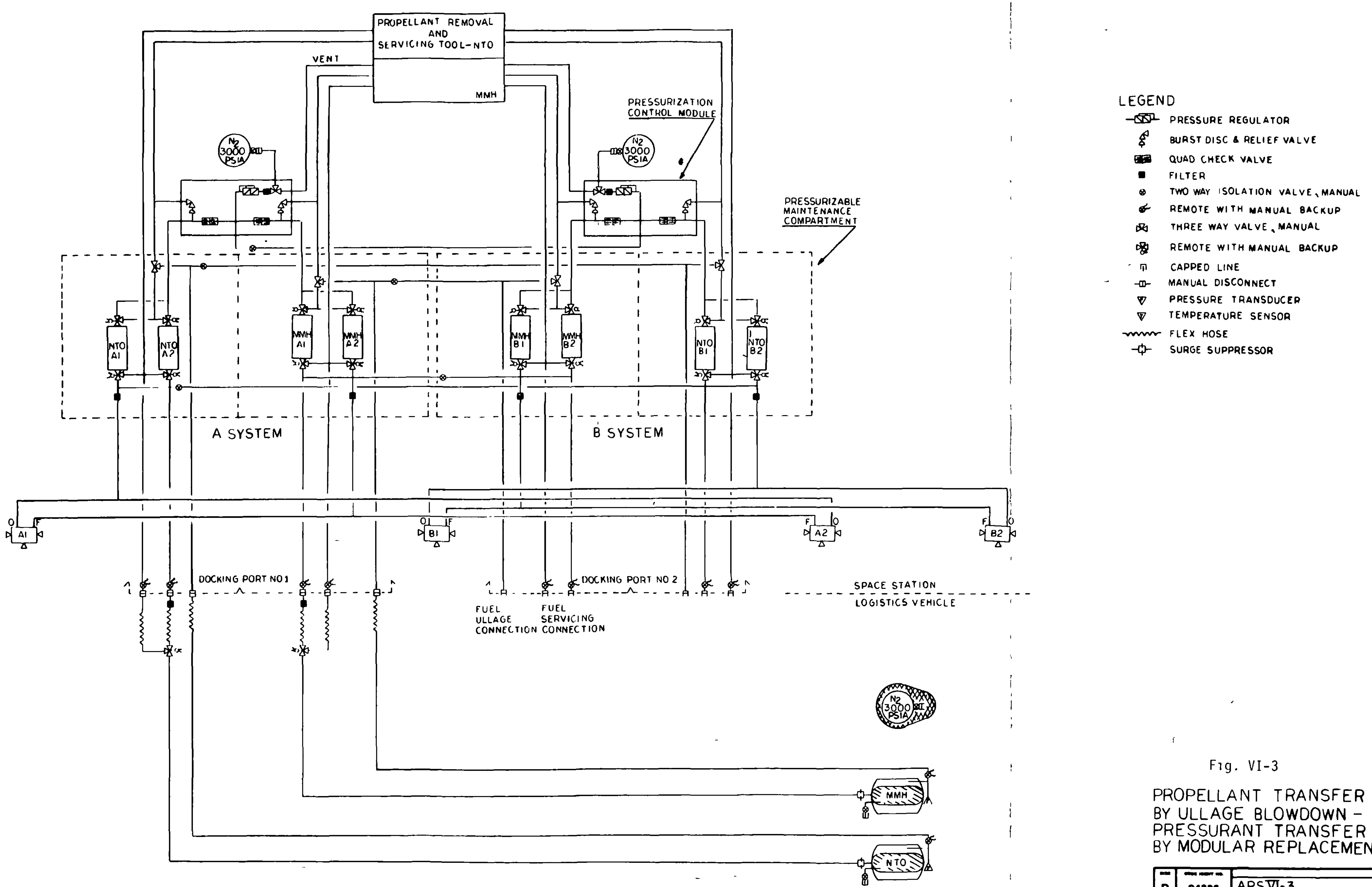
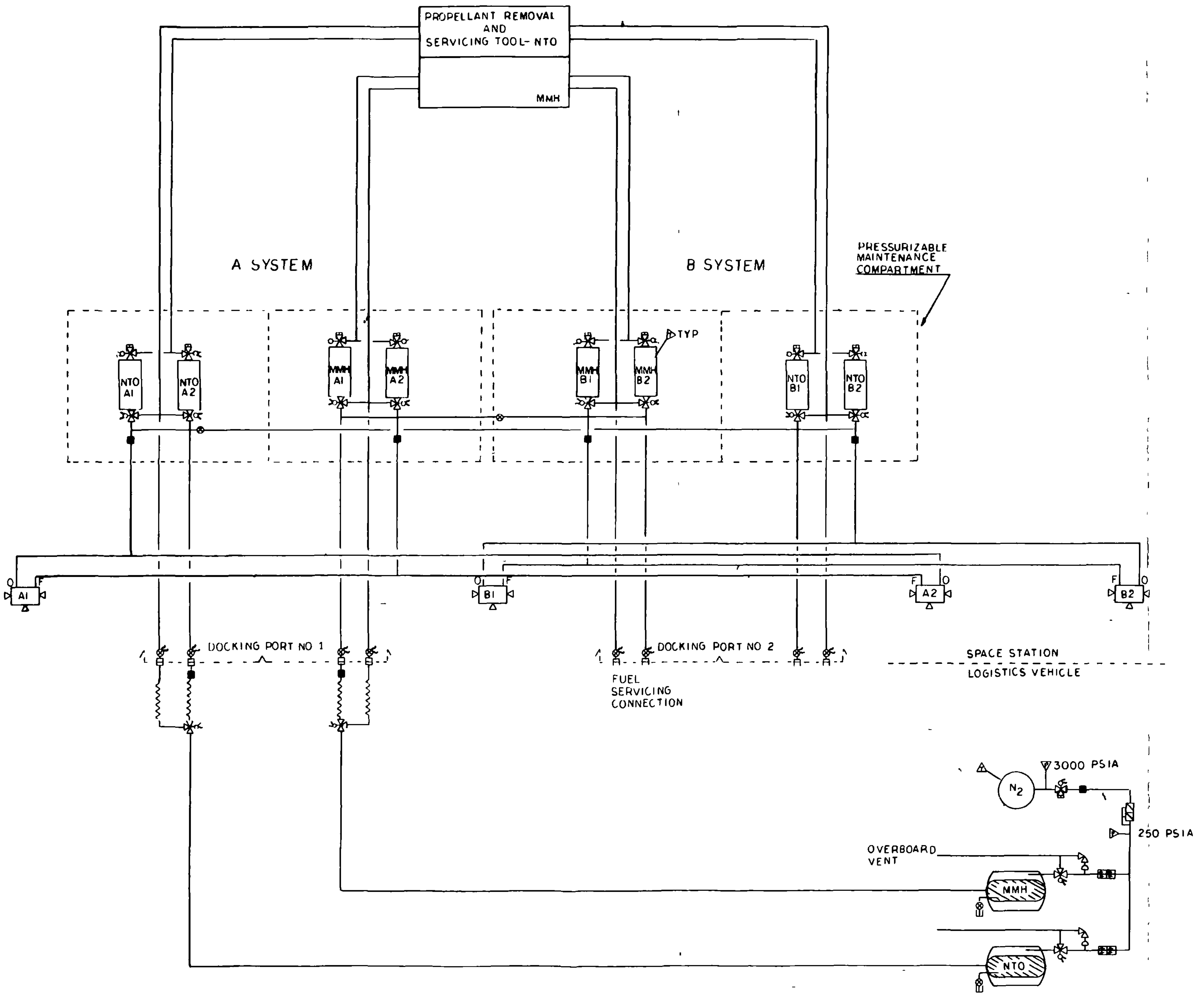


Fig. VI-3

PROPELLANT TRANSFER BY ULLAGE BLOWDOWN - PRESSURANT TRANSFER BY MODULAR REPLACEMENT

D	04236	APSVI-3

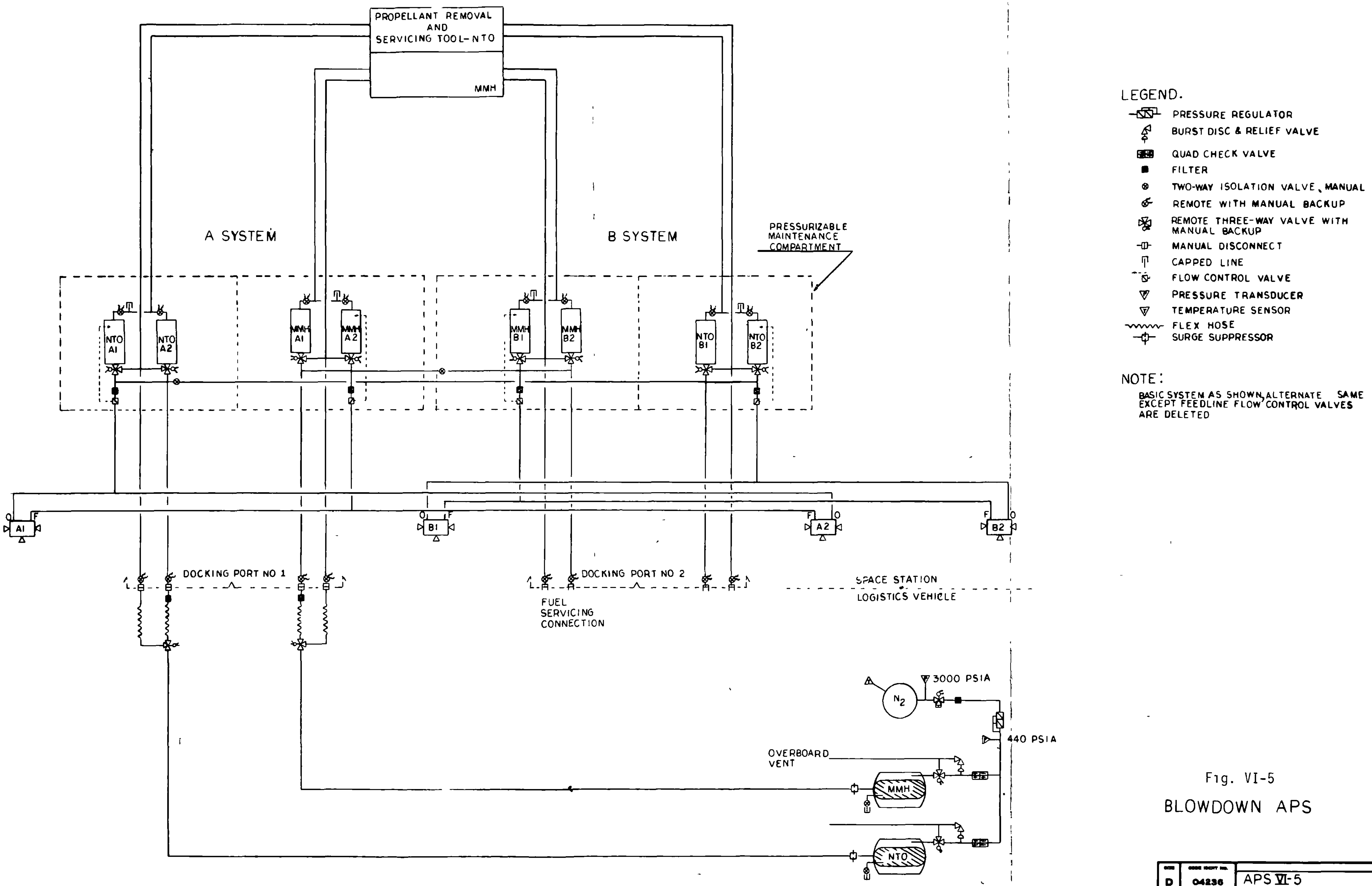


LEGEND
- PRESSURE REGULATOR
- BURST DISC & RELIEF VALVE
- QUAD CHECK VALVE
- ■ FILTER
- ⊗ TWO WAY ISOLATION VALVE, MANUAL
- REMOTE WITH MANUAL BACKUP
- THREE-WAY VALVE, MANUAL
- REMOTE WITH MANUAL BACKUP
- MANUAL DISCONNECT
- PRESSURE TRANSDUCER
- TEMPERATURE SENSOR
- CAPPED LINE
- FLEX HOSE

Fig. VI-4

VOLATILE LIQUID
PRESSURIZED APS

D 04236 APS VI-4



NOTE:
BASIC SYSTEM AS SHOWN, ALTERNATE SAME EXCEPT FEEDLINE FLOW CONTROL VALVES ARE DELETED

Fig. VI-5

BLOWDOWN APS

D	04236	APS VI-5

FOLDOUT FRAME

FOLDOUT FRAME

System VI-4 - This system was rejected because of the increased program costs and added development risk, without any significant improvements in weight or reliability.

System VI-5 - This system was rejected for reasons similar to those applied to System VI-4. The basic system can be modified to reduce development costs and risk, but the system weight is increased and performance flexibility reduced.

B. DETERMINATION OF AN OPTIMUM RESUPPLY INTERVAL

For the propellant load and impulse requirements specified for the baseline design, a resupply interval of 180 days is necessary to satisfy reliability and inflight maintenance requirements.

Space Station Phase B Definition studies, also have specified 180 days as the interval for resupply of the integrated consumables requirement. Recognizing that the APS must be integrated into the overall Space Station resupply schedule, the maintenance, resupply, and design studies reported here have been based on a 180-day resupply interval. In addition, however, studies were made to determine the optimum resupply interval for the APS, independent of other Space Station systems.

The dominant factors influencing the determination of an optimum resupply interval are the following:

1) Reliability and inflight maintenance considerations;
2) Effects on Space Station and logistics vehicle launch weights;
3) APS total impulse requirements.

As discussed in Chapter VII, and as illustrated in Fig. VII-1, reliability considerations demand that the APS consist of two independently operable subsystems, A and B, with one subsystem on standby at all times. On the other hand, volume and weight considerations argue for a minimum number of storage tanks. Consequently, eight is the optimum number of tanks for a bipropellant APS.

Minimization of Space Station volume and launch weight suggests that the APS be sized to provide the minimum propellant quantities consistent with operational requirements. Of course for a given impulse demand, reduction in APS propellant quantities will increase the frequency of resupply. Therefore, payload launch costs for the Space Station launch vehicle as compared to the logistics vehicle must be evaluated in order to optimally size the APS. The results of such a study are summarized in Tables VI-1 thru VI-3 and Fig. VI-6. As shown here, a 90-day resupply interval is optimum for the APS from the standpoint of minimum launch costs over a ten-year program. This conclusion is based on an assumed launch cost of \$1000/lb for the Space Station and requires that launch costs for the logistics vehicle be kept below approximately \$500/lb.

Table VI-1 Estimated Launch Weight Chargeable to APS-Space Station

Item	Launch Weights for Various Resupply Intervals (lb)		
	90-Day	180-Day	360-Day
APS	850	1150	1750
Usable Propellant	500	1000	2000
Propellant Removal Servicing Tool	150	200	300
Maintenance Compartment	450	600	900
Volume Penalty @ 5 lb/ft^3	150	250	400
Total APS Launch Weight (lb)	2100	3200	5350

Table VI-2 Estimated Launch Weight Chargeable to APS Resupply-Shuttle

Item	Resupply Weights for Various Resupply Intervals (lb)		
	90-Day	180-Day	360-Day
Resupply System	156	234	398
Usable Propellant	250	500	1000
Volume Penalty @ 2 lb/ft^3	11	20	38
Total Resupply Weight/Launch	417	754	1436
Total Resupply Weight/Program	16.3×10^3	14.3×10^3	12.9×10^3

Note:
1. Weights shown are based on the recommended resupply system, i.e., blowdown propellant transfer and modular pressurant transfer.
2. Propellant weights shown are usable; pressurant and residual propellants are included in basic system weight.

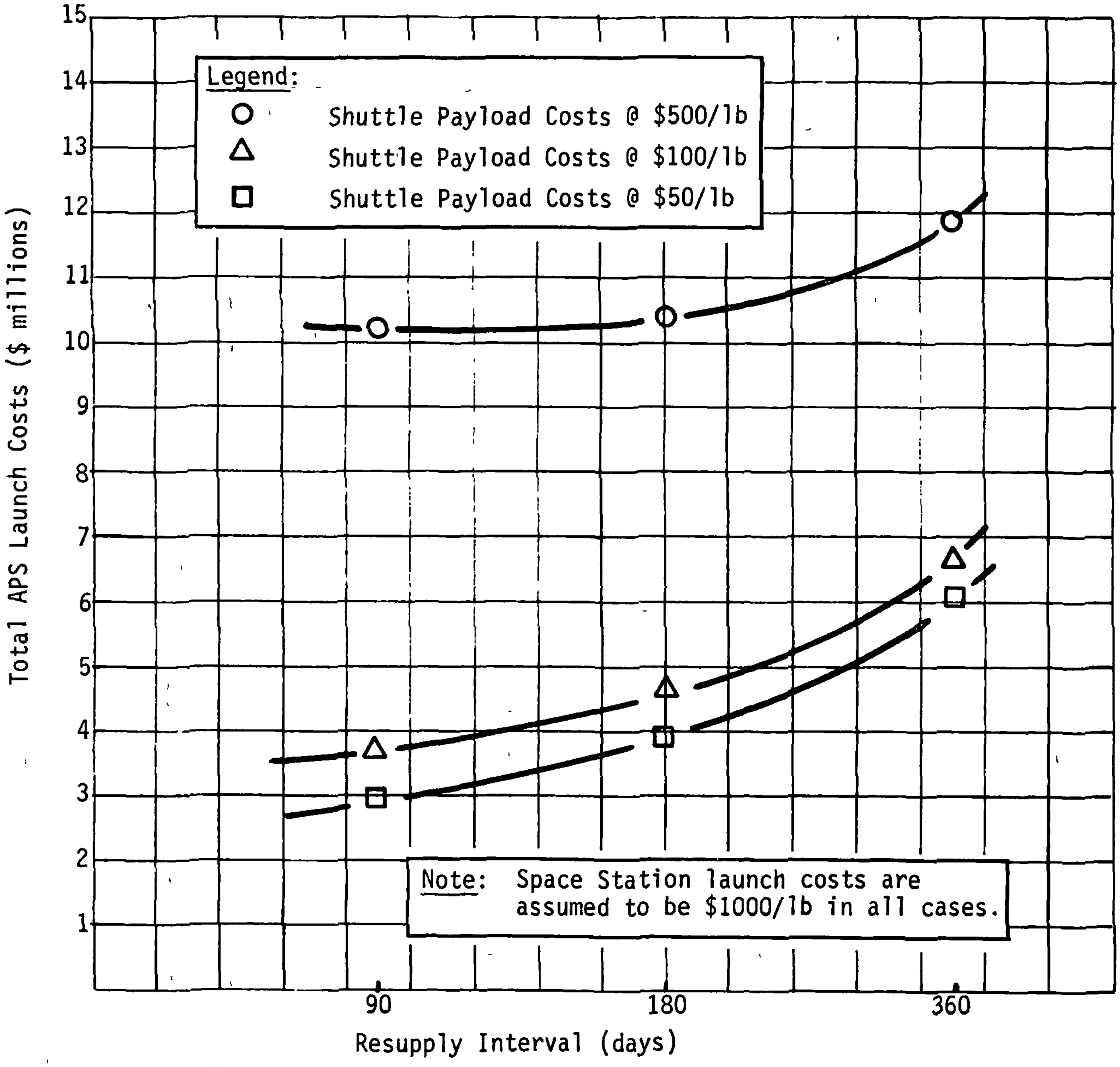


Fig. VI-6 Total APS Launch Costs for Ten-Year Space Station Program

Table VI-3 Estimated Program Launch Costs for Space Station APS

Item	Launch Costs for Various Resupply Invervals ($ millions)								
	90-Day			180-Day			360-Day		
Space Station APS Launch Costs at $1000/lb	2.1	2.1	2.1	3.2	3.2	3.2	5.35	5.35	5.35
Resupply Launch Costs at $500/lb	8.1			7.2			6.5		
Resupply Launch Costs at $100/lb		1.6			1.4			1.3	
Resupply Launch Costs at $50/lb			0.8			0.7			0.65
Total APS Launch Cost for Ten-Year Program	10.2	3.7	2.9	10.4	4.6	3.9	11.85	6.65	6.0

C. DESCRIPTION OF CANDIDATE RESUPPLY SYSTEMS

Based on the subsystem evaluations summarized above and presented in greater detail in Appendix A, five candidate resupply systems were defined for comparison and detailed evaluation during Phase IV of the study.

The candidate resupply systems illustrated in Fig. VI-1 thru VI-5 can be classified into two major categories. The systems shown in Fig. VI-1 thru VI-3 are suitable for resupply of the baseline APS. These systems require only minor modification to the APS, such as fill connections and provisions for venting the propellant tank ullage. The major differences among systems in this first category are associated with the method of pressurant resupply. System VI-1 is resupplied by blowdown from a high-pressure storage bottle, systems VI-2 and VI-3 by modular replacement of the expended gas storage bottles.

The second category of systems is shown in Fig. VI-4 and VI-5. Both of these systems require major modification to the baseline APS. System VI-4 replaces the baseline pressurization subsystem with a volatile liquid subsystem. System VI-5 uses a blowdown pressurization subsystem rather than the conventional regulated gas. From a resupply point of view the major effect of these modifications is to eliminate the requirement for pressurant resupply. Pressurant can simply be recompressed or recondensed during propellant servicing.

Each of the five resupply systems is described in greater detail in this section.

1. System VI-1

a. Pressurant Resupply - Pressurant is resupplied by equalizing pressures between a 3000 psia nitrogen storage bottle onboard the logistics craft and a 1000 psia nitrogen storage bottlb onboard the Space Station. The maximum operating pressure of the APS nitrogen storage spheres is reduced from the baseline value of 3200 psia to 1000 psia. To accommodate this reduced pressure, a maximum of 3000 psia has been selected for the logistics vehicle tanks. Selection of this pressure combination is based on a weight optimization analysis summarized in Table VI-4. As shown, reduction in the APS operating pressure can reduce the logistics vehicle payload by approximately 32 to 64 lb, or from 640 to 1280 lb over a ten-year mission. This is accomplished at the expense of a 24-lb increase in Space Station liftoff weight and a slight increase in APS volume, i.e., 24.3-inch spheres vs 15.5-inch spheres. In fact, logistics vehicle payloads could be reduced even further by selecting a Space Station operating pressure below 1000 psia. However, as becomes evident when considering the 500-psia case, Space Station weights (205 lb) and packaging requirements (Eight 25-in.-diameter spheres) rapidly become prohibitive when pressures are reduced much below 1000 psia.

A regulator and relief valve are installed in the servicing line to prevent overpressurization of the APS during servicing operations. Provision of a pressure regulator avoids any requirement for active control by the crew and also allows partial resupply if desired, without venting of the receiver tank.

Table VI-4 Weight Estimates for Space Station and Logistics Vehicle Pressurant Storage Spheres

Space Station				Logistics Vehicle			
Max Pressure (psia)	Number of Spheres	Diam of Spheres (in.)	Total Weight (lb)	Max Pressure (psia)	Number of Spheres	Diam of Spheres (in.)	Total Weight (lb)
500	8	25.0	205	1,000	1	26.5	67
				3,000	1	15.9	43
				5,000	1	13.7	44
				10,000	1	11.8	51
1000	2	24.3	106	2,000	1	21.3	72
				3,000	1	17.1	53
				5,000	1	14.5	50
				10,000	1	12.1	55
3000	2	15.5	82	5,000	1	18.7	117
				10,000	1	13.9	85

Note:
1. Totals listed under Space Station are for the complete APS.
2. Totals listed under Logistics Vehicle are requirements for the normal 6-month resupply operation.

An alternative approach, not shown in Fig. VI-1, might also be considered. The logistics vehicle resupply bottle can be precisely loaded to a preselected value and the expended APS receiver bottle vented before servicing. The flow process can then be controlled by a simple throttling orifice rather than by a pressure regulator; since controlled loading of the supply bottle and venting of the receiver assures that when an equilibrium condition is reached the proper loading the APS receiver bottle is achieved. However, overdesign of the receiver bottle or extremely low flow rates may be required to avoid compressive heating problems.

The pressurant servicing line is manually connected and disconnected after docking of the Space Station and logistics craft. System A is normally serviced by docking at Port No. 1, and System B at Port No. 2. However, redundant servicing capability is provided by interconnect lines between the two systems.

b. Propellant Resupply - Before propellant resupply, the APS propellant tanks are vented to reduce backpressure during servicing. Resupply is then accomplished by pressurized transfer of propellants from the logistics vehicle tanks. Residual pressurant from the pressurant resupply operation is used as the source for transfer energy. APS ullage gases are vented through the propellant removal and servicing tool to avoid contamination of the Space Station exterior in the event of a leak in the bellows expulsion device.

Separate servicing lines are provided between the docking interface and the propellant storage tanks. Common use of the propellant distribution lines is avoided because it would result in back flow through the propellant filters.

Propellant transfer tanks of the logistics vehicle are sized to support the nominal six-month resupply operation, i.e., each transfer tank services two receiver tanks. If both Systems A and B must be serviced in a single resupply mission, identical parallel tanks would be installed in the logistics craft.

A pressure regulator is used to provide a constant transfer pressure of approximately 50 psia, which is necessary to suppress propellant vaporization in the transfer lines and to overcome hydraulic losses. Propellant flow can be automatically terminated by a signal from the APS gaging system. Pressure switches are also installed in the APS tanks to avoid overpressurization during servicing. This acts as a backup to the gaging system. Each transfer tank is provided with a relief valve and emergency overboard vent to protect against leakage or open failure of the regulator.

Propellant service lines are disconnected only after being isolated at the docking interface and vented through the propellant removal and servicing tool. This procedure serves as a backup to prevent propellant spillage in the event of disconnect leakage.

c. Recovery of Contaminated Propellant - The logistics vehicle resupply tanks serve as receivers for the contaminated propellants. Transfer occurs by pressurization of slop tanks in the propellant removal and servicing tool itself.

Maximum capacity of the slop tanks is slightly greater than that of a single storage tank. This capacity is necessary to allow replacement or repair of the APS tanks. On the other hand maximum capacity of the logistics vehicle transfer tanks is twice that of the APS storage tanks. This factor in conjunction with the relatively low operating pressure makes venting of the receiver tanks during recovery of contaminated propellants unnecessary. Ullage control can be provided by any of the several devices discussed in Appendix A without fear of contaminating the Space Station exterior. Check valves are provided in the pressurant lines leading to each tank to avoid any possibility of mixing the hypergolic propellants.

Contaminated propellant is transferred from the propellant removal and servicing tool to the docking interface through separate transfer lines rather than through the propellant servicing lines. This is required to avoid subsequent contamination of Space Station components.

2. System VI-2

a. Pressurant Resupply - The system illustrated in Fig. VI-2 employs modular replacement of the pressurant storage spheres as the means of pressurant resupply. The pressurant spheres are prepackaged before launch to avoid mechanical damage during handling and installation. Figure VI-7 illustrates a conceptual packaging design.

The size of the pressurant package will permit a manual transfer of the sphere from the logistics craft to the Space Station.

A manually operated isolation valve and self-sealing disconnect are integral parts of the pressurant package. This allows the expended pressurant bottle to be vented before removal. The isolation valve also serves as a backup to the disconnect during installation of the replacement unit.

b. Propellant Resupply - After venting the APS receiver tanks, propellant is resupplied by pressurized transfer from the resupply tanks of the logistics vehicle. Tank pressurization is by means of a blowdown system, which is incorporated as an integral part of the tanks and avoids the requirement for high-pressure gas storage, pressure regulators, and relief valves. This approach is feasible because of the relatively low operating pressures required for transfer of propellants. A minimum operating pressure of 50 psia is maintained to assure suppression of propellant vaporization during transfer, and a maximum operating pressure of 250 psia was selected to allow minimum gage tank design. Orifices are provided in the transfer lines to dampen out flow surges during the initial transfer process.

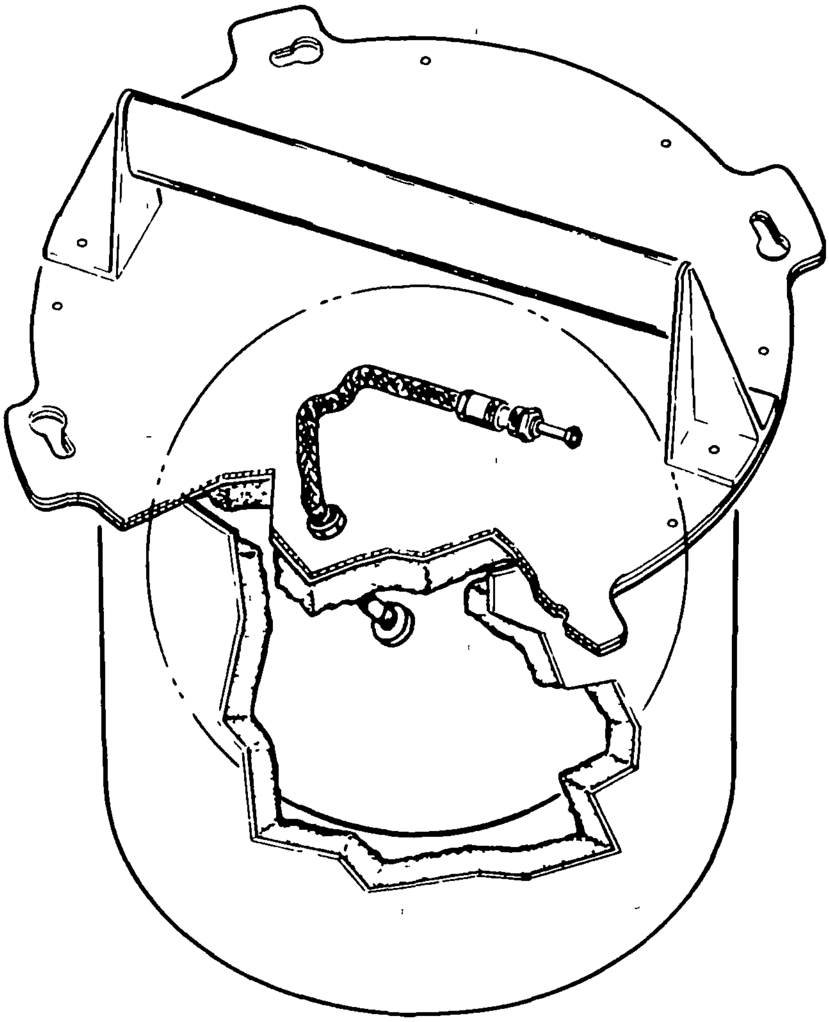


Fig. VI-7 Modular Resupply, Pressurant Sphere

Other features are similar to those of System VI-1. These include redundant docking and servicing capability, passive control of the flow processes, and backup of the service line disconnects.

c. Recovery of Contaminated Propellants - Recovery of contaminated propellants is identical to that described for System VI-1.

3. System VI-3

a. Pressurant Resupply - Resupply of pressurant is identical to that described for System VI-2.

b. Propellant Resupply - As with the previous two systems, propellant is resupplied by pressurized transfer from the resupply tanks of the logistics vehicle. Pressurization is accomplished by using ullage gases from the expended APS propellant storage tanks. This involves venting the first tank of each of the propellants to be serviced and allowing ullage from the second tank to pressurize the corresponding transfer vessel on the logistics vehicle. After venting the second tank it is then serviced by blowdown of the logistics vehicle transfer tanks. Use of the APS ullage permits a minimum ullage volume for the logistics vehicle tanks without requiring a high-pressure system as in System VI-1. Other features are similar to those of System VI-2.

c. Recovery of Contaminated Propellants - Recovery of contaminated propellants is similar to that described for Systems VI-1 and VI-2, except that the resupply tank ullage can be vented through the APS propellant removal and servicing tool before propellant recovery. This allows use of the total tank volume without the danger of venting propellant vapor overboard.

4. System VI-4

a. Pressurant Resupply - In System VI-4 the baseline pressurization system is replaced by a permanent volatile liquid system that incorporates a heat storage material for maintaining required operating pressures. Pressurant is recompressed and condensed during propellant resupply, thus eliminating the necessity of periodically resupplying pressurant. Difluoromethane (Gentron 32) was selected as the APS volatile liquid pressurant and is used with Nonadecane as a heat storage material for thermal conditioning of the pressurant during operation and servicing of the propulsion system. A heat storage material is used rather than external thermal control equipment because of the anticipated duty cycle characteristics of the Space Station APS. Engine operation is expected to consist mostly of relatively long-duration burns for maneuvering and CMG desaturation, rather than short-duration pulses for attitude control.

Experience by TRW Systems* indicates that in cases where average propellant flow rates are relatively low and the level of pressure decay associated with a single expulsion pulse can be tolerated, heat can usually be added between pulses by using an available external heat source such as a waste heat loop. However, in cases where the propellant flow is continuous for a prolonged duration, the response characteristics of a reasonably sized external heat source is generally too slow to satisfy system pressure requirements. Consequently, in these cases, a heat storage material is recommended for incorporation in the pressurant cavity in intimate contact with the volatile liquid.

A tentative selection of the specific combination of pressurant and heat storage material was based on a comparison of the results of these studies and the anticipated operating pressures and temperature of the Space Station APS. A final decision would require specification of the APS operating conditions, duty cycles, and allowable thrust variation.

b. Propellant Resupply - Since a permanent pressurant is used for this system, propellant must be resupplied without venting ullage from the APS propellant storage tanks. This, in turn, results in a relatively high servicing pressure, 250 psia. Propellant transfer by a blowdown pressurization system, such as used in System VI-3, therefore, becomes unattractive on the basis of required volume and weight. Consequently, a regulated gas was selected as the pressurizing mechanism for propellant resupply of this system. Requirements for pressurization control and distribution are similar to those described for System VI-1. Propellant servicing connections are also handled in a similar manner to that of System VI-1.

c. Recovery of Contaminated Propellants - Contaminated propellants are recovered by venting the logistics vehicle tanks and using them as receivers for the contaminated propellants. Venting of these tanks requires that only nonpermeable expulsion devices be used for ullage control. As with the previously discussed systems, propellants are transferred by pressurization of the storage tanks in the propellant removal and servicing tool. Servicing connections are also handled in a similar manner.

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*S. F. Giffoni: *All Metal Volatile Liquid Positive Expulsion System.* No. ER-5980, TRW Electromechanical Division, Final Summary Report to NASA under Contract No. NAS9-1004, June 1964; and R. G. Eatough: *All Metal Volatile Liquid Positive Expulsion System.* No. 05019-6001-R000, TRW Systems, Inc., Final Summary Report to NASA under Contract No. NAS9-4550, June 1967.

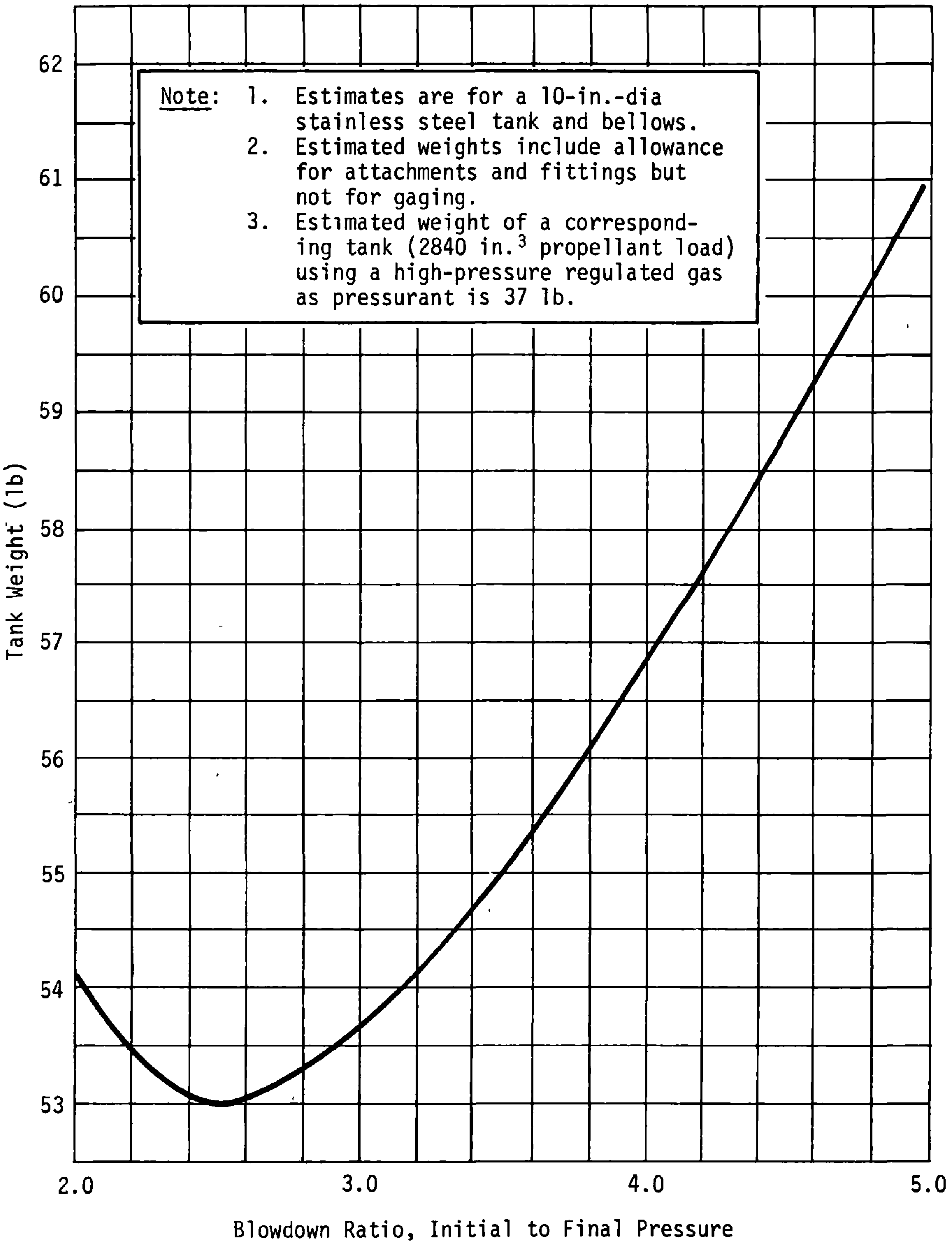
5. System VI-5

a. Pressurant Resupply - System VI-5 replaces the APS baseline pressurization system with a blowdown system. Pressurant is therefore recompressed during propellant servicing, thus eliminating the necessity of periodic resupply. Optimum engine inlet conditions are maintained by flow control valves in the propellant feedlines rather than by maintaining constant ullage pressures. An alternative system, without feedline control valves, was also considered. Here the engine inlet conditions are allowed to vary directly as the propellant tanks blow down.

A blowdown ratio of 2:1 was selected for the modified APS based largely on the results of weight estimates summarized in Fig. VI-8. Although, as shown here, the blowdown ratio which results in minimum weight is approximately 2½ to 1, tank weight is relatively insensitive over a reasonable range of blowdown ratios. Consequently, the selection of a design ratio can consider other factors in addition to Space Station weight, e.g., packaging constraints and the effect on logistics requirements. A blowdown ratio of 2:1 was tentatively selected for the candidate system as being near optimum from the standpoint of Space Station weight and its effect on logistics requirements. Operating pressures are also maintained in a range that will minimize leakage and safety hazards without imposing a major packaging (volume) penalty.

b. Propellant Resupply - As with System VI-4, the increased operating pressures required during propellant resupply demand a regulated gas as the source of transfer energy. Requirements for pressurant control and distribution as well as servicing line connections are therefore similar to those described for Systems VI-1 and VI-4.

c. Recovery of Contaminated Propellant - Contaminated propellants are recovered in a manner identical to that described for System VI-4.



Note:
1. Estimates are for a 10-in.-dia stainless steel tank and bellows.
2. Estimated weights include allowance for attachments and fittings but not for gaging.
3. Estimated weight of a corresponding tank (2840 in.^{3} propellant load) using a high-pressure regulated gas as pressurant is 37 lb.

Figure VI-8 Estimated Propellant Tank Weights vs Blowdown Ratio

D. EVALUATION OF CANDIDATE RESUPPLY SYSTEMS

1. Evaluation Criteria

The comparison of candidate systems was based on system weight, performance, reliability, safety, human factors, technology status, refurbishment potential, and effect on APS performance and inflight maintenance requirements. The following categories were considered the most important criteria in the selection of a resupply system for the APS:

1) Cost;
2) Reliability;
3) Weight;
4) Technology status;
5) Safety and human factors;
6) Performance;
7) Effect on APS.

a. Cost - Because of the anticipated high usage rate, operating costs will be a major factor in the design of vehicle systems for an advanced logistics system. Systems must be designed for a minimum of maintenance and with ease of inspection, cleaning, and refurbishment or replacement of components. Refurbishment of equipment becomes a major consideration and use of specialized facilities and equipment such as clean rooms and vacuum facilities must be minimized. Methods of reducing refurbishment requirements and vehicle turnaround time are discussed in Chapter X of this report. Although of major importance, these factors were not found to have a dominant influence on the relative rating of the various candidate systems; because all systems require similar propellant components. Differences among systems are primarily with respect have pressurization components that require a minimum of refurbishment for each resupply and will allow quick vehicle turnaround.

Development cost remains as a major consideration and the technology status of each system has been evaluated based on the number and magnitude of areas requiring further developmental effort. The cost factor, along with development risk, were the major reasons for rejecting Systems VI-4 and VI-5.

b. Reliability - Reliability was viewed as a major evaluation criterion, however variations among the five candidate systems were found to be slight and this factor did not have a major effect on the selection of a suitable resupply system.

Reliability assessments of the airborne APS and the resupply systems are summarized in Tables VI-5 and VI-6, respectively.

APS reliability predictions are an estimate of the probability of continuous APS operation for a ten-year period and assume the following:

1) Although the normal consumable resupply interval is six months, the opportunity exists for consumables and spares replacement every three months if required;
2) Subsystems A and B are operated sequentially, i.e., one subsystem is maintained in a standby status at all times;
3) An inflight maintenance and restoration capability, as well as an advanced fault detection and isolation system, will be provided for the APS.

Reliability estimates for the five candidate resupply systems are a prediction of the probability of a successful resupply of consumables, and assume the following:

1) Successful docking of the logistics craft and Space Station;
2) Resupply systems are operable at the time of launch;
3) APS components and subsystems are functioning properly at the time of docking;
4) Actual transfer of consumables occurs within 30 minutes to an hour;
5) Resupply operations may be delayed for as many as seven days after docking;
6) Repair of resupply system and/or APS components during this seven-day period is prohibited (worst case).

Table VI-5 Estimated APS Reliability

Configuration	Probabilities of Mission Success			
	One Year			Ten Years Overall
	Pressurization, P_p	Propellant System, P_s	Overall, $P_pP_sP_E$*	
APS VI-1	0.9997	0.9996	0.9965	0.9655
APS VI-2	0.9999	0.9996	0.9967	0.9675
APS-VI-3	0.9999	0.9996	0.9967	0.9675
APS VI-4 (with active heating system)	--	0.9994	0.9966	0.9665
	--	0.9983	0.9955	0.9559
APS VI-5 (with no flow control)	--	0.9989	0.9962	0.9622
	--	0.9996	0.9968	0.9685

*P_E = Probability of mission success for engine modules = 0.9972 for all configurations. Quad solenoid valves employed on engines in lieu of single solenoid valves. Engine modules physically separated to minimize engine detonation effects.

P_s = Probability of mission success for propellant storage and transfer subsystem (S&T)

P_p = Probability of mission success for pressurization subsystem.

Table VI-6 Estimated Resupply System Reliability

Configuration	Probability of Success Per Resupply		
	Space Station, P_s	Logistics Vehicle, P_L	Overall = P_sP_L
APS VI-1	0.9998	0.9989	0.9987
APS VI-2	0.9998	0.9992	0.9990
APS VI-3	0.9998	0.9991	0.9989
APS VI-4	0.9999	0.9990	0.9989
APS VI-5	0.9999	0.9990	0.9989

c. Weight - Weight estimates of the five candidate systems are summarized in Table VI-7 which includes weight estimates of both the Space Station APS and the logistics vehicle resupply system. Two major conclusions regarding resupply of APS consumables result from these studies.

1) Space Station APS weight will be a secondary factor in the selection of a consumable resupply system, because variations between candidate systems are estimated to be less than 8% of the total APS weight, excluding usable propellant;
2) Although logistics requirements may vary as much as 50 lb/resupply cycle, or 1000 lb over a ten-year operating life, system weight is not the dominant factor in the selection of a resupply system. If, as estimated, payload costs of less than $100.00/lb are achieved, little development effort can be justified to reduce payload weight.

Payload weight is expected to become a major consideration only if the following two factors apply to the particular payload in question:

1) The payload package becomes weight limited, i.e., greater than the payload capability of the shuttle; and
2) Payload requirements cannot be partially deferred to the next resupply mission.

d. Technology Status - Major differences were found among the candidate systems with regard to their status of required technology. Variations in technology status will have a significant effect on anticipated development costs and risk. Systems VI-1 thru VI-3 are well within the current state of the art; while Systems VI-4 and VI-5 will require additional development effort to assure their suitability for application to the Space Station requirements.

As mentioned in the discussion on costs, a significant development expense might be justified if it results in a material reduction in operating expense. Although the principal components for the shuttle portion of the five resupply systems are currently on hand, serious consideration should be given to redesign of these components, including tanks, expulsion devices, pressure regulators, valves, etc. Design of current equipment for these applications has generally stressed performance and weight. As a shuttle payload, however, reliability, refurbishability, and operating life become much more important considerations.

Table VI-7 Weight Estimates for Space Station APS and Logistics Vehicle Resupply Systems

Configuration	Space Station APS Weight* (lb)	Logistics Vehicle Resupply Weight (lb)	Remarks
Modified WACS-APS	989	--	Modified for installation internal to Space Station structure. No provision for resupply or maintenance.
Recommended APS Configuration	1094	--	Modified for maintenance; reliability upgraded (0.42 to 0.97) by engine placement, sequential operation, quad valves, and component isolation.
APS VI-1	1171	280	Modified APS - two with pressurized propellant resupply using residuals from regulated pressurant resupply.
APS VI-2	1150	234	Modified APS - two with modular replacement of gas storage spheres and pressurized propellant resupply using blowdown pressurization.
APS VI-3	1164	240	Recommended APS with modular replacement of gas storage spheres and pressurized propellant resupply using residual APS ullage.
APS VI-4	1084	230	Recommended APS with permanent volatile liquid pressurization and pressurized propellant resupply using separate high-pressure source.
APS VI-5 (without flow control)	1141 (1166)	258 (267)	Recommended APS with permanent blowdown pressurization and pressurized propellant resupply using separate high-pressure source.

*Weights include basic components, structural mounting, pressurant, and residual propellant; exclude usable propellant, electrical cabling and control, thermal control and spares. Spares requirements for Systems VI-4 and VI-5 are estimated to be 40 lb less than for Systems VI-1, -2, and 3 over a ten-year life.

e. Safety and Human Factors - Qualitative evaluations regarding safety and human factors were based largely on a consideration of the complexity of each of the candidate transfer techniques. Each system has been evaluated in relation to the basic safety guidelines presented in Chapter IX. However, no attempt has been made to generate additional detailed failure mode analyses or operating procedures for each of the systems; because the preparation of such analyses would require detailed design definition down to the component level.

All of the systems considered provide passive control of the fluid transfer processes, thus encouraging operational safety and reducing the required crew commitment. In all cases propellant transfer can be terminated automatically by the APS propellant gaging system. Propellant spillage during disconnect of the servicing lines is avoided by backup shutoff valves and by venting of the disconnects themselves. Hazards associated with handling pressurant bottles are minimized by their relatively small size and mass and by special packaging to preclude mechanical damage.

With the exception of Systems VI-2 and VI-3, crew requirements are limited primarily to connecting and disconnecting servicing lines. Pre- and postoperational checkout as well as monitoring of the flow processes can be accomplished with a minimum commitment of crew time by incorporating these functions into the Space Station or shuttle Onboard Checkout System. Systems VI-2 and VI-3 require manual transfer of the pressurant storage modules from the shuttle to the Space Station. However, the small quantity of pressurant required allows transfer to be performed by one crew member in a single trip.

f. Performance - Performance was not found to be a major factor in comparison of the systems. All candidate systems provide the capability for rapid consumables resupply without requiring an external source of energy. Systems requiring prolonged operating times were excluded during the evolution of candidate designs. In all cases actual transfer of fluids can be accomplished in less than 1 hr.

g. Effect on APS - Selection of a resupply system from among the candidates considered will not have a major effect on the APS inflight maintenance requirements. As discussed in Chapter V, Maintainability, the propellant and engine subsystems will require the major portion of the predicted maintenance time for the APS. Elimination of separate pressurization subsystems, as is the case for Systems VI-4 and VI-5, would reduce unscheduled maintenance for the APS by less than 10%, or from an estimated 73.5 min/yr to 66.6 min/yr. Scheduled maintenance would also be reduced by elimination of the pressurization components. Fifty-nine minutes is allocated for filter element changeout at six-month intervals. Present life limitations for pressurization control components require that they be changed out every three years. This will require approximately 124 minutes of maintenance for each half of the system. Elimination of the pressurization system would thus result in an average savings of 195 minutes per year. Over a ten-year mission the requirement for spare components would also be reduced by an estimated 40 lb.

In summary, the modifications to the baseline APS required by Systems VI-4 and VI-5 will reduce the requirement for inflight maintenance, although not to a major extent.

Selection of a resupply system from among the five candidate systems will, with one exception, have little affect on APS performance. In general, approaches that would materially degrade APS control capability or engine performance were eliminated during definition of the candidate designs. Systems VI-1 thru VI-3 retain the baseline APS, and although Systems VI-4 and VI-5 require major modifications to this baseline, these systems also are configured to assure optimum engine inlet conditions. Only the alternative to the basic System VI-5 would have a significant effect on APS performance, and this system could be seriously considered only if Space Station control requirements would allow a pronounced variation in thrust level during the mission.

2. Comparison of Systems

Evaluations of each of the five systems are presented in this subsection.

a. System VI-1 - Pressurant is resupplied by equalizing pressures between a 3000 psia nitrogen storage bottle onboard the logistics craft and a 1000 psia nitrogen storage bottle onboard the Space Station. Residual nitrogen is then used for pressurized transfer of propellants. Recovery of contaminated propellant from the Space Station APS propellant removal and servicing tool is accomplished by using the logistics vehicle resupply tanks as receivers.

Advantages - The major advantages of System VI-1 are as follows:

- Current technology status;
- Suitability for recovery of contaminated propellants;
- Minimum requirement for crew commitment during resupply operation.

Disadvantages - The major disadvantage of System VI-1 is as follows:

- Relatively high weight.

The most advantageous characteristics of this system is its current technology status. Functionally this system is very similar to the subsystems currently used for pressurization and propellant storage in the conventional bipropellant APS. Consequently, the development program required for this system should be relatively straightforward and can take maximum advantage of past development experience. State-of-the-art components are immediately available for all of the required system functions such as propellant and pressurant storage, pressurant control, and propellant expulsion. Because of the relatively low operating pressures, venting of the propellant resupply tanks will not be necessary during recovery of contaminated propellant. This factor allows the full range of propellant tank expulsion devices to be considered. These include capillary devices and nonmetallic bladders that would otherwise be excluded because of their permeability to propellant and consequent contamination of the Space Station exterior during tank venting. Resupply of consumables by System VI-1 also allows the use of a conventional hypergolic bipropellant APS, requiring only minor modification to the system for fill connections and venting of the ullage.

As the result of the current status of technology required for both the APS and the resupply system, System VI-1 represents the earliest available approach for resupply of consumables to the Space Station APS. The only anticipated major area of development effort is the modification of current component designs to assure economical inspection, cleaning, and refurbishment -- particularly the propellant resupply tanks. As discussed further in the Future Technology chapter of this report (Chap. X), significant reductions in program operating costs may be achieved by development of easily refurbished components.

System VI-1 also demands a minimum of crew involvement during the resupply process, primarily connecting and disconnecting the fluid transfer lines. Active control of the flow processes will not be required, because automatic control is achieved by the pressure regulators and by preselected loading of the pressurant resupply bottle.

The major disadvantage of System VI-1 is its relatively high weight. This weight penalty results largely from the excessive pressurant residuals that occur when a blowdown process is used for pressurant transfer. The Space Station portion (i.e., the APS) is expected to weigh 87 lb more than the lightest weight system, System VI-4. Although this weight penalty represents only 8% of the estimated APS dry weight, the effect on the shuttle resupply requirements is more pronounced. As illustrated by Table VI-7, shuttle liftoff weight for the lightest system is estimated to be 230 lb, excluding usable propellant. The corresponding weight for System VI-1 is estimated to be 280 lb. These figures are based on a normal six-month resupply interval and result in a 1000-lb weight differential over a ten-year program.

As revealed by Table VI-5, System VI-1 is also the least reliable of the systems considered. This factor is not considered major, however, since total variations between the candidate systems are small.

b. System VI-2 - With this system, pressurant is resupplied by modular replacement of the APS gas storage spheres. Propellants are replenished by pressurization of the propellant resupply tanks that incorporate an integral blowdown pressurization system.

Advantages - The major advantages of System VI-2 are as follows:

- Near minimum weight;
- Suitability for recovery of contaminated propellants;
- Minor development requirement.

Disadvantages - The only minor disadvantage of System VI-2 is:

- Required crew commitment during modular replacement of pressurant bottles.

Compared with System VI-1, liftoff weight of the logistics vehicle is significantly reduced by incorporating a modular mode of pressurant resupply. Logistics requirements are reduced by an estimated 46 lb per resupply cycle, or excluding usable propellant, nearly 20% of the total weight chargeable to the resupply system. This value corresponds to 920 lb over a ten-year program life. Space Station liftoff weight is also reduced by an estimated 21 lb.

Low operating pressures can be used for propellant transfer ($\leq$50 psia), allowing a high blowdown ratio (5:1) for the transfer process. Thus, for the propellant quantities required by the baseline system, single, minimum gage tanks can still be used without greatly increasing total tank volume above that required for System VI-1.

Propellant is resupplied using conventional fluid components and as shown in Table VI-2, APS reliability as well as the probability of a successful resupply are slightly increased over the previously discussed system.

As with System VI-1, venting of the propellant resupply tanks is not required for recovery of contaminated propellants, thus allowing the use of permeable expulsion devices, and avoiding the possibility of contaminating the Space Station exterior.

The only areas requiring further development result from modular replacement of the pressurant bottles. Some development effort will be required to achieve safe and efficient transport of the pressurant packages. Development requirements are expected to be minor, however, because of the small size and mass of the required package.

A minor disadvantage of this system is with respect to crew requirements. Transportation and installation of the pressurant bottles will require crew involvement during the resupply operation. However, since only a single small-diameter pressurant sphere is required each six months, the required commitment of crew members and cargo handling equipment will be small.

c. System VI-3 - This system, which is a modification of System VI-2, allows the use of APS ullage as the pressurization source for the propellant resupply tanks.

Advantages - System VI-3 provides no significant advantages compared to System VI-2.

Disadvantages - System VI-3 is slightly heavier and less reliable than System VI-2.

System VI-3 was initially considered as a means of reducing tank volume and weight. However, the slight reduction in resupply tank weight is more than equaled by the weight of additional service lines and valves. The additional servicing connections also slightly reduce the probability of a successful resupply of consumables. Therefore, the only real effect of the System VI-3 modifications is to provide the additional capability of venting the resupply tanks through the Propellant Removal and Servicing Tool. This in turn permits recovery of larger quantities of contaminated propellant without the risk of exposing the Space Station exterior to propellant vapors. However, Systems VI-1 and VI-2 can easily recover a full tank load of each propellant without requiring an increase in the maximum design pressure of the resupply tanks. Consequently, the added complexity of the modified system is unjustified when compared to System VI-2.

d. System VI-4 - This system requires major modification of the baseline APS. The baseline pressurization system is replaced by a permanent volatile liquid system that incorporates a heat storage material for maintaining required operating pressures. Pressurant is recompressed and condensed during propellant resupply, thus eliminating the necessity of periodically resupplying pressurant. Expended propellants are replenished by pressurized transfer using a regulated gas as the energy source.

Advantages - The major advantages of System VI-4 are as follows:

- Minimum weight design;
- Minimum requirement for crew commitment during resupply operation;
- Noticeable reduction of inflight maintenance requirements.

Disadvantages - The major disadvantages of System VI-4 are as follows:

- Extensive development required; affecting development costs and program risk;
- Ullage venting required for recovery of contaminated propellant.

Of the candidate systems considered, System VI-4 represents the minimum weight design, both with respect to resupply weight as well as Space Station launch weight. It is not, however, recommended for incorporation into the Space Station design.

The two major characteristics of System VI-4 that detract from its suitability for application to the Space Station are the early status of its required technology and the necessity of venting the resupply tanks to recover contaminated propellants.

Although the feasibility of a volatile liquid system has been demonstrated by the programs reported by TRW, several additional factors must be considered if this pressurization technique is to be applied to the Space Station APS. For the volatile-liquid system to be competitive with other more conventional systems, condensation of the APS ullage during propellant resupply must be accomplished passively, i.e., without active cooling. Servicing of equipment during the test program reported by R. G. Eatough (TRW) suggests that transfer of propellants from the logistics vehicle to the Space Station APS can be accomplished within a reasonable length of time, say 1 hr, without an active cooling loop. Nevertheless, further analysis and testing will be required to adequately demonstrate this capability. Final selection of the specific pressurant and the optimum heating source will be highly dependent on engine inlet conditions and duty cycle. Consequently, an early but firm definition of required engine operating conditions also must be specified before serious development effort can be initiated.

These factors, in conjunction with the early status of required technology, will result in increased development costs and anticipated development risk. It is estimated that development of a volatile liquid pressurization system for the Space Station APS would increase program costs by at least $5 million.

Since a permanent pressurant is used to avoid resupply, propellants must be replenished without venting the APS receiver tanks. This in turn requires relatively high operating pressures for the logistics vehicle transfer tanks. Consequently, efficient reuse of these tanks for recovery of contaminated propellants requires that they first be vented to reduce system backpressure during the transfer process. This is particularly true if a simple pressurized transfer technique is to be used. As a result, only nonpermeable expulsion devices are considered for System VI-4. The weight estimates of Table VI-3 assume the development of a lightweight metallic bladder or diaphragm. An acceptable alternative to this design would be the provision of additional servicing connections for venting, as in System VI-3. Two other techniques for recovery of contaminated propellant might also be considered. Pumped transfer of the contaminated propellant seems feasible if it is incorporated as an additional capability of the same pump which is used for removal of propellant from the APS. Even so, the additional power requirements and inherent reduction in reliability may outweigh the problems associated with the development of a suitable expulsion device for the logistics vehicle tanks. If the receiver tanks for the Propellant Removal and Servicing Tool are sized to permit easy handling, modular replacement of these tanks may be another feasible technique for recovery of contaminated propellants.

The particular system selected as a candidate relies on a heat storage material as the heating agent rather than on an active heating source, such as a heat exchanger or electric heater. As revealed in Table VI-5, the reliability of the APS is approximately the same as that of Systems VI-1, -2, and -3, which are regulated gas systems with a degree of component redundancy. To further reduce system weight, active heating sources were also considered in lieu of the heat storage material. However, in all cases, system reliability was reduced and the complexity of the system was increased.

It was concluded finally, that although System VI-4 is a feasible approach and represents the minimum weight system, it is not recommended for incorporation into the Space Station design.

e. System VI-5 - This system also requires major modification of the baseline APS. The baseline pressurization system is replaced by a blowdown system that is an integral part of the propellant storage assemblies. Pressurant is recompressed during propellant resupply and expended propellants are replenished by pressurized transfer using a regulated gas as the energy source. The basic system includes feedline flow control valves to maintain optimum engine inlet conditions. An alternative design excludes these flow control valves and allows inlet conditions to follow propellant tank blowdown.

Advantages - The major advantages of the basic System VI-5 are as follows:

- Minimum requirement for crew commitment during resupply operation;
- Noticeable reduction of inflight maintenance requirements.

Disadvantages - The major disadvantages of the basic System VI-5 are as follows:

- Moderate increase in development requirement;
- Ullage venting required for recovery of contaminated propellants.

Compared to the basic system, the alternative blowdown bipropellant design provides the following advantages:

- Slight increase in reliability;
- A noticeable reduction in development requirements.

The following disadvantages result, however:

- Major reduction in performance flexibility;
- Significant increase in weight.

Although pressure-fed bipropellant propulsion systems have conventionally used regulated gas as the pressurizing medium, a blowdown system is considered to be entirely feasible. This technique is well established for use with monopropellant systems and, as a result, the required tankage and expulsion technology is currently available. The feasibility of employing flow control valves to maintain a constant flow rate to the engines also has been clearly demonstrated by the development and qualitication of low thrust throttleable engines such as the Lunar Lander and Surveyor vernier propulsion engines. Nevertheless, some additional development must be expected if System VI-5 is to be used. Development of flow control valves for this specific application will be required. Additional requirements for performance demonstration testing are also anticipated. These additional requirements are expected to increase program costs by as much as $1 to 2 million. However, development risk is expected to be slight.

Next to System VI-4, VI-5 is the lightest weight design with respect to Space Station launch weight. However as noted before, the total variation in liftoff weight for all of the candidates is only approximately 8%, and this factor is not considered to be significant. As shown in Table VI-7, logistics vehicle resupply weight lies approximately midway between the heavy and light systems. Compared to System VI-1, logistics requirements for a ten-year program would be reduced by an estimated 440 lb. Compared to System VI-2, however, these requirements would be increased by 480 lb. The effect, assuming launch costs of less than $100/lb, does not seem to justify a major development effort for any of the systems concerned.

Elimination of the baseline pressurization components will reduce the incidence of required maintenance. However, since exposure to propellants makes replacement of components much more difficult, this effect is partially offset by the additional requirement for flow control valves in the propellant feedlines.

System VI-5 was initially considered as a candidate because of two characteristics: the elimination of a requirement for a pressurant resupply, and the reduced number of components and resultant potential for increased system reliability. However, as shown in Table VI-5, the hoped for increase in reliability was not realized. This again results largely from the requirement for flow control valves that are necessary in the propellant feedlines if optimum engine inlet conditions and a constant thrust level are to be maintained. Therefore, if Space Station control requirements allow, consideration might also be given to eliminating the feedline control valves and allowing the engine inlet conditions to vary directly as the propellant tanks blow down. For a blowdown ratio of 2:1, the resultant thrust variation is predicted to be ±26.5%. Although some degradation in I_{sp} will also occur due to variations in mixture ratio and thrust level, it is expected to be less than 2% under worst conditions.* Compared to Systems VI-1 and VI-2, a slight increase in development and qualification costs for required performance demonstration should be anticipated. However, no major increase in development costs or risk is expected.

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*Performance estimates are based on analytical and empirical studies by the Bell Aerospace Company. Results are summarized in Fig. VI-9.

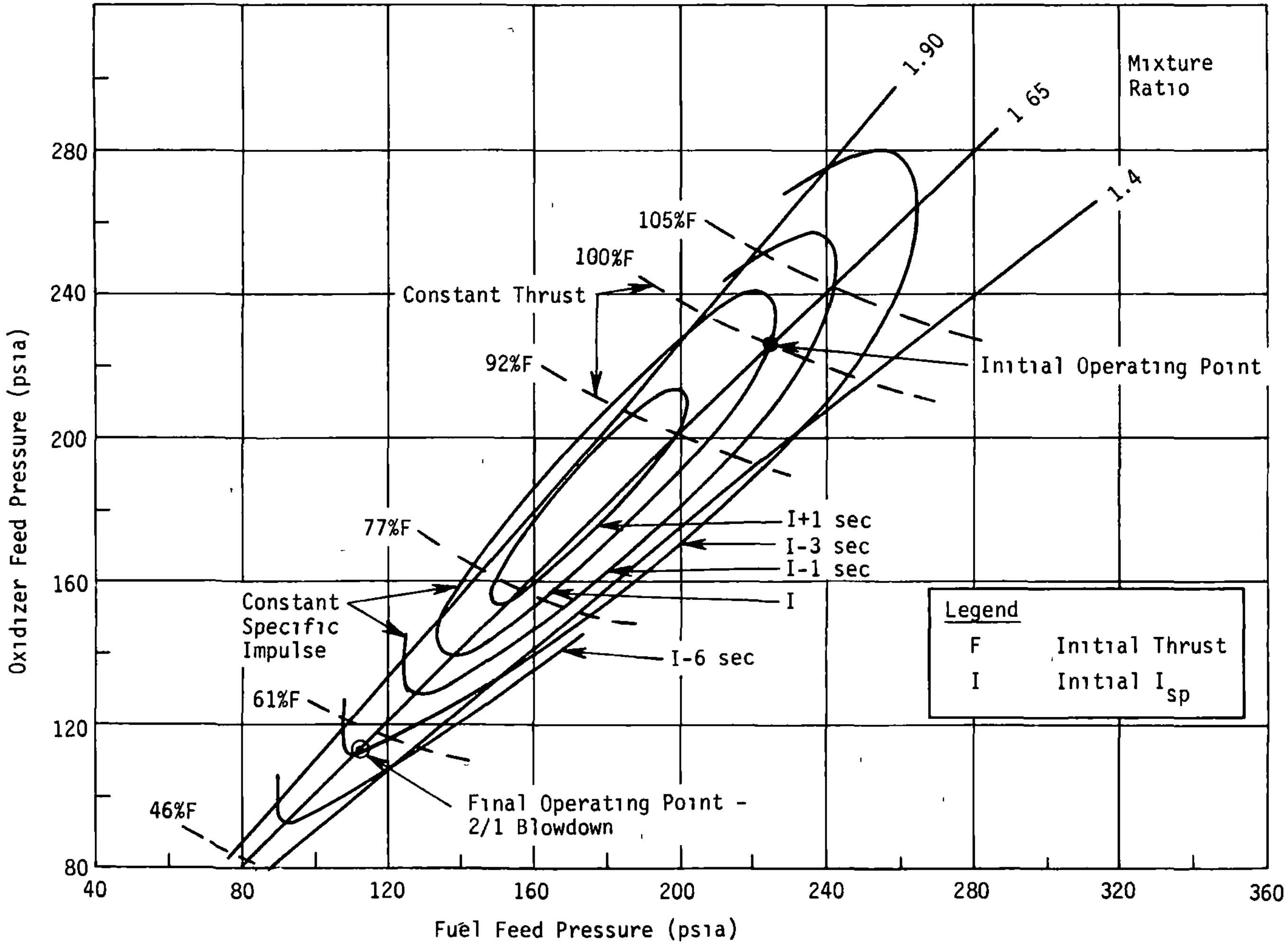

Fig. VI-9 Predicted Performance of Blowdown APS

Compared to the controlled blowdown system, i.e., with feedline control valves, a new increase of 25 lb in Space Station launch weight is expected. This results from an increased propellant load required to compensate for the predicted performance degradation and increased propellant residuals while maintaining the same total impulse capability. Degraded engine performance will also increase logistics vehicle resupply weight by an estimated 9 lb per resupply cycle.

Another noticeable effect of eliminating the flow control valves is to increase the APS ten-year mission reliability by an estimated 0.0063, making this system the most reliable of the candidates studied. The requirement for inflight maintenance is also reduced.

In spite of these factors, a blowdown system is not recommended for the Space Station APS. Compared to System VI-2, it is significantly heavier, requires additional development of new technology, and unless system complexity is increased by the addition of feedline flow control valves, allows for less flexibility in control capability.

VII. RELIABILITY

The three major objectives of the reliability analyses reported in this chapter are as follows:

1) To define an attitude propulsion system configuration that will meet the life requirements of a ten-year mission;
2) To determine the impact of reliability considerations on the design, operation, resupply, and repair of a storable bipropellant APS for an orbiting Space Station;
3) To support a quantitative evaluation of the various APS and resupply system configurations evolved during the study.

With respect to the first objective, study results show that conventional propulsion system design is not consistent with ten-year space missions. Component redundancy and improved component reliability will not, in themselves, be sufficient to support man-rated systems. To achieve the overall assurance that is required, the following will be necessary:

1) Capability to isolate the propellant tanks, and redundancy for the system components and engines;
2) Operation of the APS subsystems must be sequential with one-half of the subsystem on standby at all times;
3) A capability must be provided for isolation and replacement (inflight maintenance) of the APS components and assemblies.

With respect to the above objectives, the following basic configurations were analyzed:

1) The baseline configuration (Fig. VII-1);
2) Preliminary modified APS configuration (Fig. VII-2). This system is a minimum modification of the baseline APS to allow isolation and replacement of the major components and assemblies, i.e., inflight maintenance;
3) Recommended APS configuration (Fig. VII-3). This system is a modification to the baseline APS to provide standby operation as well as to allow inflight maintenance. Quad engine valves are also provided and engines are located to avoid detonation damage;

4) Resupply Configurations 1 thru 5 (Fig. VI-1 thru VI-5). These are the five candidate resupply systems discussed in Chapter VI. Reliability estimates were made of both the resupply system and the APS itself.

Results of the reliability analyses of the above configurations are summarized in Tables VII-1 and VII-2, and a description of the mathematical models and assumptions appears in Section D of this chapter.

Starting with the baseline APS, a building block approach was applied to establish an APS configuration that would have sufficient reliability to assure the successful completion of a ten-year mission. Configuration tradeoffs were conducted to achieve this objective with a minimum of added weight and complexity.

Figure VII-4 graphically shows those factors required to achieve a ten-year mission. As seen here, component redundancy alone is not the answer. The system must also be reparable, must be functionally redundant with standby capability,* and must provide propellant tank isolation or extra commodity tanks.

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*A standby system is one in which one-half of the system can be operated at a time, thus permitting maintenance and resupply on one-half, while the other half is operating.

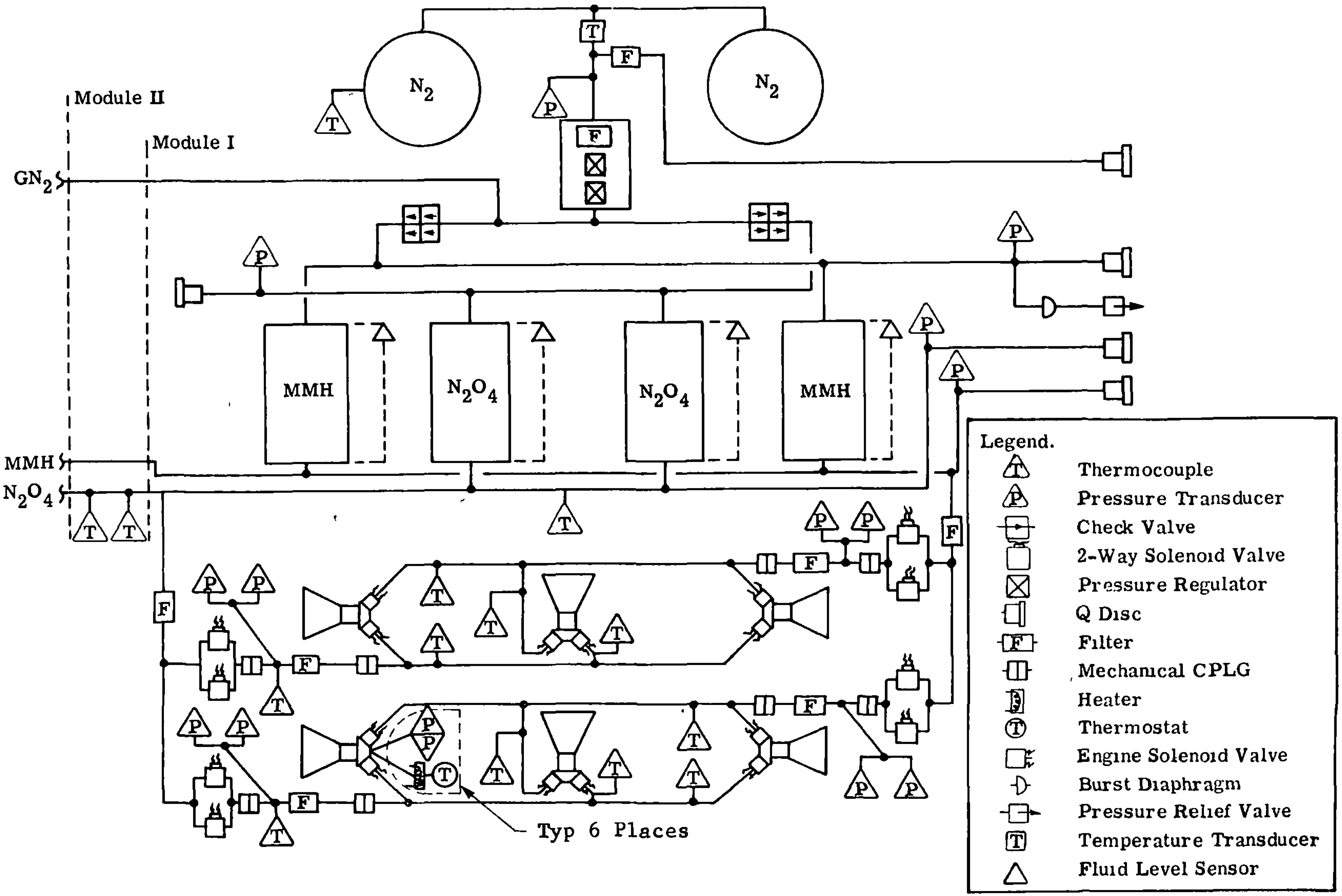


Fig. VII-1 Baseline APS

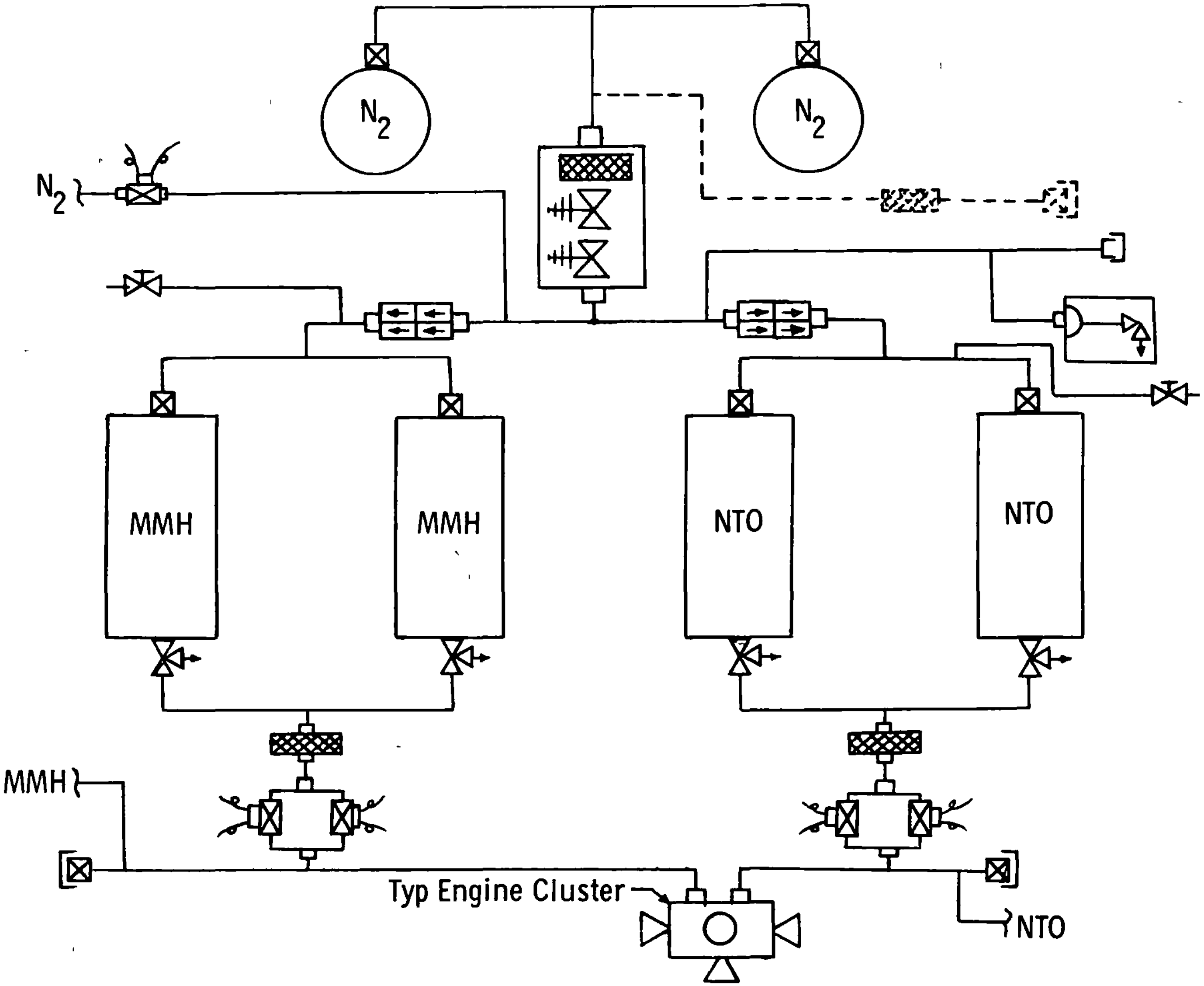


Fig. VII-2 Preliminary APS Configuration

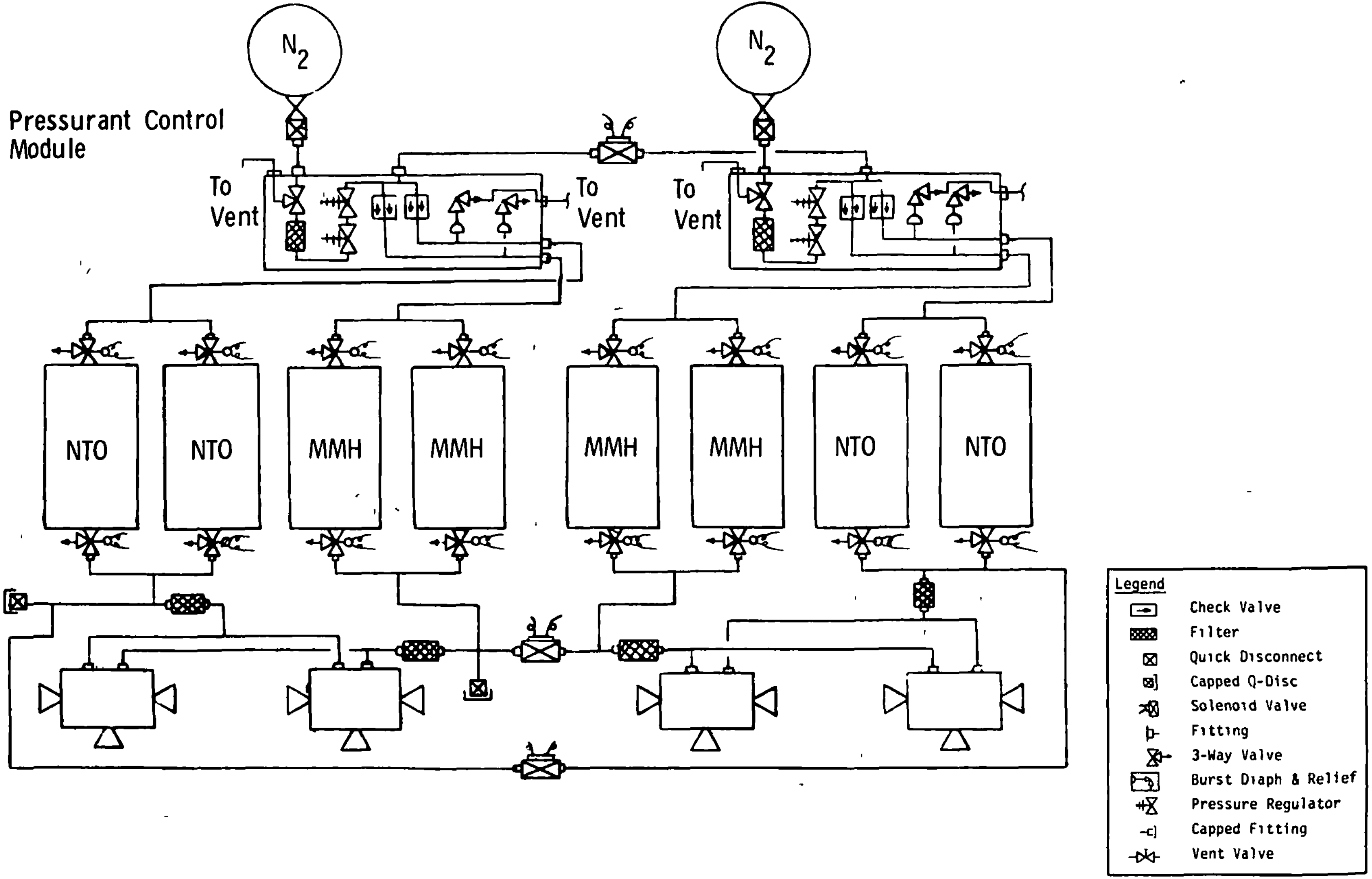


Fig. VII-3 Recommended APS Schematic

Table VII-1 APS Reliability Estimates

Configuration	Probability of Mission Success				
	One Year				Ten-Year Overall
	Pressurization	Propellant	Engine	Overall	
Baseline	0.9862	0.9495	0.9788	0.9161	0.4161
Preliminary APS	0.9987	0.9947	0.9777	0.9713	0.7472
Recommended APS	0.9999	0.9998	0.9972	0.9969	0.9689
APS Resupply 1	0.9997	0.9996	0.9972	0.9965	0.9655
APS Resupply 2	0.9999	0.9996	0.9972	0.9967	0.9675
APS Resupply 3	0.9999	0.9996	0.9972	0.9967	0.9675
APS Resupply 4	--	0.9994	0.9972	0.9966	0.9665
APS Resupply 4a	--	0.9983	0.9972	0.9955	0.9559
APS Resupply 5	--	0.9989	0.9972	0.9962	0.9622
APS Resupply 5a	--	0.9996	0.9972	0.9968	0.9685

Table VII-2 Estimated Resupply System Reliability

Configuration	Probabilities of Successful Consumable Resupply		
	Space Station, P_s	Logistics Vehicle, P_L	Overall = $(P_s)(P_L)$
APS VI-1	0.9998	0.9989	0.9987
APS VI-2	0.9998	0.9992	0.9990
APS VI-3	0.9998	0.9991	0.9989
APS VI-4	0.9999	0.9990	0.9989
APS VI-5	0.9999	0.9990	0.9989

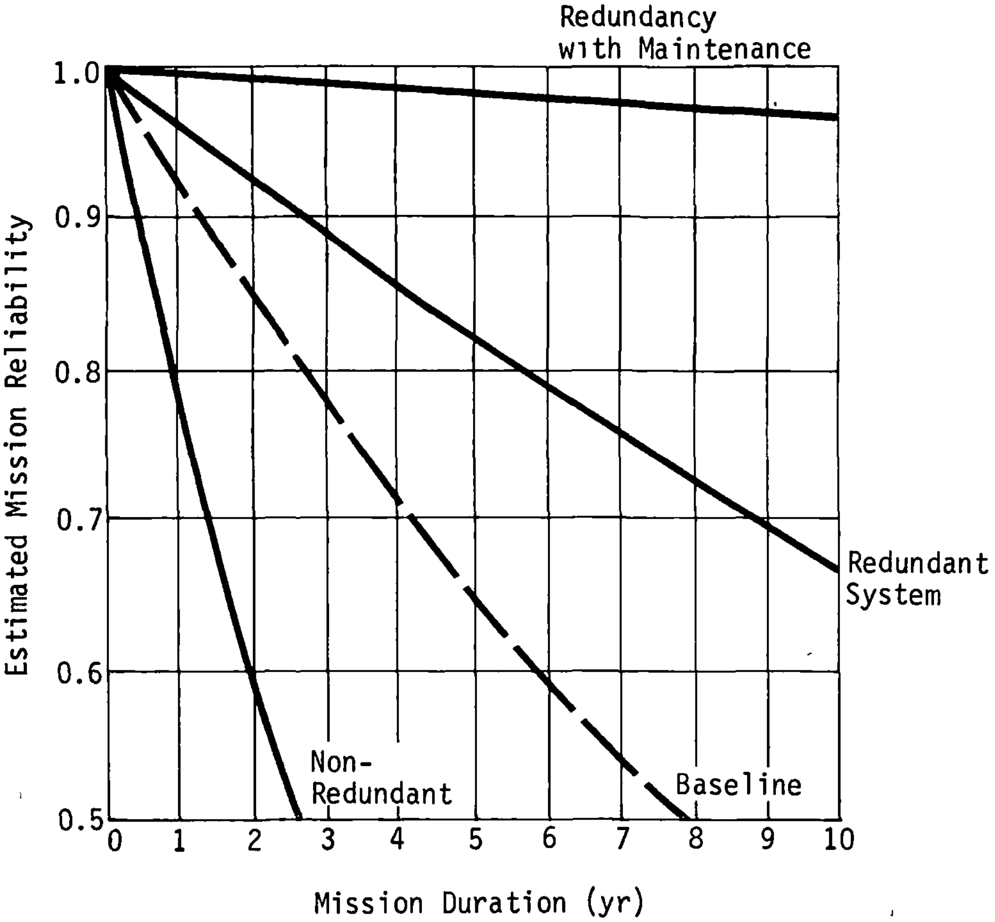


Fig. VII-4 APS Reliability Comparisons

A. BASELINE CONFIGURATION

The baseline APS schematic is shown in Fig. VII-1. In addition to the assumptions listed in the attached model description, the following assumptions were used in calculating the baseline configuration reliabilities:

1) The system does not have the capability for replacement, refurbishment, or repair of components;
2) The consumables are refurbished once a year;
3) Consumables are drawn from all propellant tanks and nitrogen spheres simultaneously.

As shown in Table VII-3, the probability of mission success was estimated to be 0.4161. The mission success estimate of 0.4161 is certainly not sufficient for a ten-year mission, but does provide a baseline to which the probability of mission success of other configurations can be compared.

Table VII-3 Estimated Probabilities of Ten-Year Mission Success

Item	Probability of Mission Success			
	Propellant Storage and Transfer	Pressurization	Engines	Total APS
1. Baseline (Fig. VII-1)	0.5957	0.8705	0.8024	0.4161
2. Baseline Except:				
a. One N_2 tank-out capability	0.5957	0.8783	0.8024	0.4198
b. One NTO and MMH tank-out capability	0.9494	0.8705	0.8024	0.6631
c. Item 2a and 2b capability	0.9494	0.8783	0.8024	0.6691

1. Propellant Storage and Transfer Subsystem

Table VII-3 also illustrates another significant characteristic of the baseline APS. A major increase in total APS reliability can be achieved by providing the propellant storage and transfer subsystem with the capability of functioning with either an NTO or MMH tank failure. This is required by the system to have a mission success probability comparable to the other two subsystems. Without this capability, the reliability of the propellant subsystem (0.5957) is two to three orders of magnitude below the estimated reliabilities of the pressurization subsystem (0.8705) or engine subsystem (0.8024). The one-tank-out capability can be provided either by redundancy, by oversizing the tanks (three of four required) or by providing a capability for refurbishment, repair, or replacement. To ensure a reasonable minimum level of mission reliability, the baseline bipropellant system will require some redundancy. As a minimum, a capability must be provided to isolate failed propellant tanks.

2. Engine Subsystem

The calculated engine subsystem reliability equals 0.8024 for a ten-year mission. Each primary engine module has an estimated one-year mission reliability of 0.9052. The propulsion system reliability calculations assume that: (1) each primary module has an identical backup module; (2) two engine modules in series must function; and (3) the probability of an engine detonation not negating the redundant features equals 0.99801 per pair of primary modules for one year. R4D engine data indicates that the *maximum* probability of an engine detonation equals 4.2% of the total probability of an engine failure. The best estimate probability of an engine detonating and destroying an adjacent engine is 2.1% of the estimated engine failure probability, which is a conservative value.

3. Pressurization Subsystem

Providing a one-nitrogen-tank-out capability improves reliability from 0.8705 to 0.8783. This small reliability increase of about 0.008 would require a weight-reliability tradeoff study before any decisions are made about providing a one-tank-out capability. The pressurization system for the baseline system is already redundant in control components.

B. BASELINE MODIFICATIONS

Table VII-4 presents the estimated probabilities of ten-year mission success for various modified baseline configurations. The weight difference between the baseline configuration shown in Fig. VII-1 and those denoted are also shown. This table indicates what reliability increases can be obtained by the addition of selected redundancies. Figure VII-5 presents some of the data of Table VII-4 in graphic form.

Table VII-4 Ten-Year Mission Success and APS Weight Differentials for Modified Baseline Configurations

Configuration	Ten-Year Mission Reliability	Δ above Baseline		$\frac{\Delta \text{ Rel}}{\Delta \text{ Wt}} \times 10^3$
		Δ Weight (lb)	Δ Reliability	
A. Baseline	0.4161	--	--	--
B. Baseline except:				
1. Two N_2 Spheres Only	0.4163	(-2)	0.0002	-0.100
2. One-N_2-Sphere-Out Capability	0.4198	24	0.0037	0.154
3. Cross Engine Detonation Effects Eliminated	0.4330	25	0.0169	0.676
4. Two Sets of Quad Valves per Engine	0.4844	24	0.0683	2.850
5. Capability to Isolate Failed Propellant Tank*	0.6516	10	0.2355	23.550
6. One-Propellant-Tank-Out Capability*	0.6631	367	0.2470	0.672

*Repair/replacement of any failed tank accomplished at end of each year.

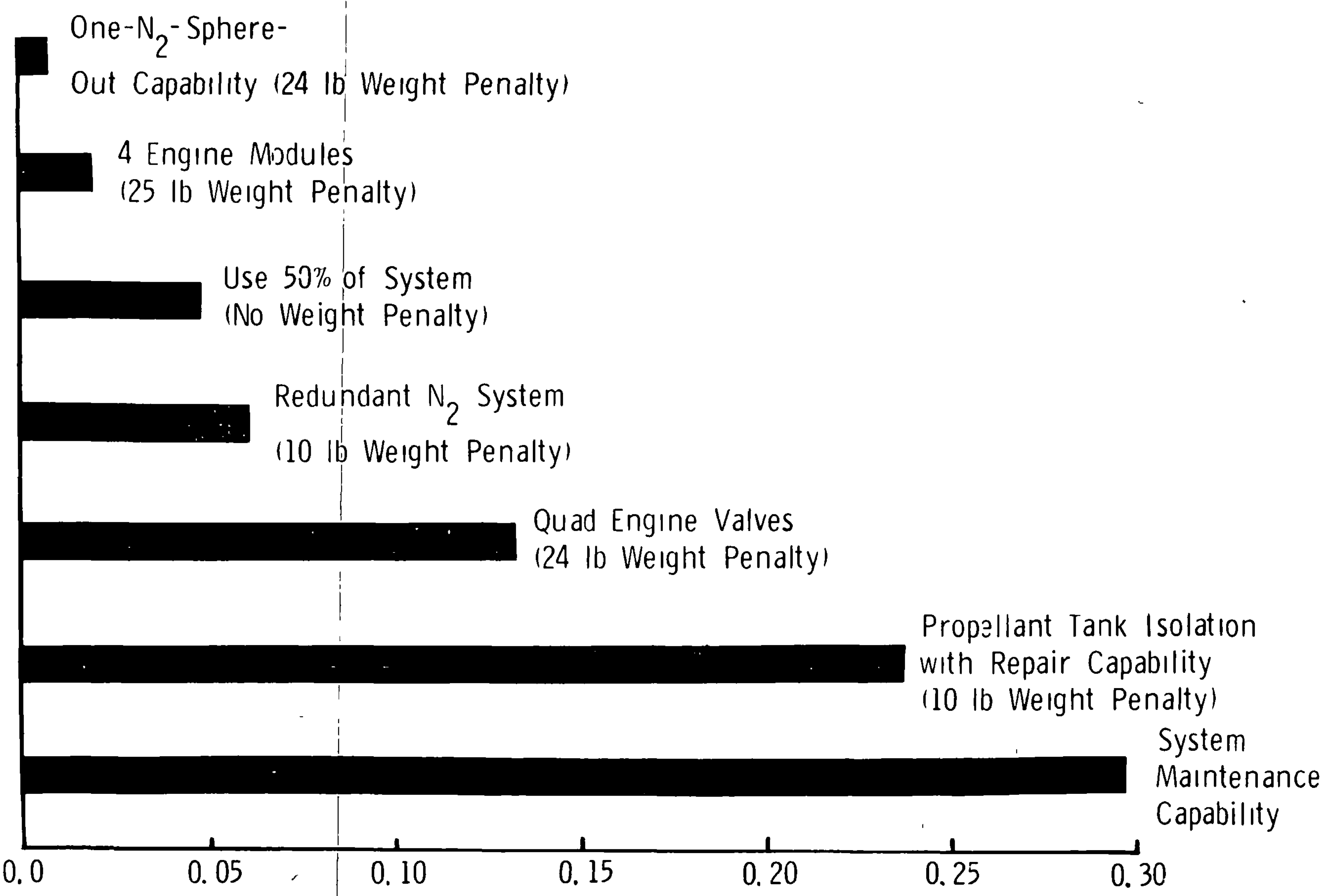


Fig. VII-5 Reliability Building Blocks

Providing the capability to isolate a leaking or malfunctioning propellant tank increases the ten-year reliability of the baseline configuration from 0.4161 to 0.6516 with a weight penalty of only about 10 lb (Table VII-4). The capability to function a complete year without replenishment/refurbishment with a failed propellant tank costs 367 lb in additional propellant and tank weight; and only increases the probability of mission success by 0.0115 above that of the previously mentioned isolation capability. The weight penalty consists of 286 lb of propellant and 81 lb of additional tankage and isolation hardware. The one-tank-out weight penalties occur only once and could be considered as an in-place spare. One would probably not choose this configuration over that of the propellant tank isolation configuration because of the weight penalty.

Replacing the two single propellant solenoid valves on each engine with two sets of quad valves increases the reliability from 0.4161 to 0.4844 with an estimated 24-lb penalty.

The baseline reliability can be increased by about 0.0169 by physically separating the engine modules sufficiently to essentially delete the possibility of one engine detonation damaging its redundant counterpart.

Replacing the four pressurization spheres with two larger spheres of total equal volume increases reliability by only 0.0002, but it reduces weight by approximately 2 lb. It is questionable that the additional 0.0037 reliability provided by a one-nitrogen-sphere-out capability justifies the weight penalty of 24 lb for the bipropellant system.

1. Preliminary APS Configuration

Figure VII-2 presents the preliminary APS configuration. This configuration is essentially the baseline configuration except that minimum modifications have been made to allow replacement or repair of components. The estimated probability of this configuration completing a ten-year mission is 0.7472. Thus, providing for component replacement or repair raises the mission reliability of the baseline configuration by 0.3311, which is a significant increase. The preliminary configuration weighs approximately 13 lb more than the baseline configuration.

2. Recommended APS Configuration

Reliabilities of the baseline APS and of the preliminary APS are not acceptable for a ten-year manned mission. However, these configurations do not take full advantage of methodology available to increase long-life reliability. Methodologies that can be applied include full use of inflight maintenance and restoration, use of either system and/or selected component redundancies, and individual component improvement.

At some point in time, the mission reliability requirements can be met only by employing inflight maintenance (IFM). Increases in the reliabilities of parts and assemblies will not be sufficient in themselves to achieve the overall levels of assurances that are sought. To maintain the high level of reliability a spacecraft initially possesses, both redundancy and inflight maintenance must be provided. The redundancies can be either active or standby. Inflight maintenance can be either replacement or repair of the failed part. IFM is discussed more fully in Chapter IV. The general problem is to obtain the optimum balance of redundancies and inflight maintenance, considering such parameters as reliability, maintenance times, crew availability, weights, volumes, useful lives, induced environments, human performance, and safety.

By selecting the most advantageous mode of operation, a significant improvement in APS reliability can be achieved with a minimum change in hardware.

If consumables are drawn from all tanks simultaneously, they must normally be replenished once a year. Emergency resupply and/or component replacement is available on a 90-day interval if necessary. Since the commodity tanks can be isolated in the pressurization subsystem and the propellant storage subsystem, APS operation can be continued until either replenishment, refurbishment, and/or replacement is made. Thus the pressurization subsystem is in effect redundant an average of 342 days a year, and the propellant storage and transfer subsystem is redundant between 320 and 342 days per year depending on the particular failure mode.

A more advantageous operating mode is now described. Consumables are drawn from only one-half the system at a time and are normally replenished every 6 months. Except for leakage, rupture, or contamination of the crossover lines and valves, this mode of operation provides an active side and a standby redundant side.

In general, the internal pressure of the inactive side will be maintained at less than that of the active side; hence, the component failure rates of the standby side are lower than those of the active side. Table VII-5 shows that Standby Mode B mission success probabilities are significantly greater than those for Mode A. Since no hardware modifications are required, total APS weight is unaffected. As illustrated in Table VII-6, the increase in launch costs necessitated by a 180-day resupply interval are small, depending somewhat on the eventual unit cost for logistic support.

Table VII-5 Mission Reliability vs Operating Mode

Configuration	Mission Success Probability for One Year/(Ten Years)
A. All Consumables Used Simultaneously Entire APS	0.9723 (0.7559)
Pressurization	0.9988
Propellant System	0.9952
Engines	0.9782
B. Only ½ Consumables Used Simultaneously Entire APS	0.9779 (0.7999)
Pressurization	0.9999
Propellant System	0.9998
Engines	0.9782

Table VII-6 Cost for Standby Operation

	Mode A			Mode B		
Resupply Interval (days)	360			180		
APS Launch Cost at $1000/lb ($ million)	3.2	3.2	3.2	3.2	3.2	3.2
Resupply Cost at $500/lb ($ million)	6.5			7.2		
Resupply Cost at $100/lb ($ million)		1.3			1.4	
Resupply Cost at $50/lb ($ million)			0.65			0.7
Total Launch Costs for Ten-Year Mission ($ million)	9.7	4.5	3.85	10.4	4.6	3.9

Sufficient data and program definition are not available at this time to permit a complete weighted parametric study for optimization of all of the minor parameters affecting reliability. However, the reliability analysis reported here can be employed to advantage to determine general conclusions.

Figure VII-4 illustrates how a reliability analysis can be a useful tool to help select a configuration that will have a satisfactory probability of mission success. Mission duration is plotted against the estimated mission reliability for various APS configurations. The curves for the configurations provide a visual aid in ascertaining how much redundancy (active or standby) and/or maintenance may be required to obtain acceptable levels of mission reliability. APS reliability requirements have not been quantitatively established to date; hence, data are presented parametrically. Mission success probabilities are normally required to exceed 0.90 for most subsystems. On this basis, it is apparent that the baseline configuration in a nonredundant form is not acceptable since its probability of mission success is less than one-half before 3 years. Figure VII-4 indicates that to meet reliability requirements the APS configuration should provide standby redundancy and a capability for inflight maintenance.

In view of these factors, the recommended APS configuration was evolved as a means of satisfying the ten-year reliability requirements. Figure VII-3 schematically illustrates this system. In this configuration, which is a modification of the baseline, the pressurization system is modularized, the number of nitrogen spheres is reduced from four to two, and minor hardware additions are provided to facilitate using one-half the system in a standby-redundant mode. If the consumables are drawn from all tanks simultaneously (no standby redundancy), consumables must be replenished once a year and failed components may be replaced on 90-day intervals, if required. The estimated ten-year reliability for this operating mode is only 0.7559. The probability of mission success can be increased to 0.7999 if standby redundancy is employed, i.e., if only one-half of the APS is used at a time. The consumables in the active half then require replenishment every six months. The increase in mission reliability by employing standby redundancy and by replenishing the consumables twice a year is thus 0.0440.

The estimated ten-year mission success probabilities for the recommended configuration and selected variations are presented in Table VII-7. The denoted variations are self-explanatory. Note that a relatively high reliability of 0.9689 can be obtained by adding sufficient "reliability building blocks" to the basic configuration shown in Fig. VII-3. These reliability building blocks are depicted in Fig. VII-5 to illustrate how the reliabilities can be increased by their use. Configuration E of Table VII-7 is the recommended APS design.

Table VII-7 Mission Success Probabilities for the Recommended APS Configuration

Configuration Variation	Mission Reliability	Δ Rel above Baseline A
A. Consumables drawn from all tanks simultaneously. Replenish once a year. Repairs every 90 days available.	0.7559	--
B. Same as A except one pressurization system used for both halves.	0.6969	-0.0590
C. Two halves of system used independently. One-half consumables replenished every 6 months. Repairs/replenishment available every 90 days (no weight penalty).	0.7999	0.0440
D. Same as C except a set of quad solenoid valves used on each engine.	0.9311	0.1752
E. Same as D except cross engine detonation effects eliminated.	0.9689	0.2130
F. Same as E except no repairs or replacements allowed.	0.6721	0.2972 less than E

Figure VII-6 presents estimated mission reliabilities for the three configurations considered (baseline, preliminary and recommended) and their variations versus the cumulative weight penalty. The configurations and variations are plotted from the baseline configuration in decreasing order of delta reliability per pound.

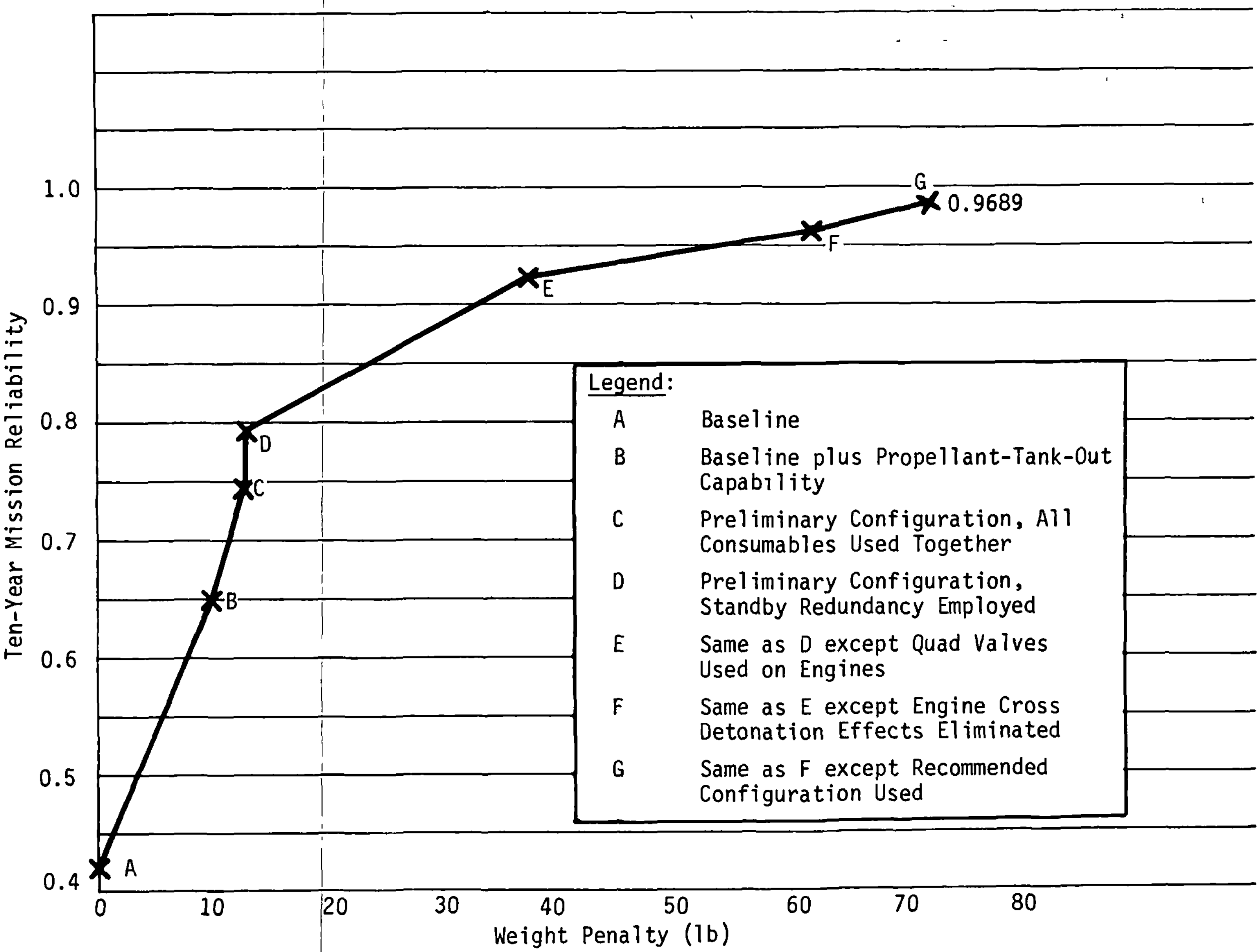


Fig. VII-6 Weight vs Mission Reliability for Various APS Configurations

Thus, if a mission reliability of about 0.92 is required, the preliminary configuration with quad solenoid valves and employing one-half the system in a standby mode will provide the required reliability at the lowest weight penalty, 37 lb above the baseline configuration. Although drawn as a continuous curve to facilitate visual interpretation, the plot points are actually discrete values. Thus, if a maximum weight penalty of 23 lb is allowed, the recommended configuration employing standby redundancy would provide the highest mission reliability (0.799) consistent with the weight constraint.

Figure VII-7 illustrates how the reliabilities of the baseline as well as the preliminary and recommended configurations can be increased by application of various methodology and configurations (building blocks).

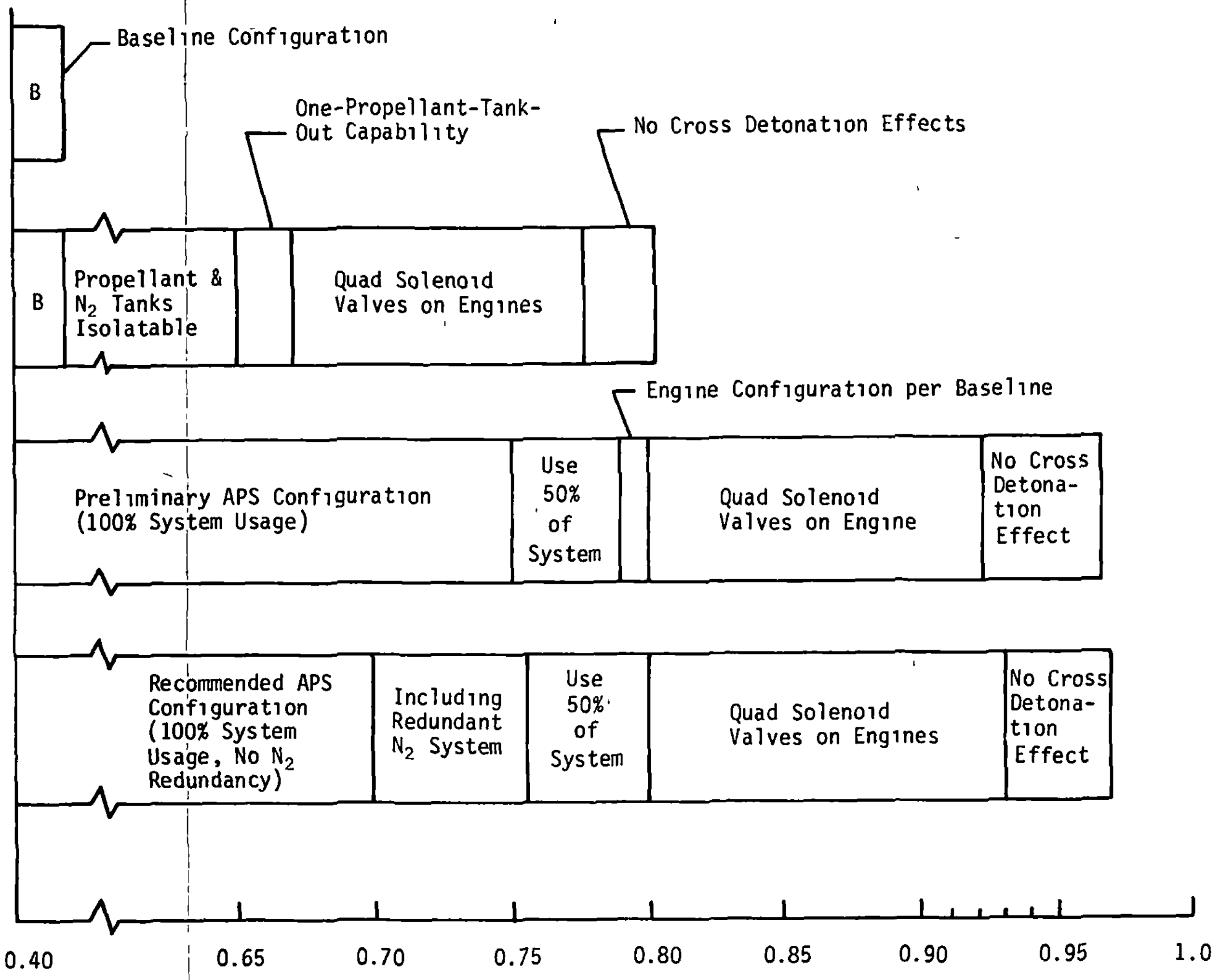


Fig. VII-7 Reliability for Various APS Configurations (Ten-Year Mission)

C. RESUPPLY CONFIGURATIONS

Reliability estimates were made of the five candidate resupply systems considered in Chapter VI (Fig. VI-1 thru VI-5). For each configuration estimates were made of the APS as well as the resupply system itself. This was necessary because in all cases some modification of the basic propulsion system is required to provide a resupply capability. Results of the reliability estimates are summarized in Tables VII-2 and VII-8, which follow. With the exception of configurations VI-4 and VI-5, the APS portion of each configuration is identical to the recommended APS configuration except for minor modifications for resupply of consumables. Configurations VI-4 and VI-5 incorporate major modification to the APS pressurization subsystems. Nevertheless, as evident in Tables VII-2 and VII-8, variations in overall system reliability are minor when comparing the various candidate resupply systems. Consequently reliability considerations did not greatly affect the selection of an *optimum* resupply system for the Space Station APS.

Table VII-8 Estimated APS Reliability

	Probabilities of Mission Success			
	One Year			
Configuration	Pressurization, P_p	Propellant System, P_s	Overall $(P_{RST})(P_p)(P_s)(P_E^*)$	Ten-Years Overall
APS VI-1	0.9997	0.9996	0.9965	0.9655
APS VI-2	0.9999	0.9996	0.9967	0.9675
APS VI-3	0.9999	0.9996	0.9967	0.9675
APS VI-4	--	0.9994	0.9966	0.9665
(with active heating system)	--	0.9983	0.9955	0.9559
APS VI-5	--	0.9989	0.9962	0.9622
(with no flow control)	--	0.9996	0.9968	0.9685

$^*P_E$ = Probability of mission success for engine modules = 0.9972/yr for all configurations.

P_s = Probability of mission success for propellant storage and transfer subsystem.

P_p = Probability of mission success for pressurization subsystem.

P_{RST} = Probability of propellant removel and servicing tool functioning = 1.0 (assumption).

The purpose of the reliability studies reported here is twofold. First, to estimate and compare the ten-year mission reliabilities of the resupply and APS configurations and secondly, to estimate the probability of a successful consumables replenishment operation.

1. Configuration Descriptions

All of the APS configurations employ one Propellant Removal and Servicing Tool (PRST) for the MMH, and one for the NTO. The design of the PRST is only conceptual at this point, therefore, an estimate of its reliability was not attempted. However, since the primary objective of the studies is to compare the various configurations, the PRST probability of functioning can be assumed a constant for all configurations and the comparisons are not affected. The PRST configuration should be nearly the same on all APS configurations. The resupply configurations are fully described in Chapter VI, however, they are briefly described below for quick reference:

Configuration	Description
APS VI-1	Regulated Pressurant Transfer Using Residuals for Propellant Transfer;
APS VI-2	Propellant Transfer by Ullage Blowdown - Pressurant Transfer by Modular Replacement;
APS VI-3	Blowdown Propellant Transfer with Modular Pressurant Transfer;
APS VI-4	Volatile Liquid Pressurized APS - a) With passive heat storage material, b) With active heating system;
APS VI-5	Blowdown APS - a) With flow control valves in propellant systems, b) Without flow control valves.

Table VII-8 presents the estimated APS reliabilities for the various configurations. This analysis assumed the following:

1) Quad solenoid valves are employed for the engines in lieu of single solenoid valves;
2) Engine modules are physically separated sufficiently to minimize engine detonation effects;

3) A standby redundant configuration and procedure is employed, i.e., only one-half the system is used at a time, consumables being replenished every six months;
4) The capability exists for inflight maintenance. Consumables and component refurbishment are available every 90 days if needed.

2. APS Reliability Comparisons

With one exception, the ten-year probabilities of mission success for all of the APS configurations which were considered are within 0.007. The one exception is alternative APS VI-4. This configuration incorporates a volatile liquid pressurization subsystem with an active heating element that detracts from mission reliability.

The probability of mission success for the recommended APS configuration is 0.9689. This is slightly higher than any of the resupply configurations. This is to be expected since the recommended configuration does not have some of the hardware refinements for consumables replenishment that the resupply configurations demand. The propellant system reliabilities for the resupply configurations are lower than that estimated for the recommended configuration, especially APS VI-4 and VI-5. The lower propellant system reliabilities of the volatile liquid systems (APS VI-4) and the blowdown systems (APS VI-5) are not offset by the elimination of a separate pressurization system. This is because of the high degree of component redundancy employed by the pressurization subsystem of the recommended APS configuration.

3. Resupply Reliability Comparisons

The estimated probabilities of a successful resupply operation are presented in Table VII-2 for each of the candidate resupply configurations. These probabilities also fall within a narrow band (0.0008), and consequently the selection of an *optimum* resupply technique was based on factors other than reliability. The assumptions employed in estimating the values in Table VII-2 are as follows:

1) The actual transfer of consumables requires ½ hr;
2) The transfer system on the logistics vehicle was functioning properly at launch;
3) The logistics vehicle is successfully docked.

D. MATHEMATICAL MODEL AND ASSUMPTIONS

The primary purpose of the reliability estimates reported above was (1) to compare systems by identifying the more favorable configurations; and (2) to indicate the areas that require the most attention and improvement. Although mission environments and functions of the APS have not been fully defined at this time, it is believed that the indicated reliability differences between systems are sufficiently accurate to permit valid conclusions. The differences remain essentially the same although the absolute system reliability estimates may vary as environments, configuration, and program constraints become more firm. The reliabilities of the various systems tend to increase or decrease together as definitions, constraints, etc, change.

Estimating the absolute numerical reliability of each configuration was a secondary objective. Hence the probabilities of failure modes or events that do not affect either the comparison of differences between systems or are numerically insignificant have not been considered. For example, the probabilities of meteoroid damage to the various configurations are essentially equal and, therefore, not considered. The same is assumed true of the Malfunction Detection System and control systems.

The mathematical models, failure rates, and assumptions are standards generally accepted by those engaged in the reliability disciplines. The product rule was used to predict the total reliability of a number of items in series. The overall reliabilities of redundant, series-redundant, active, or passive standby redundancies, etc were calculated by accepted techniques delineated in most standard texts on reliability. The failure rate of an item was allocated among the failure modes to determine the effective failure rate of an item; this allocation is particularly necessary to determine the equivalent series failure rate of redundant items. The generic failure rates were selected from the sources deemed most recent, applicable, and accurate. The majority of the failure rates were derived from among the following references or sources:

1) *Handbook of Long Life Space Vehicles Investigations (1967 and 1968)*. M-68-21. Martin Marietta Corporation, Denver Division, December 1968;
2) *Failure Rate Data Handbook*. USN Fleet Missiles Systems Analysis and Evaluation Unit;

3) *RADC Unanalyzed Nonelectronic Part Failure Rate Data,* Interim Report NEOC01. Technical Report RACD-TR-66-828. Rome ADC, December 1966;
4) *Engineering Reliability Policy and Procedures Manual.* M-63-3. Martin Denver, October 1963;
5) Titan III Reliability Studies;
6) Titan III Experience, Test Data;
7) Average of typical aerospace components.

The following basic assumptions are used in all mission success calculations. Assumptions peculiar to a particular configuration are stated in the section on that configuration:

1) The duration of the mission is ten years;
2) Double malfunctions are statistically improbable;
3) Instrumentation is configured such that failure of one sensor does not preclude calculating performance parameters;
4) An active system to cool components is not required. Active heating units are redundant;
5) The response rates of ancillary equipment such as sensors and controls are sufficiently fast enough to permit successful switchover to the backup component/system;
6) Leakage through either an engine or propellant feedline solenoid valve constitutes a failure, although they are in series. Upon detection of leakage, a switch will be made to the backup engine module;
7) All components have been checked out and are functioning properly at the start of the time period $\left(t_o\right)$ for which reliabilities are being calculated;
8) Infant mortality has been eliminated through preinstallation burn-in or operation. The cyclic/wear or calendar limits of components are not exceeded; replacement or refurbishment is allowed for all configurations except the baseline configuration;
9) The engine modules are identical for all configurations;
10) Explosion of an engine will damage the adjacent engine 50% of the time (best estimate);
11) The reliability of the control and Malfunction Detection Systems (MDS) are equal for all configurations studied.

For convenience of calculation and comparison, each system was divided into three parts as shown in Fig. VII-8: pressurization subsystem, propellant storage and transfer subsystem (S&T), and engine subsystem. The reliability of each part was calculated separately. The probability of mission success $P_{(s)}$ is as shown.

$$P_{(s)} = \left(R_p\right) \left(R_{S\&T}\right) \left[\left(R_E + 2R_E\, Q_E\right) R_D\right]^2 R_C$$

where:

R_p = probability of mission success for the pressurization system -- expressed as the series equivalent probability for redundant systems;

$R_{S\&T}$ = probability of mission success for the propellant storage and transfer system expressed as the series equivalent probability for redundant systems;

R_E = probability of mission success for one engine module containing three engines, propellant manifolds, instrumentation and connections. Proper functioning of both Module 1 (or backup) and Module 2 (or backup) is required for mission success;

$Q_E = 1 - R_E$;

R_D = probability of one engine module not detonating or the detonation not damaging at least one engine in its backup module during a mission. R_D approaches 1.0 if the modules and their backup are sufficiently separated in distance;

R_C = 1.0 = probability of mission success for controls and MDS. Equals 1.0 for comparative purposes.

The system probabilities of mission success such as R_p, $R_{S\&T}$, and R_E are calculated by applying the product rule to the reliability of each item in a system. The reliabilities of redundant items or subsystems are converted to a series equivalent reliability before applying the product rule.

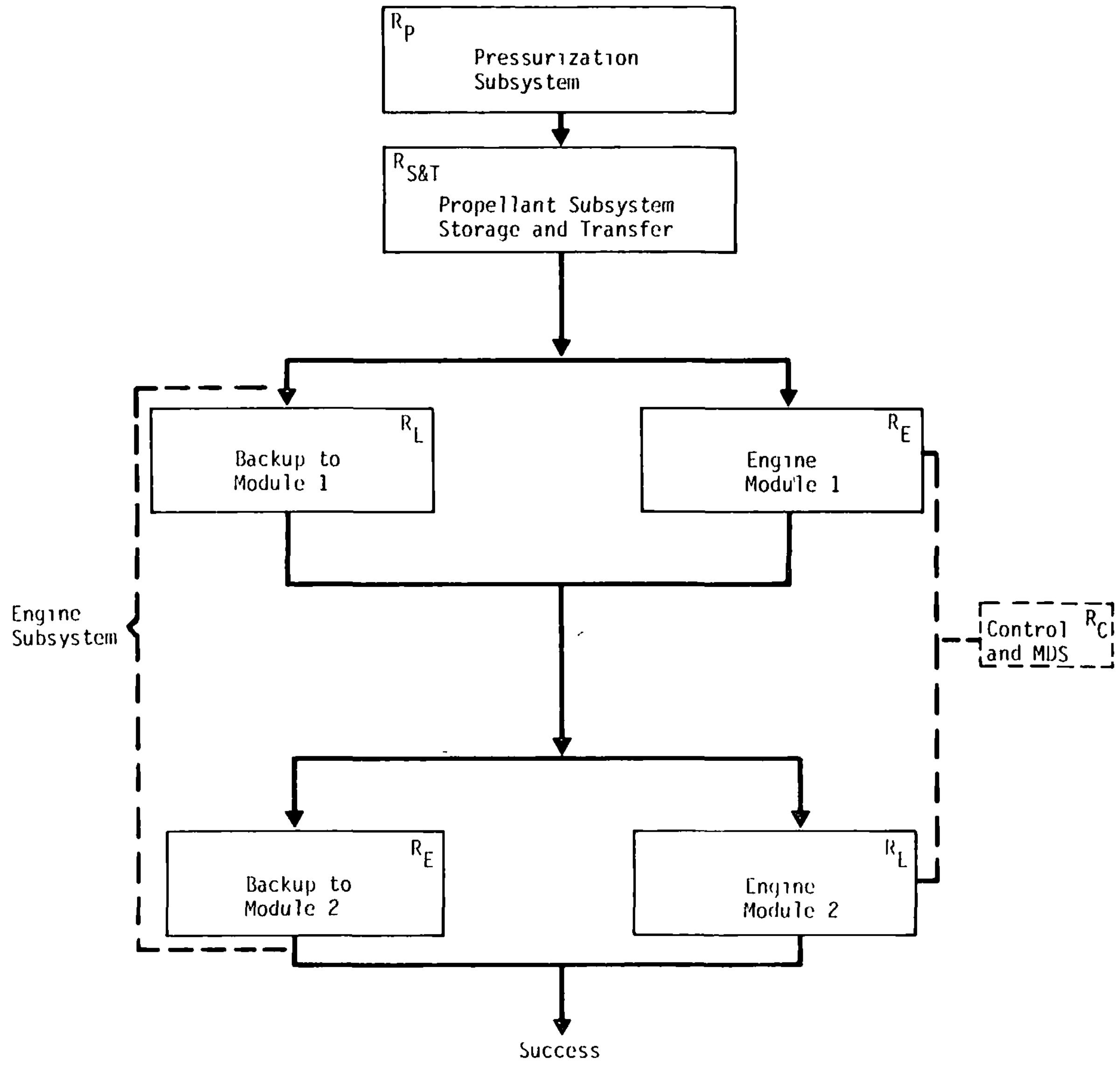


Fig VII-8 Baseline Configuration

The more general equations employed to calculate the phase failure and mission success probabilities of an item are:

1) $Q_i = K_{op} K_a G_{FR} n t_i$; an approximation of $Q_i = 1 - e^{\lambda_i t_i}$

2) $P_{(s)} = 1 - Q_T = 1 - \sum_{i}^{i=b} Q_i$; an approximation of $P_s = \prod_{i}^{i=b} P_i$

where:

Q_i = total failure probability of an item during mission phase i,

K_{op} = operational environmental modifier during phase i, during which the environments are essentially constant,

K_a = application modifier during phase i,

G_{FR} = generic failure rate,

n = number of items,

t_i = elapsed time during phase i,

λ_i = total effective failure rate during phase i = $K_{oP} K_a G_{FR} n$,

$P_{(s)}$ = probability of mission success for an item,

Q_T = total failure probability of an item during the entire mission,

P_i = probability of success for an item during phase i = $1 - Q_i$,

b = number of mission phases.

Note: The approximations of Q_i and $P_{(s)}$ are used only where the results would be accurate to the fifth decimal place.

The operational environmental modifiers $\left(K_{op}\right)$ increase the generic failure rates to account for the higher operational failure rates associated with the actual service environments encountered. Service environments are usually more severe than the benign environments under which the generic failure rates are established. The K_{op}'s are less than one during periods of nonoperation. A review of K_{op}'s employed by Martin Marietta Corporation, Aerospace Companies, and NASA resulted in the use of the following K_{op}'s that reflect the severity of the environments at various locations and mission phases.

Type Item	K_{op} for Denoted Phase		
		In Orbit	
	Boost	No APS Burn	APS Burn
Mechanical			
Operating	80	1	1
Not Operating	50	0.100	0.100
Engine Burning			
"Structure" Portion	80	N/A	1000
Valves	80	N/A	100
Engines, not Burning			
"Structure" Portion	80	0.001	10
Valves	80	0.100	10

The application/installation modifier, K_a, is used to modify the generic failure rate to account for the increase in failure rate due to installation and test effects. These effects of installation and tests vary according to class of equipment. The K_a's used are based primarily on data and experience obtained at the Denver Division of the Martin Marietta Corporation. The numerical values of those employed are:

System	K_a
Hydraulic	1.60
N_2 Pressurization	1.30
Propellant Storage and Transfer	1.20
Engine*	1.00

*K_a factor was included in engine failure rate data.

One sample calculation of the reliability of a component should illustrate the general approach. The reliability estimate of the four nitrogen spheres in the baseline configuration was accomplished as follows:

Failure Modes	Generic Failure Rate (ppm/hr)
Leakage	0.0044
Rupture	0.0352
Contaminates the System	0.0044
Total G_{FR}	0.0440 each

These spheres are always "operative" in the sense that they are always pressurized and stressed. Thus $K_{op} = 1$ during orbit, and $K_{op} = 80$ during boost. The $K_a = 1.30$ since they are part of a pressurization system. Boost time, t_1, equals 10 minutes. In orbit time, t_2 = 10 years = 87,600 hr.

$$Q_i = K_{op} \; K_a \; G_{FR} \; t_i \; n,$$

$$Q_T = Q_1 + Q_2,$$

$$Q_T = (1.30) \; (0.044) \; (10^{-6}) \left[80 \left(\frac{10}{60}\right) + (1) \; (87{,}600)\right],$$

$$Q_T = 0.0050115 \text{ each sphere},$$

$$P_T = e^{-0.0050115} = 0.99500 \text{ each sphere},$$

$$P_{(s)} = \left(P_T\right)^4 = \text{probability of all four spheres functioning for entire mission},$$

$$P_{(s)} = 0.9801.$$

When standby redundancy is employed, the following equation was employed:

$$R_b(t) = e^{-\lambda_1 t} + R_{ss}\left(\frac{\lambda_1}{\lambda_1 + \lambda_3 - \lambda_2}\right)\left(e^{-\lambda_2 t} - e^{-(\lambda_1+\lambda_3)t}\right)$$

where:

$R_b(t)$ = probability of mission success for time, t,

λ_1 = operating failure rate of primary system,

λ_2 = operating failure rate of standby system after becoming operational,

λ_3 = nonoperating failure rate of standby system,

R_{ss} = probability of switch-over to standby system.

VIII. FAULT DETECTION AND ISOLATION

As discussed in Chapter VII, Reliability, a capability for inflight maintenance is absolutely essential if the ten-year life requirements of the Space Station are to be achieved. This requirement, in turn, demands a fault detection and isolation capability that can be satisfied only by an onboard checkout system (OCS). Such a system has been designated for control, monitoring, and checkout of the integrated Space Station systems.

The major results of the study reported in this chapter are as follows:

1) The primary fault detection and isolation requirements for the Space Station APS have been identified;
2) The feasibility of an advanced OCS has been established;
3) Requirements for integration of the Space Station APS with the OCS have been identified;
4) Incorporation of an OCS for checkout and monitoring of the Space Station APS has been shown to reduce instrumentation requirements.

A. FAULT DETECTION AND ISOLATION REQUIREMENTS

The required level of fault detection and isolation will be directly influenced by the level of component replacement and repair and by the maintenance techniques used. The level of fault isolation must correspond to the lowest level of repair specified. Three possibilities were considered:

1) System end-to-end test and replacement;
2) Module level test and replacement;
3) Component level test and replacement.

Only on-line testing was considered. Bench testing and trial and error techniques do not support a continuous standby operating capability.

For the inflight maintenance plan developed in Chapter IV, a capability of fault isolation at the component level is necessary. On-line fault isolation at the component level will, in turn, require the development of an advanced OCS for reasons of mission effectiveness, reliability and safety, ground station limitations, and inflight maintenance.

1. Mission Effectiveness

Incorporation of an automatic OCS will promote mission effectiveness by providing the flight crew with sufficient performance information so that the mission can be adjusted as necessary to adapt to unique problems as they occur. The OCS will also provide a means for effective operation of marginal equipment through interpretation of calibration data. Propulsion system data can be validated by calibration before, during, and at the completion of each maneuver. Before each maneuver, maximum assurance of a successful operation will be provided by assessing the system status before commitment. Test integrity is improved by on-line, real-time calibration. A means of determining resupply requirements will also be available before the logistics vehicle is launched.

2. Reliability/Safety

The OCS will alert the flight crew in real time to performance degradation or system malfunction so that corrective action or alternative operating modes can be implemented. System performance can be verified before each operation and performance repeatability can be established immediately afterwards. Operational status can also be verified immediately following maintenance or resupply operations.

Long life reliability is achieved by providing the capability to isolate faults to the required level for component or modular replacement. A key factor with respect to safety and reliability is that fault isolation is achieved in real time and under actual operating conditions. This allows immediate response by one of the following actions:

1) Computer-initiated automatic switching to a replaceable spare;
2) Computer-initiated automatic switching from a redundant to simplex mode;
3) Manual switching or replacement of the failed module;
4) Subsequent failure analysis and correction for follow-on flights.

Here, immediate response is the key characteristic of an OCS.

An automatic checkout capability also reduces the required crew training and improves crew performance by reducing or eliminating routine monitoring tasks. The number of onboard displays that require continuous on-line presentation is also reduced. Because of the added depth of system interrogation, control can be expanded to such functions as automatic sequencing, control of the propulsion systems operation, and data management.

3. Ground Station Limitations

An OCS can provide onboard data reduction to relieve potential ground station overloads. Since accessibility to data handling ground stations is only periodic, fault isolation may not always be possible, particularly for intermittent failures. Also test requirements may be compromised due to transmission limitations or priorities. For a ten-year mission the level of system monitoring required will also be prohibitively expensive if ground station monitoring is used as the primary mode.

4. Inflight Maintenance

An OCS provides rapidly accessible instructions for troubleshooting and repair procedures that are keyed directly to the test and monitor operations. This will reduce the reaction time required to isolate and correct faults. Continuous trend analysis will be possible, allowing prediction of performance degradation and impending failures.

B. ADVANCED CHECKOUT SYSTEM CONCEPT

An advanced, automatic, OCS is necessary to satisfy the fault detection and isolation requirements of the Space Station APS. As a consequence, an advanced checkout concept was developed during the study to demonstrate the feasibility of an OCS for application to the Space Station APS. The major characteristics of this system are discussed in this section. The functional units of the system are described along with operation and performance characteristics.

The checkout system concept, as depicted in Fig. VIII-1, is a general data system that can process performance data and experimental data, and can initiate command data. The concept comprises (1) a man interface; (2) the checkout system; and (3) the system in test.

1. Man Interface

The man interface provides the initial or final evaluation of system performance, and also provides the necessary decisions. These man interface functions can be executed by initiating one or more of the following options:

1) Enable monitor;
2) Select checkout sequence;
3) Start and stop points and bypasses;
4) Enable step by step or automatic checkout;
5) Halt monitor or checkout;
6) Enter new test;
7) Modify existing test.

2. Checkout System

The checkout system provides the functions of data acquisition, data processing, and display of results.

During data acquisition, signal conditioning equipment ranges and/or formats the electrical quantities of subsequent processing. The signal conditioning equipment may be a part of the checkout system or part of the system under test.

The data processing function consists of processing three types of data: performance data, experimental information, and initiate command data. Performance data are necessary to evaluate the performance of the system under test, while experimental information are necessary for trend analysis, curve fitting, and mathematical manipulations. "Initiate Command" data are the instructions issued by the checkout system for command and control of the evaluation of the system under test. Data are processed in two function steps.

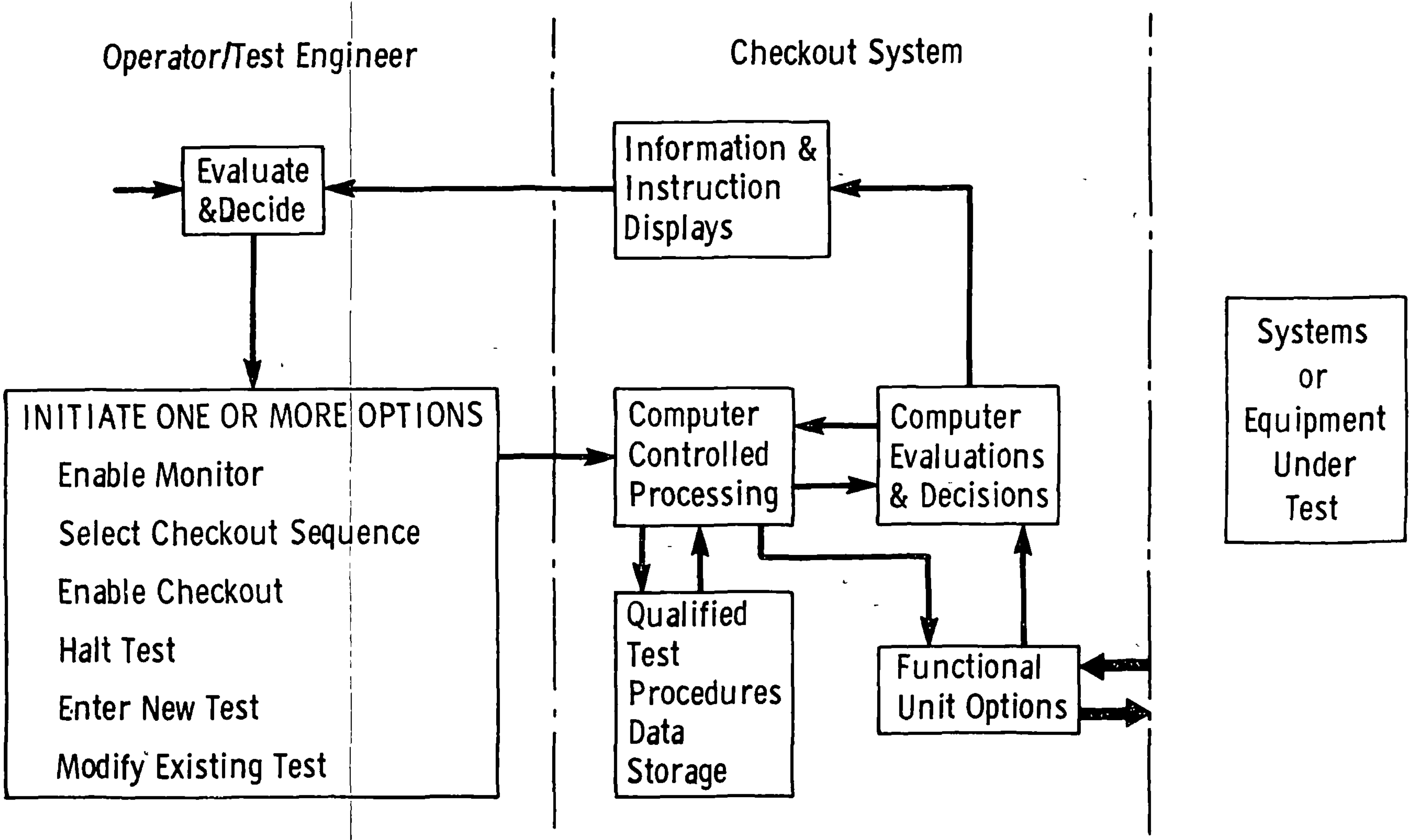


Fig. VIII-1 Onboard Checkout Systems Concept

The first data processing function may take the form of data compaction and/or data evaluation. For experimental information, the emphasis is placed on the accumulation of meaningful data, therefore, data compaction is desired. Data are compacted by eliminating redundant information and meaningless zeros and by data rearrangement. However, limits can be set up, which if exceeded, will result in automatic display to the crew for evaluation and command action.

For performance data, the emphasis will be placed on comparing results against stored limits which, if exceeded, will cause automatic displays and/or commands. The commands will alert the crew to take corrective action to restore system integrity. If of a critical nature with respect to reaction time, the commands can be automatic. The data are then stored in the form of change information oriented to a time base. The data can be stored totally onboard, totally within the ground network, temporarily onboard, permanently on the ground, or any combination of these alternatives.

The second processing function provides the longer term reduction of the data that includes trend analysis, curve fitting, mathematical manipulation, and cleanup operations such as noise removal and presentation formatting. Rate of change limits can be established which when exceeded will result in automatic displays and/or commands. Tabulated or displayed data will be provided to the crew on call and on a periodic basis for evaluation and required command action.

The Onboard Checkout System (OCS) combines the versatility of an Airborne Digital Computer (ADC), the flexibility of peripheral hardware, the adaptability of test oriented and interpretive software, and the capability of a technician to perform the following functions:

1) Sequence a series of predetermined mission operations, as required;
2) Determine the performance status of the interfacing APS system by periodic monitoring, by end-to-end checkout, and by system interrogation;
3) Analyze the performance of the APS system by accomplishing the necessary computations, by comparing the results with prestored standards, by evaluating the significance of the results, and by deciding subsequent action;

4) Accomplish the necessary control over the operations of the APS system, either as a part of normal operations or as dictated by emergency conditions, by initiating start/stop functions, by switching to alternative equipment systems, and by communicating results/decisions for operator knowledge and/or action.

OCS System Description - The OCS itself will comprise the following units that are shown in the functional diagram, Fig. VIII-2.

Airborne Digital Computer (ADC) - The ADC contains mission-oriented programing, decision making, data processing, and sequencing information.

Data Interchange and Control Unit (DIACU) - The DIACU is an input/output timing unit that comprises the single inter/intra-system interface and, as such, provides data formatting, signal level conversion, and timing. In providing for interface conversion the DIACU must accomplish the following functions:

Perform logic level conversion;

Perform serial-to-parallel conversion for computer operations;

Perform parallel-to-serial conversion for other unit operations;

Perform computer word packaging;

Verify proper receipt of transmitted data;

Control application of power to other units when changing between standby and operate modes;

Provide interface capabilities with ground equipment and space station systems.

Stimulus Generator Unit (SGU) - The SGU is a programable signal generator that converts digital data into the required type and level of stimulus or command signal.

Measurement Unit (MU) - The MU is a signal scaler/digital converter that converts the performance and experimental data into digital format. The MU performs the following data manipulations and conversions:

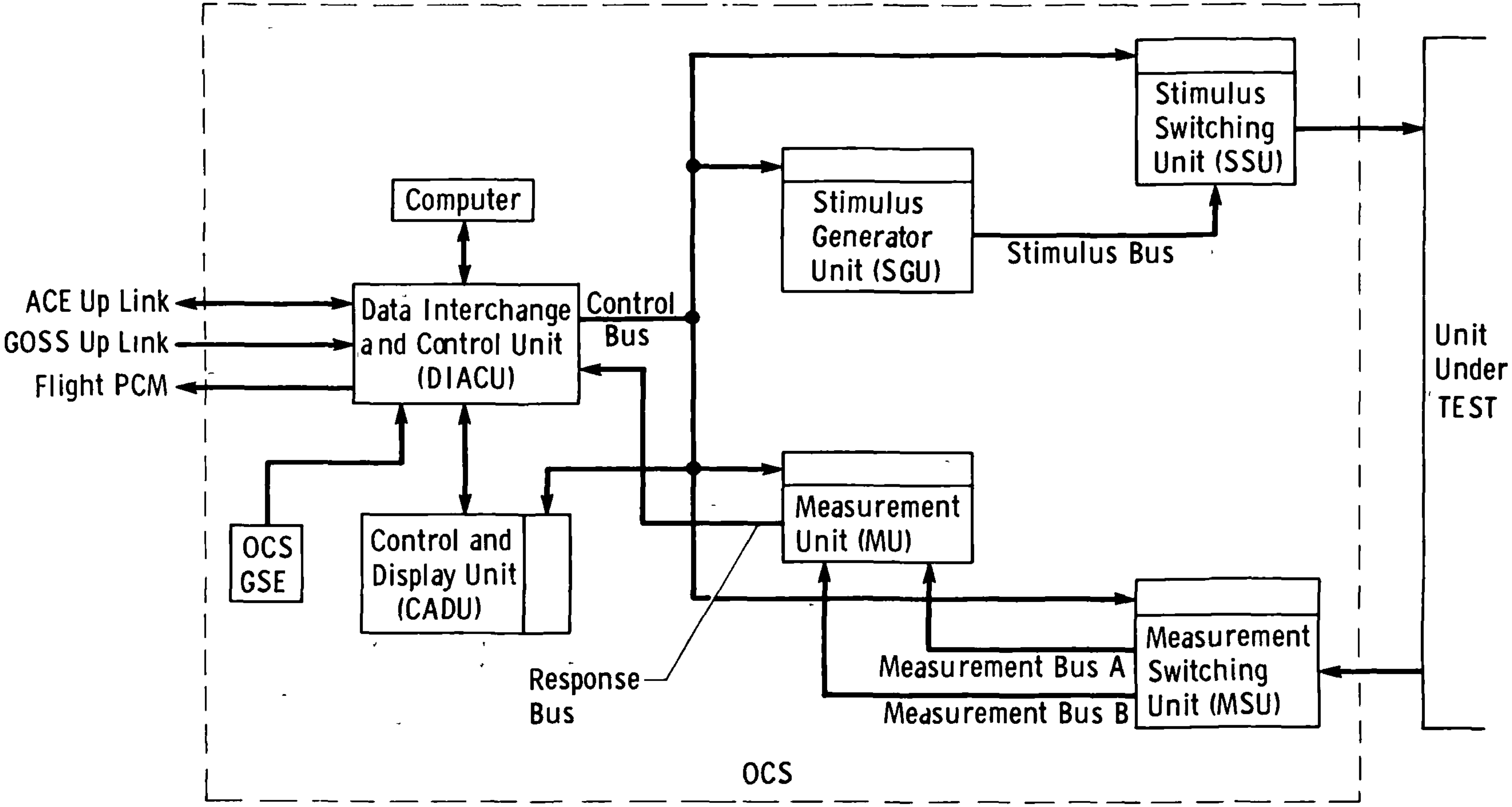


Fig. VIII-2 OCS General Block Diagram

DC voltage to digital;

AC voltage to digital;

Detects discrete voltage levels;

Detects contact closure;

Converts signals carrying time information to digital data;

Recovers a low frequency modulation signal from an AC carrier and converts to digital.

Stimulus and Measurement Switching Units (SSU-MSU) - The SSU and MSU are remote switching units that route signals between the OCS and the system under test (APS) or supporting control systems (ACS).

Control and Display Unit (CADU) - The CADU enables the operator to initiate checkout operations, diagnostics testing, and experiment information processing that might also be programed for periodic accomplishment; revise stored computer operations or add new operations; and present critical performance data on a continuous basis, "exceptional" results, trend data, and specifically requested data.

Each unit in the OCS is addressable and receives instructions from a common control bus. The address and accompanying instruction is recognized by the proper unit, an error check is performed, and a verification signal is transmitted. The transmission of verification responses and requests for data are accomplished by a common response (data) bus. The transmission of signals to and from the remote switching units is by a common stimulus or measurement bus.

OCS Software - The OCS software is a test oriented interpretive system that effectively bridges the flight communications with the checkout equipment. The software consists of an airborne system and a ground system.

Ground System - The ground system provides the means for translating test engineer documented test procedures into a set of test descriptions for loading into the airborne computer memory. Test procedures comprise a sequential set of general test elements (e.g., stimulate, measure, sense, delay, compare, transmit, display, etc). These elements are modified to specify applications with the assignment of values and test application points (test data).

The airborne system comprises:

Supervisory/Control Program - This program is that set of processing routines used for control and processing of the OCS operating status, modes, and functions during normal system operation;

Utility Programs - Waveform generation, input/output operations, etc;

Test Orders - These orders provide test element subroutines for the test descriptions produced by the ground system.

OCS Characteristics - Listed below are the characteristics of the present OCS being developed by Martin Marietta for NASA-Houston under NASA Contract NAS9-8000. Although this system has less capacity than will be required by the integrated Space Station systems, the data shown are representative of a "500 tests" capacity system.

Power (avg.) - 0.165 kw-hr/mission day;

Average Heat Dissipation - 12.2 watts;

Reliability - 0.995 goal for 90-day mission;

Test Capacity - 500 separate tests;

Computer Memory Size - 24 K words (32 bits/word)

Mean Time to Repair - 0.25 hr/occurrence exclusive of EVA repairs;

Duty Cycle - 3.6% to 4.2% of mission time;

Maintainability - Replace modules - total of 105 modules, 62 different configurations;

Data transfer Rates - 1/30 sec, 14.2 bits/occurrence average, 1 M bits/sec.

The OCS measurement characteristics are tabulated in Table VIII-1, and stimulus characteristics are indicated in Table VIII-2.

OCS Operation - The OCS operations are divided into performance data processing, command data processing, and experimental information processing.

The performance evaluaton of an APS interfacing system comprises a sequential series of individual tests that will verify the system's operability. Monitor, checkout, and diagnostics testing, listed in the order of increasing depth of interrogation, are encompassed within the function of performance data processing.

Table VIII-1 OCS Measurement Characteristics

Measurement	Range	Accuracy
AC Voltage (Sine Wave, Square Wave, Triangle Wave)	50 mV to 40 V Peak	±1%
Frequency	0.1 Hz to 1 MHz	±0.1%
Time (Time Interval, Pulse Width)	5 sec to 10 min	±0.1%
Phase Delay	0.1 Hz to 100 KHz	±0.1%
DC Voltage	50 mV to 40 V	±1%
Discretes	2 V to 32 VDC	±5%
Contact Closure	Logic Decision	--
Digital Data (Serial or Parallel)	RZ or NRZ	--
PCM	8 bits/word to 40 bits/word, 40 bits/sec to 64K bits/sec	

Table VIII-2 OCS Stimulus Characteristics

Stimulus	Range	Tolerance
AC Voltage (Sine Wave, Square Wave, Triangle Wave)	50 mV to 40 V Peak	±1%
Frequency	0.1 Hz to 1 MHz	±1%
DC Voltage	50 mV to 40 V	±1%
DC Current	1 ma to 250 ma	±2%
Discretes	2 V to 28 VDC, 50 ma Simultaneous Supply	±5%
Voltage Pulse	5 sec to 1 sec	±1%
Current Pulse	5 sec to 1 sec	±2%

A typical checkout or diagnostics test would proceed with a computer instruction to close a particular switch in a remote switching unit. The next instruction would be to the signal generator to supply a specific signal to the common bus, which then would apply the stimulus to the particular point desired in the APS. A remote switching unit would then be directed to connect a specific test point to the MU (signal scaler/digital convector) for conversion to digital format and serial transmission along the periodic response but to the DIACU (Input/output/timing unit). Signal level conversion is accomplished and response data are sent to the computer. The computer would then make a decision based on an evaluation of the response. This decision might be to proceed to the next test, store the results as change data, go into "standby" mode, perform a diagnostics test sequence, alert the crew, or initiate a correction command. The monitor operation is performed passively, negating the requirement for stimulus application, consequently the first two steps of the checkout test are thereby excluded. A particular type of monitor operation, such as continuous and direct display, would be routed over the continuous response but to the CADU instead of the computer.

Command data processing comprises the first two types of steps described for the checkout test and will provide excitation of some element or elements in the APS or supporting systems, Guidance Control (GC) and Electrical Control System (ECS).

The experimental information processing encompasses the same functions as the checkout test, with two exceptions: the first two steps are excluded, and the data are routed over the continuous response bus to the bulk storage unit instead of the computer. On a periodic basis, perhaps concurrently with the monitor cycle, the computer compares the new data with previous data also stored in the bulk storage unit, updates the file with change data, and eliminates redundant and meaningless data. Should a rate of change limit be exceeded, the computer makes a decision to initiate a correction command and/or alerts the operator. Mission requirements or storage limitation may dictate direct transmission of some types of data over the telemetry link instead of to the bulk storage unit. Functions such as curve fitting and trend analysis can be accomplished by the computer performing further data processing on performance data and experimental data, and the results can be displayed or correction commands initiated.

The OCS has two functional states: standby and operating. In the standby state all power is turned off except that power required for timers in the DIACU; circuits needed to bring the system up to the operating state; isolated circuits that process the experimental information and continuous display data. In this manner a limited number of circuits are isolated for special reliability emphasis. The system can be changed from standby to operating, by a programable time or by external command. In the operating state, the OCS can perform a programable periodic monitor operation or a periodic or requested checkout operation concurrently with experimental data and direct display data processing.

The OCS has three operating modes: automatic, semiautomatic, and manual.

Automatic Mode - In the automatic mode a complete series of tests is commanded and cycled through until the last selected test is completed. If a malfunction is detected, a specific group of tests are performed to isolate the fault to a failed module. After the fault has been isolated, the OCS will stop and display pertinent information. The operator may restart the sequence if so allowed by the program.

Semiautomatic Mode - This mode is very similar to the automatic mode in that a series of tests is commanded. However, when enabled, the tests proceed one at a time. After each single test is completed, the next test is called up but is not performed until the operator enables it. This allows the operator to step through a test sequence and view actual test values as well as NO/GO status.

Manual Mode - In the manual mode the operator may perform a single test, accomplish emergency control of OCS, revise an existing test, or construct a new test.

3. System under Test

In the system under test, a sensor, which is an integral part of the system, converts some physical quantity such as temperature, pressure or mass quantity into an electrical quantity. Where the system output is electrical, sensing is normally obtained directly from the component.

C. OCS INTEGRATION TASKS

Use of an advanced OCS for control, monitoring and checkout of the APS makes it necessary to integrate the OCS and APS functions. In turn, integration of the two systems requires that the tasks listed below be accomplished. To demonstrate the feasibility of incorporating the APS requirements into the OCS function, these tasks were completed for the modified baseline APS and the advanced OCS previously described.

1. Failure Modes and Effects Analysis

This analysis (Tables VIII-3, -4, and -5) was performed to determine those hardware items contributing most to system unreliability and crew safety problems. In addition, the level of criticality for each component is established, based on functional analysis of the system.

2. Determine Instrumentation Requirements

In determining the instrumentation requirements, the tendency is to monitor every aspect of the system under test. However, by taking advantage of the real time, on-line checkout capability of the OCS, as well as its ability to provide trend analysis and continuous diagnostic evaluation of the system, instrumentation requirements can be maintained at a reasonable level. In fact, incorporation of an onboard checkout capability was found to reduce the baseline APS instrumentation requirements by approximately 40%, from 90 to 50 sensors. Fig. VIII-3 illustrates the optimized instrumentation required by the modified APS for integration with the advanced OCS.

3. Fault Isolation Flow Diagrams

This task involves the definition of the sequence of events necessary to detect and locate malfunctions. This sequence of events consists of operator and/or OCS actions and/or decisions. Events are a series of cue and response actions between OCS and the APS. The fault isolation flow diagrams for the APS system test, APS dynamic test, and the pressurant standby checkout are shown in Fig. VIII-4, -5, and -6.

4. Develop Test Sequences

During this task the flow diagrams are translated into test sequences that are sequential groups of single tests required to test the performance aspects of the APS. These test sequences are developed from the performance characteristics of the APS system. The performance characteristics required are:

1) Mission profile;
2) Timing sequences;

3) Parametric values and tolerances;
4) Interfaces within the APS and with the supporting systems (GC, ECS).

5. Develop Crew Maintenance and Repair Procedures

As discussed in Chapter IV, Inflight Maintenance, detailed procedures are required for each maintenance and repair function. These procedures are programed and stored by the OCS for immediate reference by the crew and are directly keyed to the appropriate failure analysis.

Table VIII-3 Failure Modes, Pressurization Subsystem

POTENTIAL FAILURE		FAILURE MANIFESTATION	FAILURE MODE	PERFORMANCE MONITOR	DIAGNOSIS
HIERARCHY LEVEL	PROBABILITY OF SUCCESS FOR 1 YEAR				
1 Pressure Regulators	0 9938	1. No Fuel and/or Oxidizer Flow 2. Low Engine Performance or no Engine Ignition 3 Leakage	Regulator a) Filter 1. Clogged 2. Leakage 3. Rupture b) Main Sensing Poppet 1 Fail Open 2. Fail Closed 3. Improper Regulation 4. Instability 5 Leakage c) Module Structure 1. Leakage 2. Rupture	1. $P_{N_2}-P_{N_2O_4}$ or P_{MMH} = ΔP_G 2. P_{N_2} and T_{N_2} (Mass) 3. P_{N_2} and T_{N_2} (Mass) 4. $P_{N_2O_4}$ and P_{MMH} 5. $P_{N_2O_4}$ and P_{MMH} 6. $P_{N_2O_4}$ and P_{MMH} 7 $P_{N_2O_4}$ and P_{MMH} 8 P_{N_2} and T_{N_2} (Mass) 9. P_{N_2} and T_{N_2} (Mass) 10. P_{N_2} and T_{N_2} (Mass)	1. Evaluate ΔP_G 2. Compare PV = MRT to Trend Limits 3. Is $P_{N_2O_4}$ or P_{MMH} High? 4. Is $P_{N_2O_4}$ or P_{MMH} Low? 5 Is $P_{N_2O_4}$ or P_{MMH} Steady? 6. Is $P_{N_2O_4}$ or P_{MMH} Pulsating? 7 Compare PV = MRT to Trend Limits 8 Compare PV = MRT to Trend Limits
2 N_2 Spheres	0 9979	1 Leakage	Sphere Structure a) Worn Seals b) Rupture due to Wear-out or Corrosion Stress	1 P_{N_2} and T_{N_2} (Mass)	1 Compare PV = MRT to Trend Limits 2. Sound Alarm when Nearing Empty Condition
3 Resupply Filters	0 9992	1 No Pressurant Flow 2 Leakage 3. Resupply Impossible	a) Filter Clogged b) Rupture c) Contaminant	1. P_{N_2} 2. P_{N_2} 3. P_{N_2}	1. Monitor P_{N_2} during Resupply 2 Is P_{N_2} Increasing?
4 Burst Discs	0.9999	1 Partial Loss of Pressurant 2. Gross Contamination of Relief Valve 3. No-Over Pressure Relief 4 Leakage	a) Premature Rupture b) Improper Performance (No rupture) c) Produced Gross Contamination	1 P_{MMH}	1 Inspect Disc Visually 2. Is P_{MMH} Staying Continually High?
5 Relief Valve	0 9999	1 Total Loss of Pressurant 2 No-Over Pressure Relief	a) Fail Open b) Fail Closed	1 P_{MMH}	1 Is P_{MMH} Low? 2. Is P_{MMH} High?
6 Low Risk Components					
A Check Valves	0 9994	1 Loss of Pressurant 2 Leakage	a) Rupture b) Worn Seals	1 P_{N_2}	1 Monitor Quiesent Pressure of Sphere
B Joints	0 9995				
C Lines	0 9998				
D Quick Disconnects	0 9999				

Table VIII-4 Failure Modes, Propellant Subsystem

POTENTIAL FAILURE		FAILURE MANIFESTATION	FAILURE MODE	PERFORMANCE MONITOR	DIAGNOSIS
HIERARCHY LEVEL	PROBABILITY OF SUCCESS FOR 1 YEAR				
1. Tanks A. Shell B Bellows	0.95380	1. Loss of Propellant 2 Low Performance of Engine or No Ignition 3. Resupply Not Possible	A. Shell 1. External Leak 2. Rupture B. Bellows 1. Pressurant mixed with Propellant (Rupture or Puncture) 2. No Expulsion (Bellows Stuck)	1. Quantity Level Sensors (Mass) 2. Gas Analyzer	1. Compare Quantity to Trend Limits 2. Is Pressurant Ingested with Propellant?
2. Filters	0.99860	1. No Propellant Flow 2. Leakage	1. Clogged 2. Leakage Due to Worn Seals 3. Rupture 4. System Contaminated (Element Failure)	1. ΔP Across Filter 2. Quantity Level Sensors (Mass)	1. Is ΔP Across Filter Approaching 80% of Maximum Contamination? 2. Compare Steady State Quantity to Trend Limits
3 Transducers A. Pressure B Temperature	 0.99870 0.99870	1 Improper Data Input 2 Leakage	1. Sensing Element Shorted 2. Sensing Element Open 3. Out of Calibration 4. Leakage Due to Worn Seals	1. E, voltage 2. I, current 3. Quantity Level Sensors (Mass)	1 Is E = 0? Implies a short 2. Is I = 0? Implies an Open Circuit 3. Are Instruments Within Calibration Limits? 4. Compare Steady State Quantity to Trend Limits
4 Quick Disconnects (Fill and Vent)	 0.99970	1. Loss of Propellant 2. Leakage 3. Resupply Not Possible	1. Rupture 2. Leakage Due to Worn Seals	1. Quantity Level Sensors (Mass)	1. Compare Steady State Quantity to Trend Limits
5 Low Risk Components A Joints B. Lines C. System Structure D. Quantity Sensors	 0.99980 0.99991 0.99993 0.99995	1. Leakage 2. Leakage 3. Affected by Boost Phase Only 4. Improper Data Input	1. Rupture 2. Rupture 3. Misalignment Due to Vibration 4. Jammed Bellows 5. Open Electrical Connection	1. Quantity Level Sensors (Mass) 2. Quantity Level Sensors (Mass)	1 Compare Steady State Quantity to Trend Limits 2. Compare Steady State Quantity to Trend Limits

Table VIII-5 Failure Modes, Propulsion Subsystem

POTENTIAL FAILURE		FAILURE MANIFESTATION	FAILURE MODE	PERFORMANCE MONITOR	DIAGNOSIS
HIERARCHY LEVEL	PROBABILITY OF SUCCESS FOR 1 YEAR				
1. Engine Module (3 each Engines)	0.9052	1. No Thruster Ignition 2 Irregular Ignition and/or Burn 3 No Thruster Shutdown 4. Explosion 5. Nozzle Rupture 6. Leakage	1. Engine Solenoids Failed Close 2. Injectors Clogged 3. No Pressurant 4. No Propellant 5. Filters Clogged 6. Delayed Feeding of one Propellant 7. Gas Ingestion 8. Throat Errosion 9. Engine Solenoids Failed 10. Electrical Control System Failed 11. Improper Propellant Feed 12. Excessive Heat 13. Worn Seals 14. Rupture	1. Coil Current 2. Chamber Pressure 3. P_{N_2} 4 ΔP Across Filter 5. Gas Analyzer 6. Coil Current 7. Voltage Across Coil 8. Thruster Temperature 9. Inspect System Physically for a) Leaks (Detector) b) Thruster Condition c) Tank Ruptures	1. Is Current On or Off Continuously? 2. Is P_{N_2} Low? 3. Is ΔP Across Filter Approaching 80% of Maximum Contamination? 4. Is Pressurant Ingested with Propellant? 5 Is Current On or Off Continuously? 6. Is Voltage On or Off Continuously? 7. Is Thruster Temperature Within Limits?
2. Thermal Control System 3. Heating Unit	0.9993 0.9997	1. Frozen Lines 2. Heat Soak Back	1. Heater Coil Open 2. Thermostat Control Failed Open 3. Electrical Control System Fail Open 4. Heater Coil Shorted 5. Thermostat Control Failed Close 6. Electrical Control System Failed Close	1. Feedline Temperature 2. Feedline Pressure 3. Heater Coil Current 4. Thermostat "On-Off" Indication 5. Electrical Input to Heater	1. Is Feedline Temperature within Limits? 2. Is Feedline Pressure within Limits? 3. Is Heater Current On or Off Continually?
4 Low Risk Components					
A. Temperature, Transducer B Pressure, Transducer C. Lines and Joints D. Filters E Line Couplings F. Structural Support	0.9999 0.9999 0.9999 0.9999 0.9999 0.9999	1. Improper Data Input 2. Leakage 3. No Propellant Flow 4. Structure Affected by Boost Phase	1. Sensing Element Shorted 2. Sensing Element Open 3. Transducers Out of Calibration 4. Filters Clogged	1. E, Voltage 2. I, Current 3. Δ P Across Filters	1 Is E = 0? Implies a short 2. Is I = 0? Implies an open circuit 3. Are Instruments within Calibration Limits? 4. Is ΔP Across Filters Approaching 80% of Maximum Contamination?

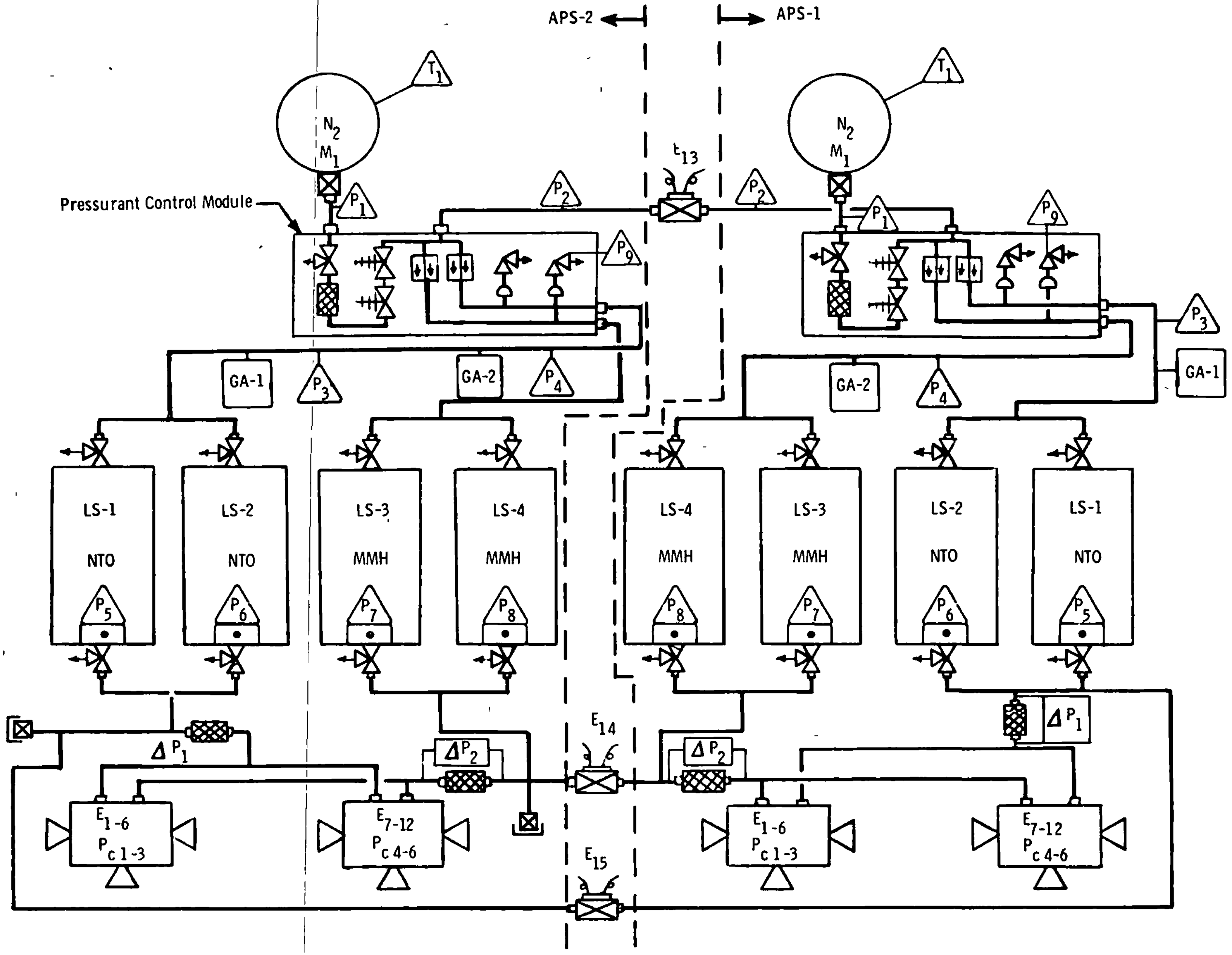
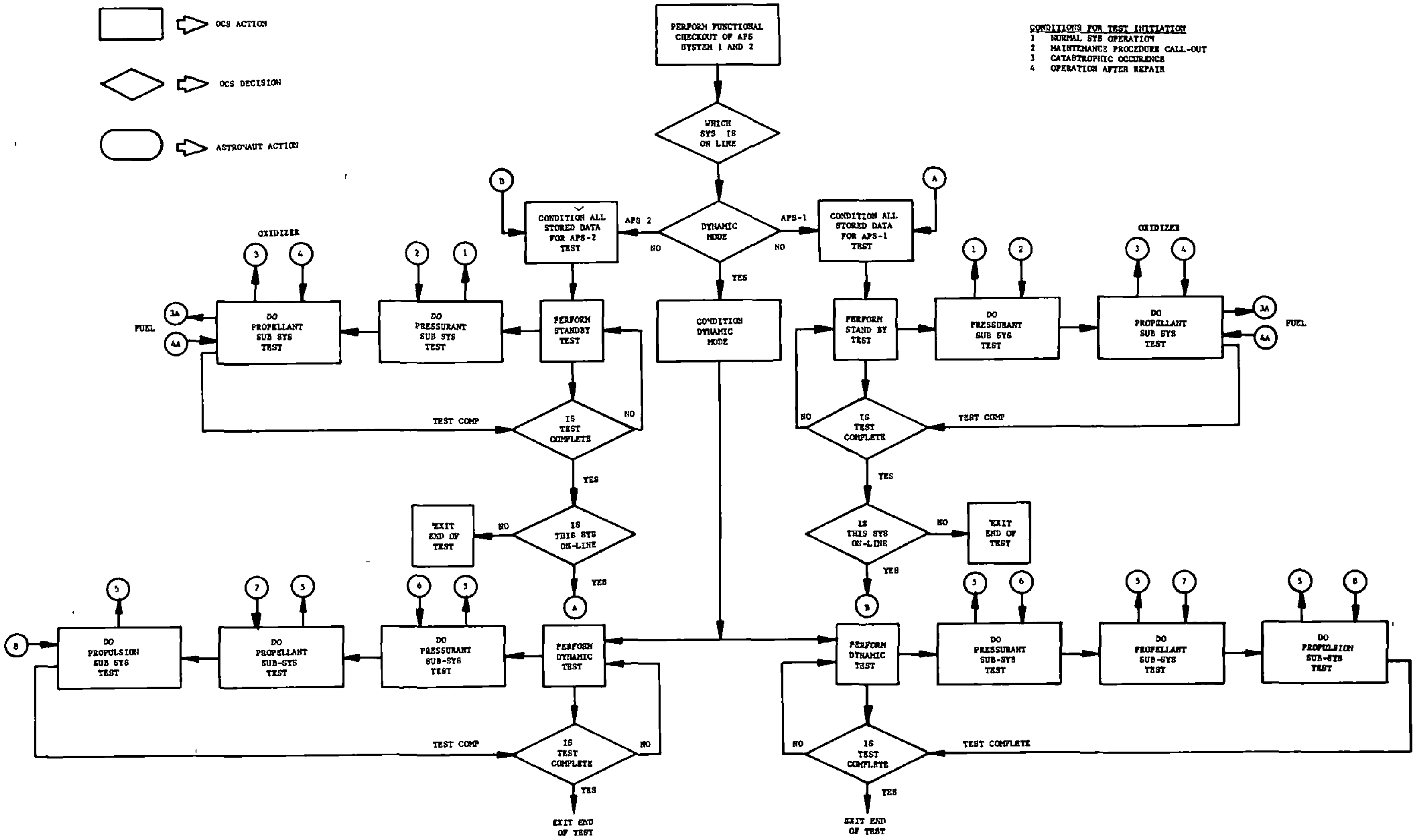


Fig. VIII-3 Instrumentation Requirements



CONDITIONS FOR TEST INITIATION
1 NORMAL SYS OPERATION
2 MAINTENANCE PROCEDURE CALL-OUT
3 CATASTROPHIC OCCURENCE
4 OPERATION AFTER REPAIR

Fig. VIII-4 APS Test Flow Diagram

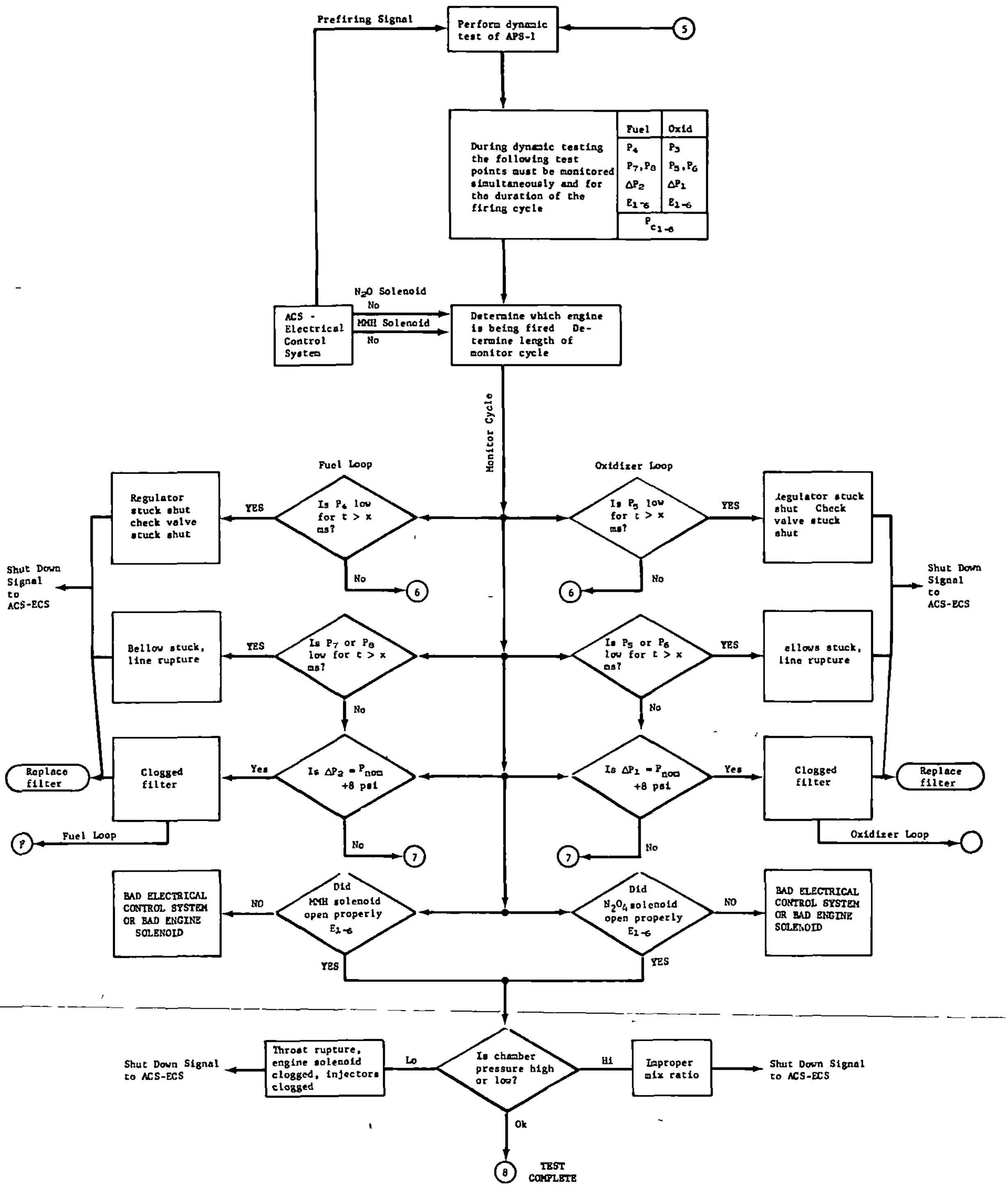
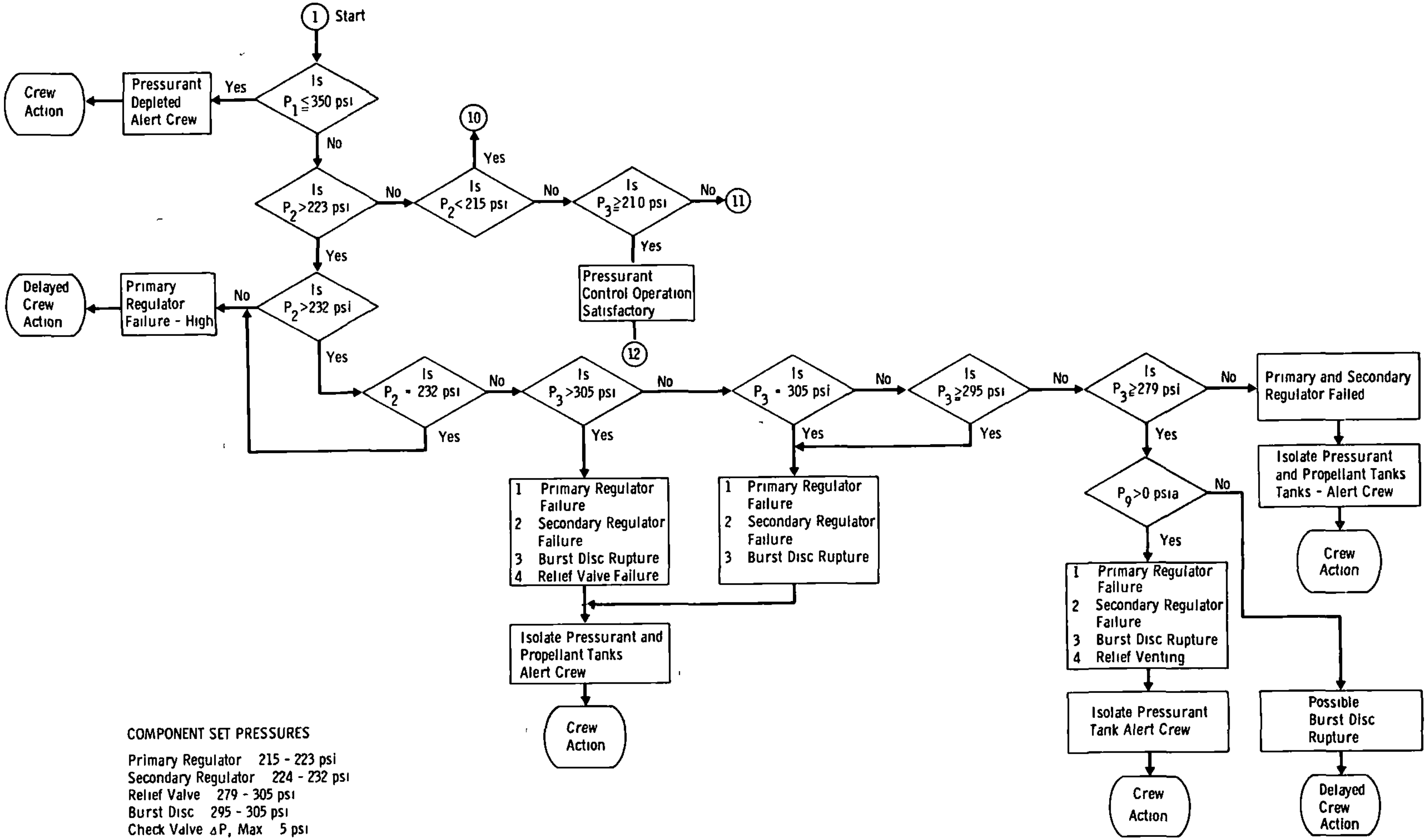


Fig. VIII-5 Fault Isolation Logic Diagram, APS Dynamic Test



COMPONENT SET PRESSURES

Primary Regulator	215 - 223 psi
Secondary Regulator	224 - 232 psi
Relief Valve	279 - 305 psi
Burst Disc	295 - 305 psi
Check Valve ΔP, Max	5 psi

Fig. VIII-6 APS Pressurant Standby Checkout

IX. SAFETY GUIDELINES

Adequate safety provisions is one of the most critical parameters in the ability to repair or replace components in a Space Station propellant system. The following criteria and guidelines must be considered for safe operation and maintenance of the Space Station auxiliary propulsion system. This analysis only considers those items that are peculiar to resupply and repair of the Space Station Auxiliary propulsion system. It does not denote common safety criteria that should be considered in the design, build, and operation of any propulsion system for a manned mission. The safety guidelines are as follows.

1) The system shall be designed so that no single failure, other than primary structure, will cause a fatality to personnel.

2) No single failure shall cause an abort of the mission.

3) Equipment that is critical to system performance shall have redundancy to prevent a single mode of failure.

4) High-pressure vessels, volatile gas, or propellant tanks shall be located outside of and as remotely as possible to crew living and operating areas.

5) High-pressure vessels and propellant tanks shall be located within a compartment, normally at a lower pressure than the Space Station. The compartment must be capable of being pressurized for maintenance activities.

6) The propellant and high-pressure gas compartment shall relieve or vent to atmosphere, in the event of an overpressure within the compartment.

7) Provisions shall be made to preclude the leakage of propellant vapors into the Space Station.

8) The NTO and MMH propellant storage compartments shall be either separated or shall have a leaktight pressure barrier between the two.

9) Astronaut EVA shall be minimized and in general used for emergency conditions only.

10) The astronauts shall wear protective clothing when opening or performing maintenance on a propellant system. The clothing shall be propellant compatible.

11) Equipment, fittings, and connections shall be designed so that the fuel and oxidizer equipment, parts, fittings, and connections cannot be interchanged or connected.

12) Propellant removal equipment shall provide a positive indication of safe toxic levels before component removal from the system.

13) The propellant storage compartment shall have indicators to provide the astronaut an assessment of toxicity and pressure levels within the compartment.

14) Provisions shall be made in the design of the compartment to contain, isolate, and control major propellant spills.

15) All materials located within the propellant storage compartment shall be compatible with the propellant stored.

16) The propellant compartment shall have provisions for a flow of air through the compartment when maintenance is being performed on the system. The flow shall be from the compartment to the exterior of the spacecraft.

17) Individual emergency self-contained oxygen supplies shall be located in close proximity to the propellant system. They shall be designed so that they may be connected to the central oxygen distribution system.

18) Instrumentation shall be provided to indicate NTO and MMH toxicity levels on the Space Station level where the propulsion system is located.

19) Interlocks, automatic valves, or other means of isolation shall be provided in the Space Station atmosphere distribution system to prevent the distribution of toxic vapors throughout the Space Station in the event of a major spill.

20) All systems shall be leak checked after maintenance repairs have been performed, and before system activation.

21) High-pressure gaseous storage containers shall be vented before transport back to earth.

22) Propellant tanks and equipment shall be decontaminated to MAC levels before transport to earth. If this procedure is not compatible, the tanks or components shall be drained and purged of the bulk liquid and transported in sealed reinforced containers.

23) Reinforced protection shall be provided for tanks that are either pressurized or contain toxic fluids, and are being transported into or around the Space Station.

24) All EVA shall be conducted using the "buddy" system, or, alternatively, within visual range of an astronaut inside the Space Station ready to exit.

25) A secondary logistic resupply connection and transfer system shall be provided in the event of a docking mechanism failure.

26) In general, subsystems should be designed for fail-safe operation.

27) Inadvertent activation of critical systems shall be inhibited by design of systems and protective devices.

28) Design and procedures shall ensure that all electrical and propellant systems are inhibited before maintenance or removal of a propulsion engine.

29) The propellant compartment overpressure vent shall be separate from vents used to depressurize or vent liquids to space. Common vents may freeze and prevent overpressure vent.

30) Emergency lighting shall be provided in all compartments independent of the prime power systems.

31) A communication system is required which will support communications between crewmen and with the primary Space Station communication center.

32) All doors or hatches shall be fitted with release mechanisms operable from both sides. Appropriate indicators of conditions in adjacent compartments shall be displayed near the doors or hatches.

33) Fire suppressant techniques such as fire extinguishers or automatic isolation and decompression of separate compartments shall be employed.

34) Pressure walls should be accessible for inspection and repair purposes.

35) Any electrical equipment that is maintained by the crewmen shall be designed to be electrically isolated by interlocking switches or the equivalent before physical access to exposed connections and compartments.

36) Suitable crew and equipment restraints shall be furnished to allow crewmen to exert necessary forces to perform routine or maintenance work without personal injury or equipment damage.

37) Intra- and extravehicular environment shall be free of rough edges, projections, or sharp corners that could snag a space suit or cause physical injury.

38) Intra- and extraveh1clar equipment shall be designed to allow the astronaut ready access to items to be serviced or maintained.

39) No extravehicular tasks shall require the astronaut to enter an area or enclosed volume within which he cannot rotate freely in a fully extended position.

40) Sensors shall be installed in sensitive or danger areas to provide fire warnings and to initiate automatic fire suppressant systems.

41) CO_2 sensors and automatic fan cutoff controls (to reduce propagation of fire) will be installed.

42) Tools and equipment must be restrained at all times when not in use to prevent interference with operating systems during zero g.

43) Tools and equipment should be made of nonsparking materials if possible or protected in such a manner to prevent an ignition source.

44) Materials, grounding techniques, and operational procedures should be such as to minimize a static charge buildup.

45) Propellant fill and purge ports or disconnects shall be designed to ensure that no propellant spills will occur in the event of a single failure (i.e., poppet stuck open) upon disconnect.

46) All vents to the exterior of the spacecraft shall be designed with zero-thrust nozzles.

47) When a propulsion engine is being removed or maintained, both the fuel and oxidizer systems must be purged and decontaminated before disconnecting or removing any of the propellant connections or components.

X. FUTURE TECHNOLOGY REQUIREMENTS

One of the requirements of this study was to identify those areas of technology that require additional study to develop the required technology base for inflight maintenance and resupply.

The primary functions required for resupply and repair of the system can be accomplished, in most cases, by the use of modifications to currently available components and systems. The feasibility of more advanced concepts and systems, which are recommended in the study, has been demonstrated either by the study itself or by referenced programs. There are, however, several areas of specific technology that require resolution so that the technology development will be consistent with the Space Station and shuttle requirements.

Thirteen specific areas of technology are discussed in this chapter. Each description contains a statement of the problem, the technology requirements, and possible avenues of attack that may provide a solution to the problem.

A. FLUID REMOVAL AND DECONTAMINATION

One requirement that is common to the maintenance of all fluid systems is that the fluid must be removed from the system before any repair or removal functions can be accomplished. The Space Station will contain several fluid systems in the propulsion, environmental control, waste management, potable water, thermal control, and hydraulic systems.

Fluid removal from a potable water system is not critical and can be accomplished by several methods. However, one of the most critical technologies for inflight maintenance is the complete removal and decontamination of toxic fluids before component replacement or repair. As little as 3 ml of propellant will raise the toxicity level of the Space Station to the emergency tolerance level. Similar problems exist in thermal control systems because of the toxic fluids used there.

Fluids can be removed from the system by purging, inverse pumping; or in the case of nontoxic fluids, by the vacuum cleaner technique. These methods will remove the bulk of the fluid and probably will suffice for nontoxic fluids. Complete removal and decontamination of residual fluids pose a greater problem, particularly in a zero-g environment where weight penalties and fluid conservation are prime considerations. One of the most effective methods of decontamination is to vaporize the fluid by a vacuum technique.

This technology is required for both the Space Station and the shuttle programs. Fluid removal is required for all of the Space Station systems before any maintenance activities. In addition, all failed components coming from a toxic system must be thoroughly decontaminated before they are transported back to earth. After the shuttle has docked, and resupply of propellants has been accomplished, the transfer systems must be purged before disconnect and return to earth.

It is recommended that a study be conducted to determine the best methods and techniques of fluid removal and decontamination in a typical spacecraft fluid system. In addition to the study and analysis of fluid removal techniques, development hardware should be conducted to prove the concept.

B. WASTE FLUID DISPOSAL

Contamination of the Space Station heat transfer surfaces, optics, experiments, and solar arrays is a serious problem; yet unsolved. Present Space Station ground rules concerning waste disposal are that no commodities shall be dumped from the Space Station that will contaminate the Space Station or the atmosphere surrounding the Space Station. If disposal of water fluids from the Space Station is prohibited, then different methods must be devised for safe and efficient disposal.

This requirement will be especially demanding for a hypergolic propellant due to the toxicity and corrosive nature of the propellants and their vapors. To perform inflight repair, components and/or segments of plumbing must be separated from the total subsystem hardware, thus requiring removal of fluid from the system. For example, failure of a propellant storage tank may require removal, as well as storage or disposal, of large quantities of propellant. Resupply of propellants also requires removal of propellants from the manual disconnects before their disengagement. This requirement for inflight disposal of propellants, under emergency as well as routine conditions, represents a major area of new technology required for the resupply and repair of a Space Station propulsion system.

Special waste tanks transferred up on the shuttle will increase the payload cost per pound and will decrease the shuttle volume required for essential payloads. Although this method is simple, it is not very efficient. In addition to evaluating the classic methods of waste disposal, consideration should be given to converting waste propellant to a usable product. Waste propellant could be used in a simple secondary propulsion system and thus could provide usable propulsion energy for the Space Station. It would also be possible to reclaim certain forms of contaminated propellant and reuse them in the main propulsion system. Propellants could also be used for auxiliary heating or cooling, or converted back to their basic elements for use in the Space Station.

In addition to disposal or useful conversion of waste propellants, means must be devised to control vapors venting from the Space Station and also emergency spills before disposal. Freeze-out techniques (cold traps) is one method that could be used to control emergency venting of vapors from the spacecraft.

It is recommended that a study be conducted to conceive and evaluate various methods of waste propellant control, disposal, or conservation within the Space Station systems.

C. FLUID FITTINGS DESIGN AND TEST

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, the seal must be reparable, require simple tools for assembly, and must provide reasonable sealing characteristics. A design and test program should be initiated to provide fittings that will meet these criteria for inflight maintenance.

D. TUBE REPAIR TECHNIQUES

Present methods of welding and brazing to connect tubing to components and fittings have several deficiencies when considering repair in a zero-g environment. New methods and tools 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.

Swaging fittings onto the tube appears to be a simple and effective method of joining the fitting to the tube. It may be feasible to use redundant joining methods such as the swaging process and an epoxy seal. Replacement fittings with longer shanks than the original fittings could be swaged onto the tube and would allow for the delta length that occurred because of the tube cutting operation.

The ability to cut or remove a section of tubing, without contaminating the system or requiring a cleaning operation, is a basic technology that has not been solved. This technology is required regardless of the tube joining method.

It is recommended that various tube repair concepts be evaluated and that tools be developed to demonstrate the best tube repair methods.

E. LEAK PREVENTION AND REPAIR

Spacecraft fluid systems are normally designed and qualified to leakage criteria that will neither cause harm to personnel or equipment, nor deplete the commodity supply for the intended mission. For long missions it is anticipated that external leaks will occur due to microscopic leakage through porous materials or due to relaxation of seals. In the case of toxic propellants, leakage into the pressurized spacecraft is critical.

In addition to the safety aspects of propellant leakage, it would be highly desirable to be able to stop small external leaks without resorting to all of the purge and decontamination operations that are required to remove a component from a propellant system. For such bulky items as propellant tanks, it may be necessary to repair the leak in place. Therefore, methods should be developed to prevent microscopic leakage and to repair leaks that may occur.

A leak prevention technique that may be applicable is to add a substance to the fluid that will seal microscopic holes when it comes in contact with the surrounding environment. This concept is similar to that used in certain popular commercial antifreezes.

Some leak repair considerations, other than welding are: liquid plastic that sets with heat or in contact with the environment, epoxy resin sealers, and sealing tapes or other sealing methods that will adapt to odd shapes as well as more conventional shapes.

F. INFLIGHT MAINTENANCE EXPERIMENT

An inflight maintenance experiment is required to provide further definition and development of Space Station operational and technology concepts, system designs, and crew performance evaluation.

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 is scheduled for Skylab I and is designed to acquire basic human factors data in a zero-g environment.

A logical extension of experiment M-508 would be to assemble an experiment consisting of actual hardware, representative of the equipment that will be required on the Space Station, to evaluate man's capability to repair hardware in a zero-g environment. The secondary objective would be to evaluate hardware design, prove technology concepts, and evaluate the tools necessary for inflight maintenance.

The experiment should not be one-dimensional in scope or based on one technology. Such an experiment should include equipment or required IFM technology from the basic subsystems on the Space Station such as propulsion, environmental control, electronics, communications, and structures.

For example, a task involving a series of propulsion components could evaluate fault isolation, fluid removal technology, fastner design, equipment access requirements, tool design, quick release devices, component vs piece part assembly, time-to-repair, and subsystem checkout after repair. All of these tasks would involve an evaluation of man's ability to successfully perform maintenance functions in zero-g.

The experiment should be included in the Skylab II flight to benefit the Space Station objectives. The flight experiment should be preceded by a definition phase, prototype hardware, a ground test evaluation phase, and ground simulation. This phase sequence is designed to gain the maximum amount of knowledge on IFM and design, and to maximize the information gained from the experiment.

G. SYSTEM INTEGRATION FOR INFLIGHT MAINTENANCE

It has become apparent in this study that a central organization or integrator is required to effectively coordinate inflight maintenance for the multitude of systems and associated contractors that will become a part of the Space Station. This central organization should have the authority to move across subsystem interfaces, systems, and different contractor organizations to effectively establish a uniform plan to optimize inflight maintenance.

Some of the tasks that require a central coordination group are the establishment of a uniform design criteria, equipment commonality, uniform spares requirements, a common logistics plan, standardization of crew repair procedures and tools, coordinate fault isolation, and to establish standard design of equipment so as to optimize inflight maintenance.

System integration for inflight maintenance cannot be considered as a technology development item, but is listed here as a firm recommendation because it is so necessary for the efficient coordination of an inflight maintenance program.

H. COMPONENT DESIGN FOR MAINTAINABILITY

To date, space flight hardware has been designed with only two main criteria: optimum performance and lightweight design. None of the components 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 to reduce spares and piece parts is to have common components for like functions. That is, to design components that function for several systems rather than a particular system. Another consideration is to use a common valve body for several functions, such as, shutoff valve, regulator, check valve, etc. This approach would standardize the valve body, which has the largest area and weight of a valve assembly; thus a considerable savings could be realized in 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.

It is recommended that a design activity be initiated to design representative components for inflight maintenance.

I. SHUTTLE RESUPPLY SYSTEM REFURBISHMENT

The capability for rapid and economic refurbishment of the logistics vehicle will be essential if a low cost logistics system is to be achieved. This factor is expected to be of major importance in the Space Station program, since to a great extent the program itself will be contingent on a low cost logistics capability. Refurbishment of the resupply system for the APS therefore becomes a major design consideration, and component design must consider economical refurbishment as a major design criteria. Most of the components employed in the resupply systems are of a conventional design and have been applied previously to the transfer of hypergolic propellants. Application to the resupply function, however, will require that many of these components be modified to allow economical inspection, decontamination, and refurbishment.

Development of a lightweight metallic expulsion device that is also replaceable and economically expendable should be investigated. Such a device may be an attractive alternative to the metallic bellows, which is undesirably heavy, and to the capillary devices or nonmetallic bladders that are expected to be expensive to inspect, decontaminate, and refurbish.

As a part of the shuttle recycle, it will be necessary to rapidly isolate failures and to repair subsystems. The evaluation should also consider the tradeoffs of in-place decontamination, refurbishment, and repair, as opposed to complete subsystem removal and refurbishment at another facility.

J. FAULT DETECTION AND ISOLATION

Long-term missions require some form of fault detection to predict failures, alert the crew, and isolate the failure. Present concepts of fault detection involve sensors that send an electrical signal to a centralized computer system that predicts trends, isolates the anomaly, and alerts the crew. However, this method of detection does involve some complexity, and is subject to a certain unreliability within itself. Some types of failures are very difficult to predict, require substantial equipment, and demand a significant amount of computer logic to isolate the failure.

More direct methods of fault detection would ease the load on the OCS and would possibly improve the total reliability of the system. Some failures, such as structural failures, cannot be detected by conventional sensors.

Direct methods of fault detection, that also involve the astronaut, are visual indications (color changes, position of devices or indicators, etc.) noise (change in noise level, irregular sounds, leakage flow), smell (propellant leakage, etc), and touch.

Certain methods of detection already exist, such as ΔP pop-up button indicators on filters; and color changes to litmus paper as a result of moisture. Other possible means of detection that may be feasible would be a color change in a chemical, painted on a fluid fitting, as a result of a propellant leak; or stress coatings to detect structural failures. An individual can also detect propellant vapors at lower ppm's than at the MAC level.

Another method for reducing maintenance time, independent from the technique of anticipatory maintenance, is that of built-in test equipment (BITE). The failure of many of the vehicle components will require their immediate repair; however, troubleshooting techniques are often time consuming. The BITE concept would provide a means of sensing faults and providing indication of the condition of the equipment being monitored, either in the vicinity of the failure or at a single monitoring point, as appropriate. This could reduce the need for certain auxiliary external test equipment to perform continuous checkout of the system performance during the mission.

It is recommended that a study be conducted to conceive and evaluate direct methods of detecting failures. The study should also trade off the BITE concept as opposed to the use of external test equipment.

K. 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 life reliability that will be required for the ten-year mission. It is recommended that long-life demonstration tests commence as soon as possible on basic components and materials so that long-life reliability data can be gained prior to the Space Station mission. This test program would also serve to correct basic design deficiencies that only show up in an extended duration type test.

L. FLEX HOSE DEVELOPMENT

Fluid systems on the Space Station will require flexible hoses that are leaktight, compatible, standardized, and contain a high degree of reliability for long-duration missions. Teflon lined hoses with steel braid have a high leakage rate and are permeable to propellant vapors. Convoluted metal hoses have low leakage rates, but are constructed of a formed metal process or are welded, both of which are generally problem areas when a long-life duration is expected. They are also difficult to clean and have a high pressure drop.

It is recommended that a program be initiated to develop fluid system flex hoses that will meet the requirements of the Space Station.

APPENDIX A

ORBITAL RESUPPLY CONCEPTS

Prolonged operation of an earth-orbital Space Station will require inflight resupply of consumables to the Auxiliary Propulsion System (APS). During this study the WACS (Workshop Attitude Control System) served as the baseline APS for the investigation of potential resupply techniques.

The WACS, which is schematically illustrated in Fig. A-1, is a conventional low thrust hypergolic bipropellant propulsion system. It consists of two propulsion modules, each of which is composed of a pressurization subsystem, a propellant storage and transfer subsystem, and an engine module that contains six 22-lb nominal thrust engines. The pressurization subsystem uses nitrogen gas as the pressurant, which is stored at high pressure (3200 psia) in two 12-in. diameter spheres and regulated to propellant tank operating pressures (219 psia). There are four (2840 cu in.) propellant storage tanks per propulsion module. Two of these tanks store fuel [monomethylhydrazine (MMH)] and the other two oxidizer [nitrogen tetroxide (NTO)]. All of the propellant tanks employ metal bellows for positive expulsion of the propellant under zero- or random-gravity conditions.

A. SUMMARY

The number of fluid handling techniques that can be used for resupply of consumables (pressurant, fuel, and oxidizer) to a system such as the baseline APS is quite large. Many however, must be rejected because of their development status or because they are inherently unsuited for transfer of the relatively small quantities of consumables required for each resupply cycle.*

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*Early study ground rules (Ref A-1), established a propellant requirement of approximately 860 lb/year. Later studies (Ref A-2) predict a propellant requirement for the Space Station APS of no more than 1000 lb/year, excluding spin/despin requirements. Although these requirements correspond closely to the total impulse capability of the baseline APS, it was decided to resupply one propulsion module every six months rather than the entire system once each year, because of reliability and inflight maintenance considerations. Also a basic resupply interval of 180 days, excluding crew rotation, has been recommended as optimum by Reference A-2.

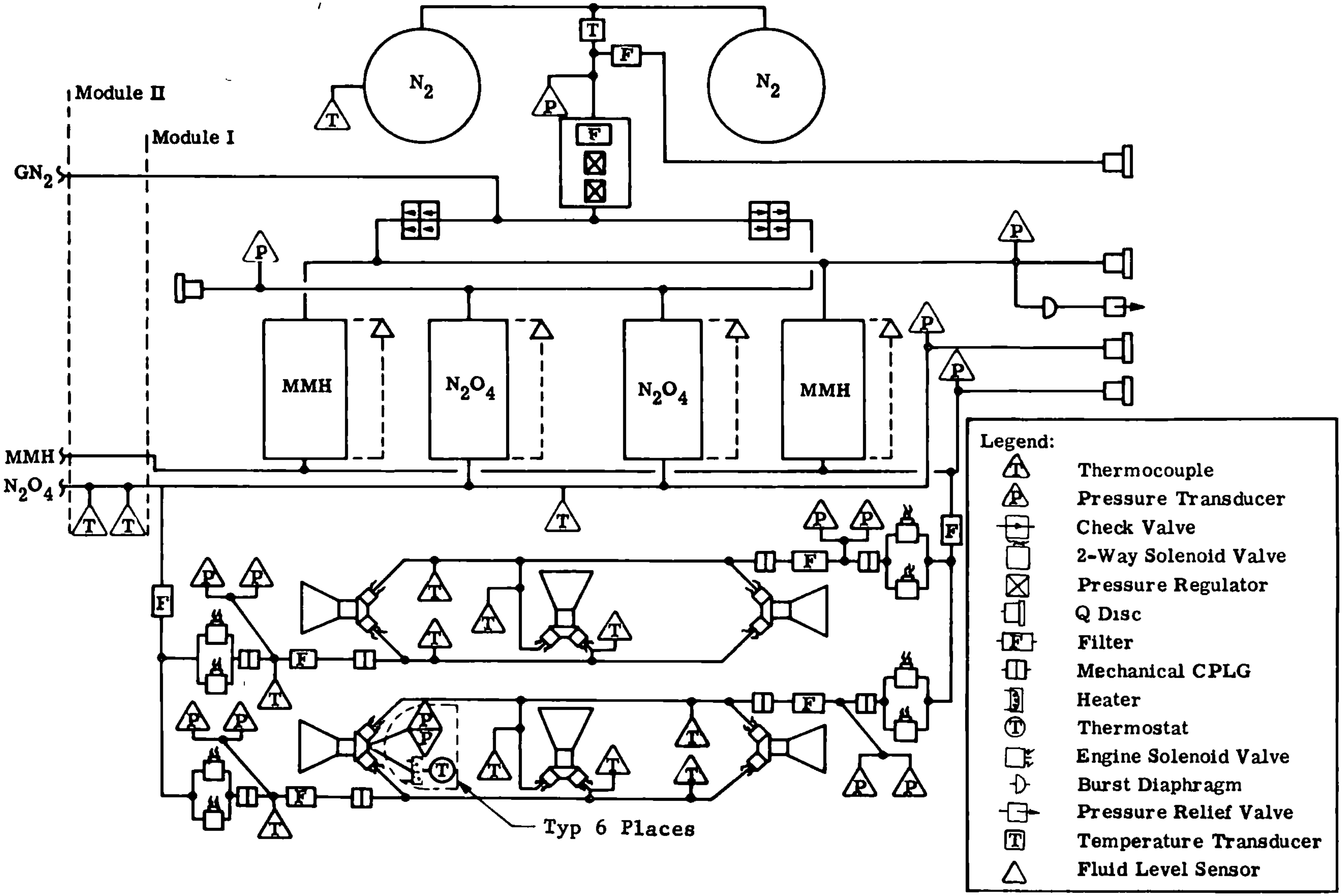

Figure A-1 Baseline APS Schematic

1. Propellant Resupply

Three fundamental approaches to the resupply of propellants were considered: fluid transfer, module replacement of the propellant storage tanks, and integrated consumable resupply systems.

Modular replacement was rejected primarily because of the extensive commitment of crew members and cargo transfer capability that would be required by the excessive transfer times anticipated for this approach.

Integrated resupply concepts, such as replacement of the propulsion modules, or continuous supply from a docked logistics vehicle or attached consumables module, were found to be very attractive from strictly a resupply and maintenance point of view. Problems may be encountered, however, with respect to program and vehicle integration. Since these factors affect major program elements such as Space Station and logistics vehicle configuration, their proper consideration requires evaluation at the program definition level. An evaluation of integrated resupply system appears in Fig. A-2.

If propellant is to be resupplied by transfer through fluid distribution lines, three major requirements must be met. Provision must be made for a ullage control mechanism, an energy source for fluid transfer, and a means of coupling the Space Station and logistics vehicle transfer lines.

Separation of gas and liquid, i.e., ullage control, can be accomplished by positioning the propellant mass or by separation with a physical barrier -- positive expulsion.

Among the propellant positioning techniques, surface tension devices represent the only technique considered suitable for resupply of Space Station propellants. Settling by means of rotational or translational acceleration is expected to impose unacceptable constraints on the operation of Space Station/logistics vehicle systems during the resupply operations. Unacceptable propellant quantities would also be required to provide effective propellant settling by this mechanism alone. More advanced systems such as dielectrophoresis, acoustic pumps, and spray impingement techniques are judged unsuitable for the relatively small propellant quantities involved, particularly when considering their early development status.

Resupply Technique	Major Subsystem Design Option	Development Risk/Status	Performance	Reliability	Safety	Integration Potential	Weight	Growth Potential	Cost	Life/ Maintenance
Integrated Consumable Resupply	Propulsion System Replacement Docked Logistics Vehicle Attached Consumables Module	B	A	B	A	C	B	A	A	A

Legend

A	Major Advantage
B	Satisfactory
C	Major Disadvantage

Fig. A-2 Summary of Subsystem Evaluation for APS Integrated Consumables Resupply

Evaluation of positive expulsion techniques indicates that several devices are suitable for application to resupply of the Space Station propellants. These include nonmetallic bladders and diaphragms, metal bellows, and several versions of metallic diaphragms and bladders. Selection of the most appropriate of these devices depends on the relative importance placed on system weight, development status, growth potential, and cost. All of the above concepts are considered feasible at this time for the application being considered.

Use of pumps, ullage control forces, and various pressurization techniques were evaluated as potential energy sources for propellant transfer. Ullage control forces were rejected as insufficient for the application. The power requirements, weight, and system complexity associated with pumping systems are not considered justified by the relatively low flow rates and back pressures required for the propellant resupply function.*

Several lightweight, simple, state-of-the-art pressurization systems were found to be adaptable to the propellant resupply function. These include the use of residual pressurant from the pressurant resupply operation, a separate high-pressure source, a conventional blowdown pressurization system, and a modified blowdown system using residual ullage from the expended propellant storage tanks.

Selection of a specific design for transfer line coupling will depend to a large extent on definition of the vehicle configurations and the docking mechanism. Therefore, this aspect of the resupply function was not investigated in depth. However, no major development or operational problems are anticipated.

A summary of the propellant resupply subsystem evaluations appears in Fig. A-3.

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*Transfer of 860 lb of propellant within a maximum time period of one-half hour was assumed as a baseline criteria for evaluating the various propellant resupply techniques. Further reduction in actual transfer time seems to be of little advantage when it is recognized that preparation and checkout time are also essential but time consuming requirements in the overall resupply operation.

Resupply Technique	Major Subsystem Design Option	Development Risk/Status	Performance	Reliability	Safety	Integration Potential	Weight	Growth Potential	Cost	Life/Maintenance
Fluid Transfer										
	Ullage Control									
	Propellant Positioning									
	1) Surface Tension	B	B	A	B	C	A	A	B	B
	2) Spray Impingement	0	--	--	--	--	--	--	--	--
	3) Artificial Gravity									
	a) *Translation*	A	C	B	B	C	C	B	A	B
	b) Rotation	A	C	B	B	C	B	A	A	B
	4) Acoustic Forces	0	--	--	--	--	--	--	--	--
	5) Dielectrophoresis	0	--	--	--	--	--	--	--	--
	Positive Expulsion									
	1) Nonmetal Bladder/Diaphragm	A	A	B	B	B	A	B	B	C
	2) Pistons	C	B	C	B	A	C	C	C	B
	3) Metal Bellows	B	A	B	B	A	C	C	B	A
	4) Metal Bladder/Diaphragm	C	A	B	B	A	A	C	C	C
	Energy Source									
	Pressurization									
	1) Residual Pressurant	A	A	B	B	C	A	A	A	B
	2) Stored Gas	A	B	B	B	A	B	B	B	B
	3) Blowdown	A	A	A	B	B	B	B	A	A
	4) PSA Ullage	A	A	A	B	A	B	A	A	B
	5) Miscellaneous	--	0	--	--	0	--	--	--	--
	Pumps	B	B	C	B	C	C	B	B	B
	Ullage Control Forces	0	0	--	--	--	--	--	--	--
	Transfer Line Coupling									
	Proximity Rendezvous	--	--	--	--	0	--	--	--	--
	Docking	--	--	--	--	--	--	--	--	--
Modular Replacement		C	C	A	C	C	A	B	C	A

Legend

A	Major Advantage
B	Satisfactory
C	Major Disadvantage
0	Unacceptable

Figure A-3 Summary of Subsystem Evaluations for APS Propellant Resupply

2. Pressurant Resupply

A number of techniques for resupplying pressurant for the baseline APS were evaluated. In addition several modifications to the baseline APS were considered as potential means of reducing the overall resupply requirement.

a. Baseline APS - For application to the baseline APS both a simple blowdown system and modular replacement of the gas storage spheres are considered feasible. The primary disadvantage associated with modular replacement is its early development status, whereas the major disadvantage of the blowdown system is the weight penalty (approximately 50 lb/resupply cycle) resulting from large pressurant residuals left aboard the logistics craft.

Several other more sophisticated systems were evaluated to reduce or eliminate the weight penalty resulting from residual pressurant. These systems included cryogenic storage of the pressurant, addition of energy to the residuals by means of a compressor or heat exchanger, and recompression of the propellant tank ullage. It was concluded, however, that the added system complexity, power requirements, and integration problems were not warranted for the relatively small pressurant quantities involved.

b. Modified APS - Several modifications to the baseline propulsion system were also investigated to determine whether they would materially reduce the resupply requirements. Of these techniques, systems such as cryogenic pressurants, evaporated propellants, and chemical reaction systems were rejected for a variety of reasons including unwarranted complexity, excessive weight, possible propellant contamination, limited development experience, and potential safety hazards. Several other systems were found to be potentially applicable to the Space Station APS, however.

Volatile liquid systems afford an attractive potential in that resupply of pressurant can be entirely avoided, barring malfunction or damage to the tankage. However, the possibility for development and operational problems should be recognized because of the early development status, sensitivity to certain duty cycles, and thermal conditioning required for these systems.

Use of a conventional blowdown pressurization system for the Space Station APS represents another means of eliminating the pressurant resupply requirement. This is accomplished by allowing recompression rather than venting of the ullage during propellant resupply. Disadvantages result from the lack of experience with regard to bipropellant applications. Some difficulty may be encountered in assuring proper engine inlet conditions, particularly during the pulsing mode of operation. However, development of such a system seems entirely feasible.

Integrated APS/ECLSS nitrogen supply systems were also evaluated. Although the total nitrogen requirement for the ECLSS is expected to be an order of magnitude greater than that required by the APS, the propulsion system will likely impose the maximum demand rate. This factor may greatly increase power requirements or compromise ECLSS design and/or operation. Since these effects are highly sensitive to duty cycle, detailed evaluation of this approach requires further definition of both the ECLSS and APS operating duty cycles.

A summary of the pressurant resupply subsystem evaluations appears in Fig. A-4.

B. PROPELLANT RESUPPLY DISCUSSION

Three fundamental approaches to the resupply of propellants were evaluated. These are fluid transfer, modular replacement of the propellant storage tanks, and integrated consumables resupply systems.

1. Fluid Transfer

A large number of techniques and design options are available for transferring propellants from the logistics resupply vehicle to the Space Station through fluid distribution lines. Differences in the various concepts are primarily related to methods of providing ullage control, energy for the fluid transfer process, and coupling of the distribution lines between the logistics vehicle and the Space Station. Various methods for satisfying these three major design requirements are evaluated below as to their feasibility for application to the Space Station resupply function.

Resupply Concept	Major Subsystem Design Option	Development Risk/Status	Performance	Reliability	Safety	Integration Potential	Weight	Growth Potential	Cost	Life/Maintenance
Resupply of Baseline System										
Fluid Transfer										
	Blowdown	A	B	A	B	A	C	C	B	A
	Energy Addition	B	C	B	C	C	B	B	B	B
	Cryogenic									
	1) Subcritical	C	B	B	B	B	A	A	C	C
	2) Supercritical	B	B	B	B	B	A	A	C	C
Modular Replacement of GSAs		C	B	A	B	B	A	B	B	C
Recompressed Ullage		B	C	B	B	C	A+	A	B	C
Resupply of Modified System										
Misc		--	0	--	--	0	--	--	--	--
1) Cryogenic										
2) Evaporated Propellant										
3) Chemical										
Volatile Liquid		C	B	B	A	C	A+	C	B	B
Integrated ECLSS/APS N_2 Source		B	B	B	B	C	A	A	B	B
Blowdown		C	B	A	A	B	A	C	B	B

Legend

A	Major Advantage
B	Satisfactory
C	Major Disadvantage
0	Unacceptable

Fig A-4 Summary of Subsystem Evaluation for APS Pressurant Resupply

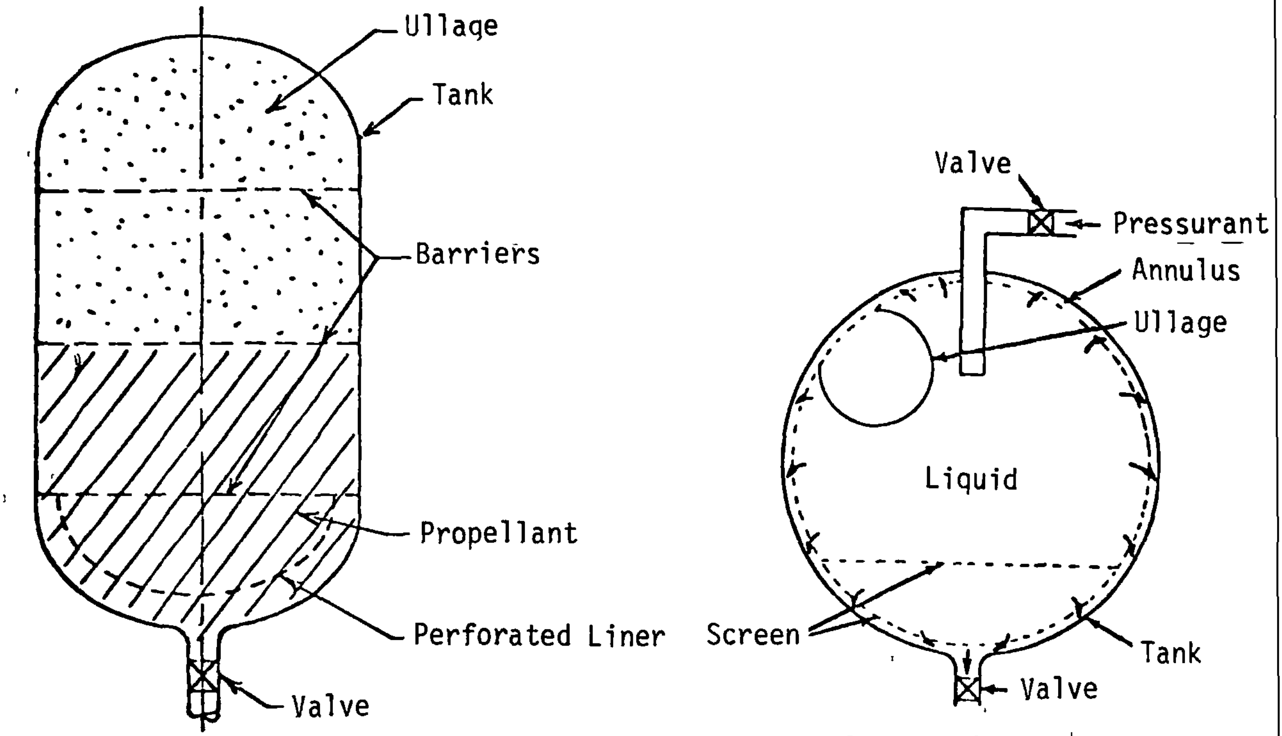
a. Ullage Control Methods - Regardless of the selected transfer mechanism, ullage control will be necessary for separation of the gas and liquid within the propellant transfer tanks of the logistics vehicle. This is required to prevent ingestion and entrapment of noncondensable gas (pressurant) in the Space Station receiver tanks. To satisfy this requirement, ullage control can be accomplished by either of two general approaches: positioning of the liquid mass, and separation of the gas and liquid by means of a physical barrier. The latter approach is often referred to as positive expulsion. A comprehensive survey of these techniques appears in Ref A-3 and A-4.

1) Propellant Positioning - During propellant transfer, gas and liquid can be separated by applying various generated or naturally occurring forces. Since transfer will occur in a nearly zero-gravity environment, the forces required for positioning the propellants may be quite small. Potential techniques are surface tension devices, spray impingement, artificial gravity, acoustic forces, and dielectrophoresis.

a) Surface Tension - In a low-gravity environment, interfacial surface tension forces can be used to orient the liquid and maintain gas-liquid separation. Several design approaches are schematically illustrated in Fig. A-5.

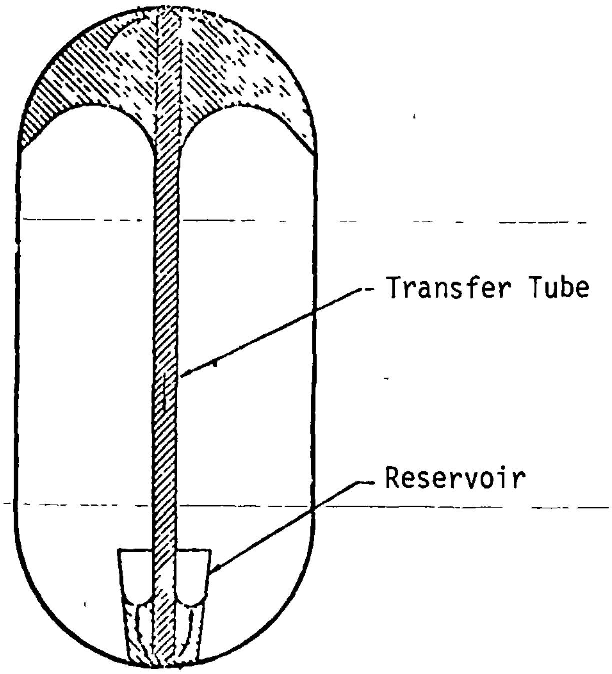
The feasibility of using surface-tension devices for propellant management is well established. The necessary technology for design and fabrication of such devices is currently available, having been applied successfully on such systems as the Apollo Service Module and Titan Transtage primary propulsion systems. Nevertheless, for systems employing more advanced materials such as woven cloth screens, a moderate development effort in the areas of fabrication, inspection, refurbishment, and quality control should be anticipated. However, the development risk involved is expected to be minimal.

Several performance characteristics of surface-tension devices make them well suited to the resupply function. These include excellent expulsion and volumetric efficiencies (particularly for large tank sizes), a virtually infinite recycle capability, and adaptability to any tank size or shape. These factors will promote flexibility in cargo placement and help facilitate design of the logistics craft. Vehicle integration would also be simplified by the independent nature of these devices which require no external forces or energy sources for operation or control. Their exceptional recycle capability reasonably advanced development status, and relatively simple construction are the major advantages of these devices for resupply of the Space Station propellants.



Multiple Barrier System

Concentric Screen



Capillary Pump

Fig. A-5 Surface Tension Devices for Ullage Control

Performance limitations for these devices do exist, however. These limitations are associated with extremely high expulsion rates, high disturbance forces during outflow, and absorption of pressurant by the propellants. The first two factors are not relevant to the Space Station application because the need for extremely high transfer rates does not exist, and the maximum screen destabilizing loads will occur during the boost phase and docking maneuvers when ullage volumes are minimum. The third factor, however, may constrain the selection of engines and/or pressurant, because under certain operating environments such as rapid thermal cycling or pressure drop in the lines, dissolved pressurant may come out of solution and damage components or degrade performance of the engines. Because the tank ullage will contain propellant vapors, the use of surface tension devices will also prevent venting of the tanks without exposing the logistics craft or Space Station exterior to contaminating and corrosive vapors. This factor may be significant if the propellant transfer tanks are also used as receivers for waste propellant from the Space Station. Cleaning and refurbishment of these devices is also expected to be difficult.

Two characteristics of surface tension devices are expected to facilitate a minimum weight design. For tank volumes in excess of 2000 to 3000 in.^{3} the weight of the expulsion device and of the residual propellants becomes a small percentage of the overall tankage and fluid distribution system weight. The option of choosing unlimited tank sizes and shapes allows selection of a minimum number of tanks based on packaging considerations only. This in turn can reduce the tankage and interconnecting hardware weights considerably, depending of course on the total propellant quantities involved.

Considering the lack of any requirement for external power, moving parts, special materials or coatings, seals or other deformable components, the reliability of surface tension devices is potentially excellent.

b) Artificial Gravity - Induced vehicle acceleration represents another method of providing a positioning force for location of the propellant mass. Acceleration can be either translational, Fig. A-6(a), resulting from continuous axial thrust, or rotational, Fig. A-6(b), resulting from spinup of the connected logistics vehicle and Space Station.

(a) Translational Settling

(b) Rotational Settling

Fig. A-6 Settling Modes

Translational Settling - As illustrated in Fig. A-6(a), the application of axial thrust represents a straightforward, well-developed approach for propellant location control. This method has been used extensively in the past to reposition propellants after coast and to maintain propellant location before engine ignition. However, the requirement for continuous thrust during the propellant transfer process represents a serious handicap for the Space Station resupply application. Assuming a combined weight on the order of a half million pounds for the coupled Space Station and logistics vehicle, and a required Bond number of at least 10 to assure adequate propellant positioning, a minimum thrust level of approximately 50 lb_f would be required for ullage control. Therefore, when considered as an ullage control mechanism only, propellant consumption makes such a system unattractive from a weight standpoint unless propellant transfer times can be reduced to a few minutes. At flow rates corresponding to these transfer times, additional hardware such as internal tank baffles or capillary screens will probably also be required to minimize propellant residuals resulting from propellant slosh and surface dip which are quite pronounced at these extremely low g levels (Ref A-4). Similar devices may also be necessary to prevent entrapment of gases in the transfer lines during preflight and boost operations. Undesirable orbital or attitude perturbations should also be expected unless the resupply maneuver can be made to coincide with requirements to make up orbital decay. With respect to absorption of pressurant and the mixing of vapors with the ullage, these techniques suffer from the same limitations as do the surface tension devices.

Rotational Settling - Two major disadvantages of the translational settling technique can be avoided by the rotational settling technique illustrated in Fig. A-6(b). These are the potential orbital disturbances and the excessive propellant requirements. Propellant quantities on the order of 10 to 20 lb should be sufficient to provide an artificial g level of approximately 10^{-4}. Since settling forces can be provided almost indefinitely without requiring additional propellant, such a system has excellent growth potential. This approach should also minimize program costs since it makes use of existing systems. Other characteristics, however, are similar to those of the translational settling technique. Auxiliary hardware may be required to control surface dip and propellant slosh during operation and to prevent gas entrapment during boost. Continuous rotation of the Space Station during resupply may also impose unacceptable constraints on the operation of experiments or other Space Station/logistics vehicle systems. Venting of tanks must also be prevented.

c) Miscellaneous Systems - Dielectrophoretic, spray impingement, and acoustic systems are discussed very briefly below. Although these approaches may be potentially applicable to large systems such as cryogenic tankers, they have been eliminated from further consideration for resupply of the Space Station APS because of their early development status and unwarranted complexity for relatively small propellant quantities.

Acoustic Forces - Propellant location can be accomplished by installing an acoustic source inside the transfer tank opposite the outlet, Fig. A-7. Acoustic forces are then used to exert a directed force on the liquid mass, resulting in settling of the propellants at the tank bottom (Ref A-5).

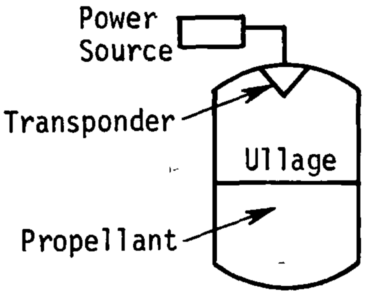


Fig. A-7 Ullage Control By Acoustic Forces

Dielectrophoresis - Ullage control is also possible using the forces derived from electric fields and the dielectric properties of the propellant and pressurant. This method is known as dielectrophoresis. By using nonuniform electric fields and the dielectric differences between liquid and gas, separation of the two can be accomplished (Ref A-6).

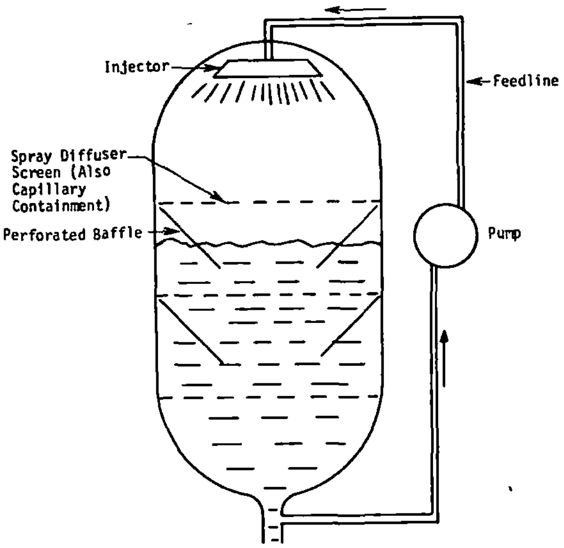


Fig. A-8 Spray Impingement System for Ullage Control

Spray Impingement - Another method that may prove feasible for controlling liquid position is shown in Fig. A-8. In its simplest form, it consists of a spray injector in the tank-end opposite the outlet, a diffuser, feedline, and a small impeller-type pump. The theory of operation is simply to provide a driving force by impinging propellant spray on the large propellant mass, driving it toward the outlet end of the tank.

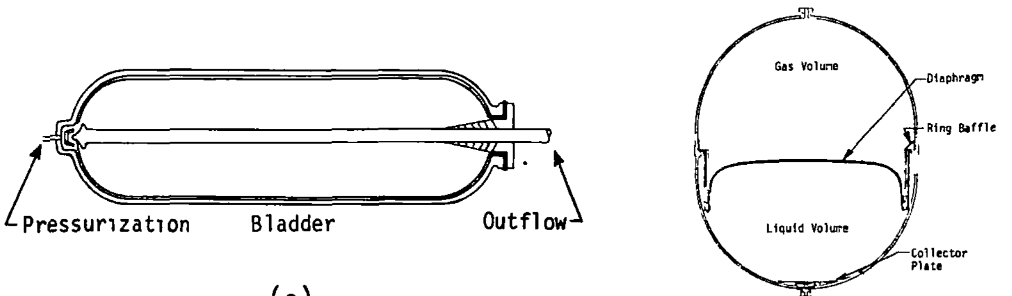
2) Positive Expulsion - In addition to the propellant positioning techniques identified above, ullage control can be accomplished by providing a physical barrier between the gas and liquid (Ref A-7). These devices have been used extensively for ullage control and represent a well-established and proven technique for assuring gas-free liquids at the tank outlet. This factor as well as their independent operation, adaptability to a broad range of flow rates, and insensitivity to the vehicle environment make them prime candidates for satisfying the requirement for ullage control during propellant transfer. Not withstanding, certain operational limitations are associated with their use -- size limitations and recycle capability.

Because the entire propellant quantity is enclosed or separated from the ullage, mechanical design complexity and system weight increases rapidly with tank size. Although considerable fabrication and development technology exist for small tank sizes, little work has been done for large tank applications.

Many of the more promising lightweight designs have an extremely limited recycle capability. These two factors may result in unacceptable costs for the large quantities of propellant required during the program.

Although numerous positive expulsion devices are available for consideration, they can generally be categorized as described in the following paragraphs.

a) Nonmetallic Bladders and Diaphragms - Nonmetallic bladders consist essentially of an enclosed membrane or bag, as illustrated in Fig. A-9(a). These devices may be of either the expanding type or of the collapsing type depending on whether propellant or pressurant is the internal fluid. As illustrated in Fig. A-9(b), diaphragms are similar to bladders with the exception that the barrier only partially contains the propellant with expulsion accomplished by reversing the barrier. Nonmetallic bladders and diaphragms have, to date, been the generally accepted method for achieving positive expulsion from small tanks in a zero- or low-gravity environment. For this application, such devices represent a minimum development risk approach. However, for service with MMH and NTO, compatibility of the bladder material may impose certain problems with respect to APS integration.



(a)

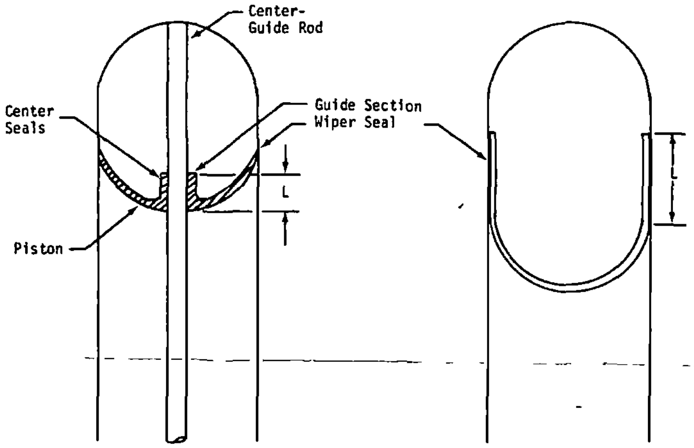
(b)

Fig. A-9 Nonmetallic Bladder and Diaphragm

The only nonmetallic material successfully demonstrated for application to this propellant combination is Teflon. In operation this material is in direct contact with the propellants, where it tends to swell and lose tensile strength, and is subjected to flexing, creasing, and vibrational loads. These factors, in conjunction with difficulties associated with cleaning and inspection, may preclude economical reuse of the devices.

Permeability of the bladder or diaphragm material allows pressurant gas to migrate into the liquid, and propellant to permeate into the ullage. Although permeation of the propellants can be expected to result in a negligible loss in usable propellants, the pressurant lines and components are exposed to cleaning, compatibility, and isolation requirements that otherwise would not be necessary. Venting would also result in the contamination of the vehicle exterior. Pressurant gas that permeates into the propellant can also severely affect engine performance and, at worst, cause engine failure. This factor, since it may impose constraints on allowable operating conditions and on engine or pressurant selection, has prompted considerable research and development effort in the area of metallic devices.

b) Pistons - As illustrated in Fig. A-10, either center-guided or peripheral-guided pistons can be used as a means of mechanically separating the liquid and gas. Pistons have been used as expulsion devices on several small diameter tactical missile systems. Their application, however, is limited to cylindrical tankage with smooth inner walls. The major problem with pistons is obtaining good seals between the piston and tank. This problem is especially critical for larger diameters. Because extremely close tolerances and smooth rigid sealing surfaces are required, the use of pistons will result in development risks and expulsion system/tankage weights that are unacceptable for the intended application.



L = Length of Guide Section

(a) Center-Guided Piston (b) Peripheral-Guided Piston

Fig. A-10 Piston Separation Techniques

c) Metal Bellows - Metal bellows may also be used as a means of providing a nonpermeable barrier between the ullage gas and the propellant. These corrugated devices may be manufactured by either forming or welding the bellows convolutions. Although most bellows are designed to operate with the propellant on the inside as shown in Fig. A-11, the reverse approach may also be used. The use of metal bellows offers a well-developed technique for providing positive expulsion of liquids. Bellows systems

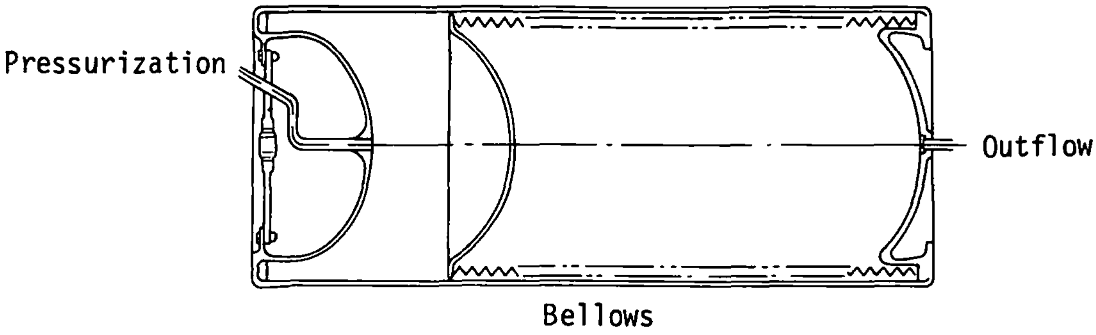


Fig. A-11 Metal Bellows

effectively avoid the problems of permeation, propellant compatibility, and limited cycle life, factors which are common to the nonmetallic devices. These characteristics, along with their applicability to simple, point sensor gaging techniques, and independence from external control or energy sources, will minimize integration problems with the logistics vehicle as well as the Space Station APS. Long life potential, simple checkout requirements, and ease of gaging may make these devices economically attractive for the logistics vehicle transfer tanks.

The major disadvantages associated with bellows are their high cost, weight, and lack of fabrication and development experience for large systems (greater than approximately 1 ft). Considering development risk and costs, bellows tanks no larger than 18 to 24 in. in diameter should be anticipated for the resupply systems. Tankage weights for such systems can be expected to be three to four times those of corresponding assemblies using nonmetallic devices. Because of the many convolutions, cleaning and inspection of these devices for reuse is also expected to be difficult.

d) Metallic Diaphragms and Bladders - Several potentially attractive metallic devices are currently being developed to reduce the weight penalty and costs associated with bellows designs, while retaining the advantages of their nonpermeability and materials compatibility. Although in general principle these devices are similar to the nonmetallic diaphragms and bladders, structural characteristics of the metallic materials require control of the barrier motion during operation. Although the development of these devices has shown substantial progress in recent years, additional effort will be required before the serviceability of many of these devices can be fully demonstrated. For the resupply function another basic limitation associated with metallic bladders and devices is their limited cycle life, normally one complete expulsion cycle. This factor may represent a serious cost disadvantage unless production expense can be reduced to very low values, allowing the development of expendable devices.

Several of the more attractive devices in this category are briefly described below.

(1) Convoluted Diaphragms - The convoluted diaphragm is a surface of revolution consisting of circular convolutions precisely formed from thin flat stainless steel or aluminum sheet. It is positioned on a diametrical plane of a spherical container with one side exposed to the propellant and the other to the pressurant. The diaphragm deforms in favor of the imposed pressure differential, expanding to conform to the container walls during expulsion, thus displacing the consumed propellant with ullage volume.

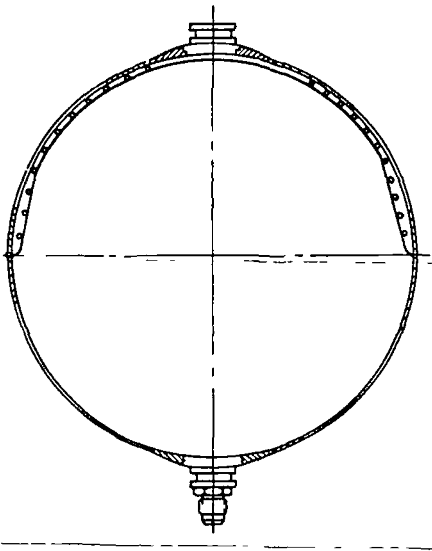
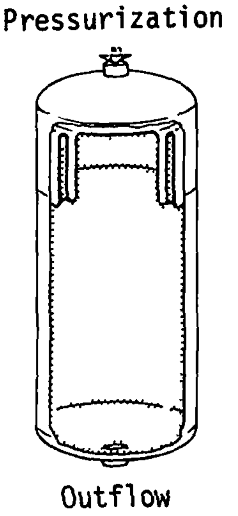


Fig. A-12 Ring Reinforced Reversing Diaphragm

(2) Ring Reinforced Reversing Diaphragms - This type of diaphragm, Fig. A-12, is supported by additional structure to permit controlled deformation of the diaphragm and recycle capability. A thin metal shell is stiffened by rings attached to the shell surface in planes parallel to a reference base, usually the diaphragm-container attach point. During expulsion, the diaphragm inverts to a mirror image of its initial shape at propellant depletion. The reinforcing rings roll with the shell in the process straining the diaphragm as the ring inverts.

(3) Rolling Diaphragms - A third class of metallic diaphragms used for positive expulsion is the rolling diaphragm. A rolling diaphragm configuration usually consists of a thin cylinder, one-half of the length of the container being expelled. One end of the cylinder is attached to the container wall at the midplane; the other to a movable end plate. When the ullage space is pressurized, the end plate moves towards the tank outlet rolling the thin cylinder inside itself during expulsion.



A-13 Rolling Diaphragm

(4) Telescoping Diaphragms - This approach, which applies to cylindrical tankage, is similar to the simple rolling diaphragm except that the diaphragm consists of a thin cylinder that telescopes within itself to form three concentric convolutions as illustrated in Fig. A-13. The outer convolution is attached to the container wall at one end of the cylindrical tank. During expulsion, rim rolling at the outer convolution occurs first, followed by rim rolling of the inner sections. In the fully expelled configuration, the diaphragm forms a stepped cylinder where the diameter decreases with each of the three steps.

(5) Transverse Collapsing Metal Bladder (TCMB) - Another very promising expulsion device for this application is the TCMB, which consists of a cylindrical type diaphragm that inverts itself transversely about the transverse diametrical plane of a cylindrical-type tank when pressurant gases are applied, to expell propellants. Aerojet-General has manufactured sizes ranging from 15.2 in.^{3} to 2800 in.^{3}. Further scaling up of the design, if required, is not expected to present any major problems. The devices have been used successfully on Aerojet's pulse engine program and for the Nike-Javelin guidance system.

Although the TCMB is suitable for a single expulsion cycle only, the most attractive characteristic of this device to the Space Station resupply function is its relatively low cost. These devices are expected to cost hundreds rather than thousands of dollars each as expected for most of the other devices being considered. Consequently an expendable device can be considered, thus eliminating a major portion of the refurbishment cost expected for the logistic vehicle transfer tanks, and potentially reducing the shuttle operating costs and required turnaround time. TCMBs in the 3000 cu in. range have been designed and built for application to commercial aircraft auxiliary hydraulic power systems. Tankage/expulsion assemblies have also been designed, which incorporate bolted connections for rapid and efficient disposal of the bladders and refurbishment of the tanks (Fig. A-14).

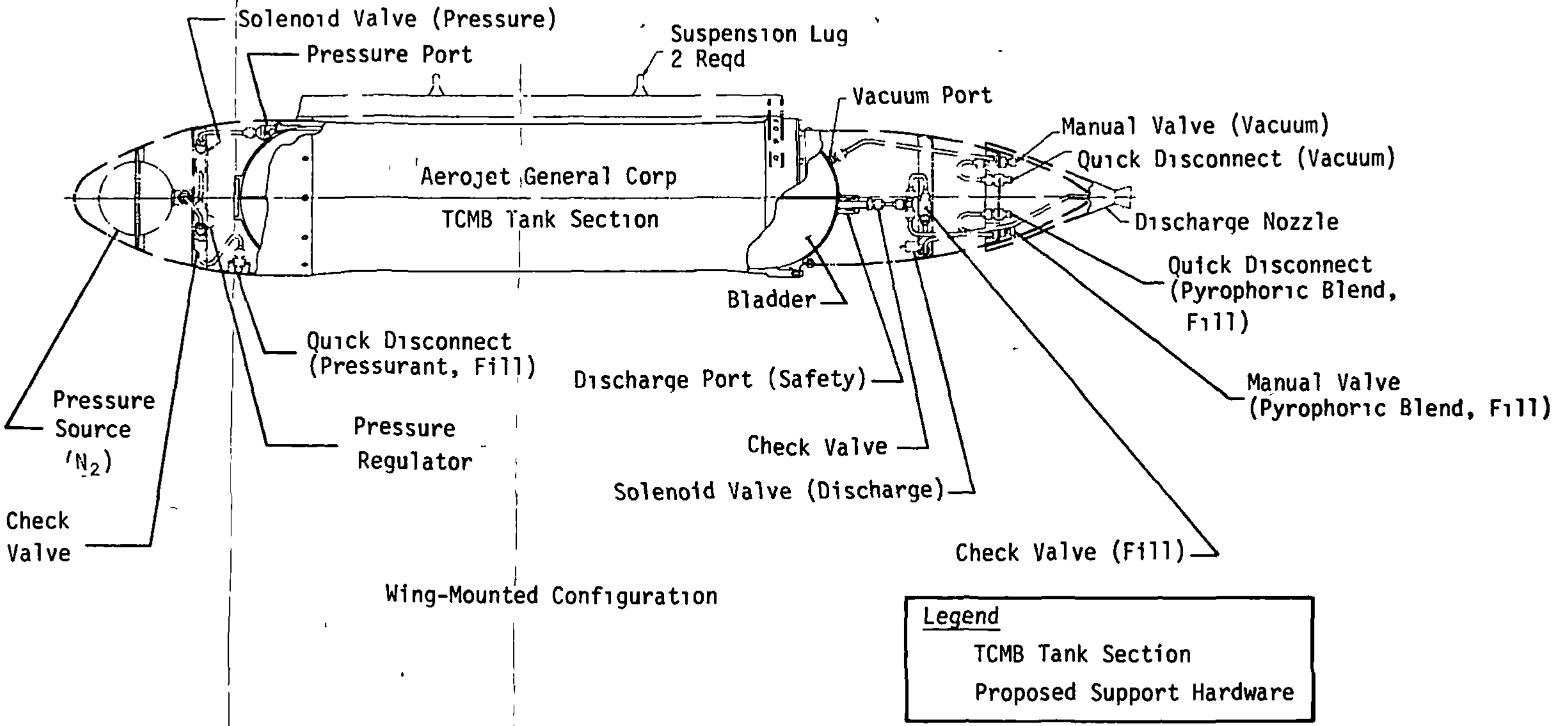


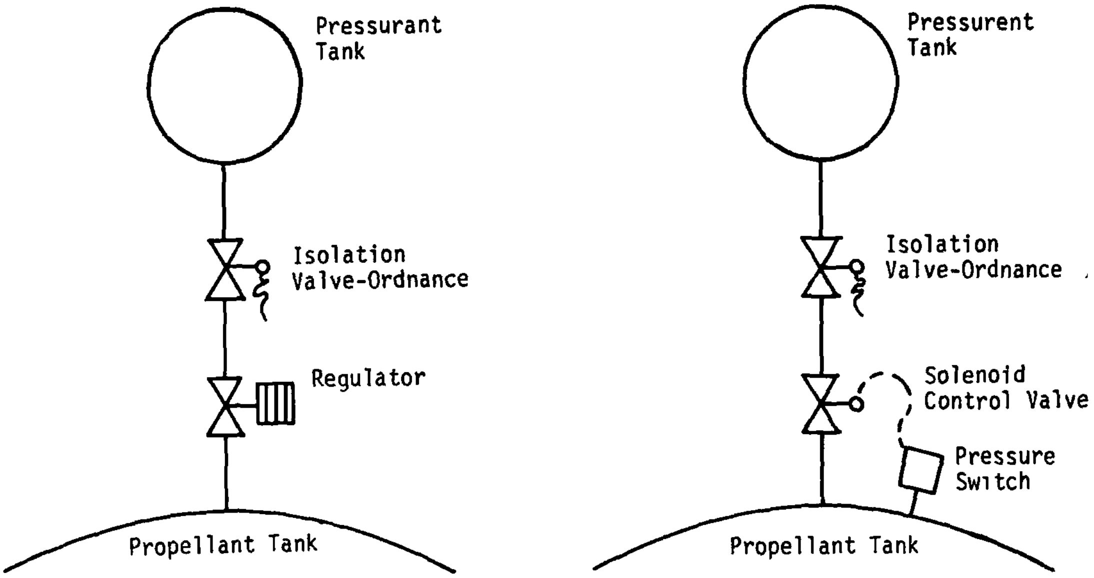
Fig A-14 Expendable TCMB Design for Rapid Replacement of Bladder

b. Propellant Transfer Forces - In addition to the ullage control requirement discussed above, transfer of propellant through fluid distribution lines will require the generation of a motivating force. Transfer of 860 lb of propellant within a minimum time of approximately 1/2 hr has been assumed as a baseline requirement for evaluating the various propellant transfer techniques. Further reduction in actual transfer times seems to be of little advantage when it is recognized that preparation and checkout time are also essential but time-consuming requirements in the overall transfer operation. Three categories of energy sources were considered for this function. These are: pressurization, pumps, and use of the ullage control forces.

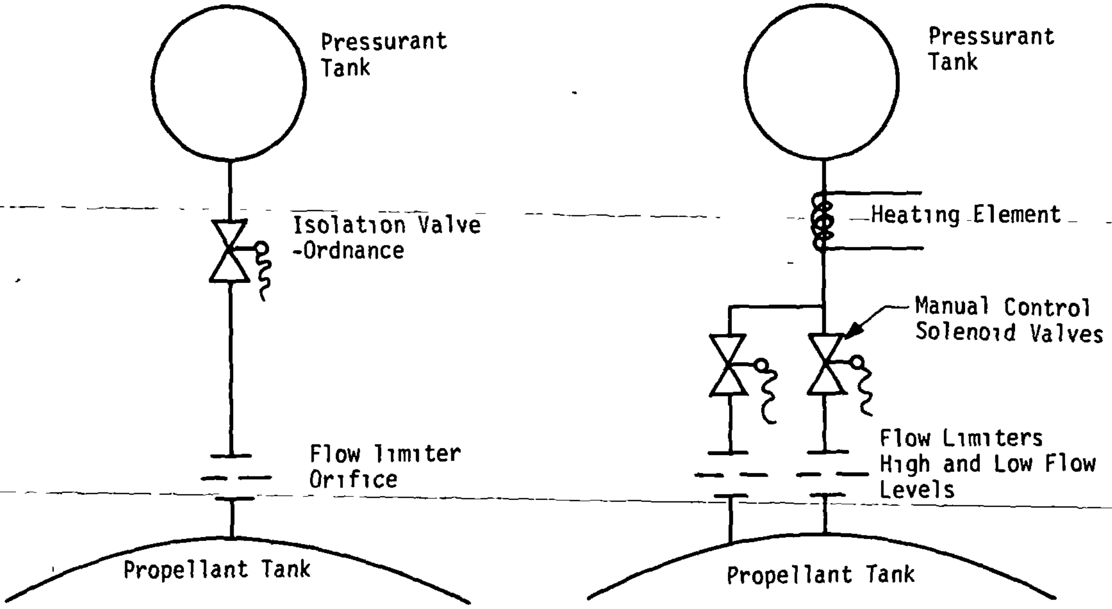
1) Pressurization - Propellants can be transferred from the storage tanks of the logistics vehicle to the Space Station receiver tanks using gas pressure forces as the primary energy source. Several techniques are available for providing these forces, e.g., high-pressure stored gas, blowdown pressurization, heated liquids, evaporated propellants, and products of chemical reactions.

a) High-Pressure Stored Gas - In this technique gaseous pressurant is stored at high pressure and ambient temperature (supercritical) in a separate container and is transferred to the propellant transfer tanks through a flow control device in the distribution lines. Many variations of this basic approach can be considered. Figure A-15 illustrates several potential concepts. Pressurant flow can be regulated using a conventional pneumatic pressure regulator or a discrete ("bang-bang") system as shown in Fig. A-15(a) or a nonregulated system can be employed, Fig. A-15(b). Heat can be added to minimize pressurant requirements and/or multiple flow levels can be employed to minimize the possibility of damaging the Space Station receiver tanks when "topping."

Evaluation of stored gas techniques as energy sources for propellant transfer also depends to a great extent on pressurant resupply considerations as well as propellant transfer requirements. If blowdown of high-pressure gas is the selected means for resupplying pressurant, residuals left onboard the logistics vehicle will provide more than enough energy to satisfy propellant transfer demands. As illustrated in Fig. A-16, such a system represents an extremely simple approach and uses well-developed techniques and hardware. As such, it should result in minimum development risk as well as excellent cost, maintainability, and reliability characteristics. This approach is also attractive from the standpoint of weight, performance, and growth potential since it reduces the residual penalty associated with the blowdown method of pressurant resupply and is capable of rapidly transferring the required propellant quantities.



a. Regulated Systems



b. Nonregulated Systems

Fig. A-15 High-Pressure Stored Gas Pressurant Systems

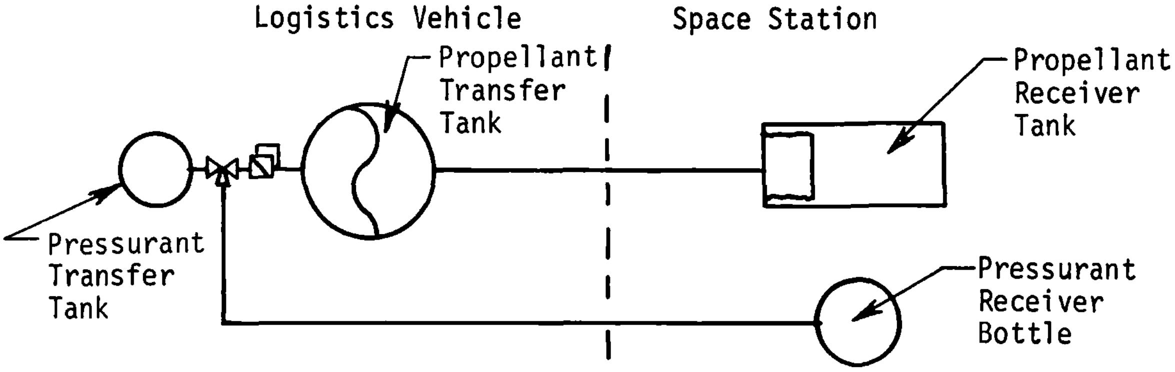


Fig. A-16 Residual Pressurant as an Energy Source for Propellant Transfer

If, on the other hand, modular replacement of the gas storage tanks is the selected pressurant resupply technique, an additional source of pressurant must be available for propellant transfer. An obvious approach is to simply provide an independent high-pressure storage bottle and pressure control device for pressurizing the transfer tanks, Fig. A-17. For the baseline propellant quantities (860 lb) a weight penalty of less than 20 lb is expected when compared to the system just discussed.

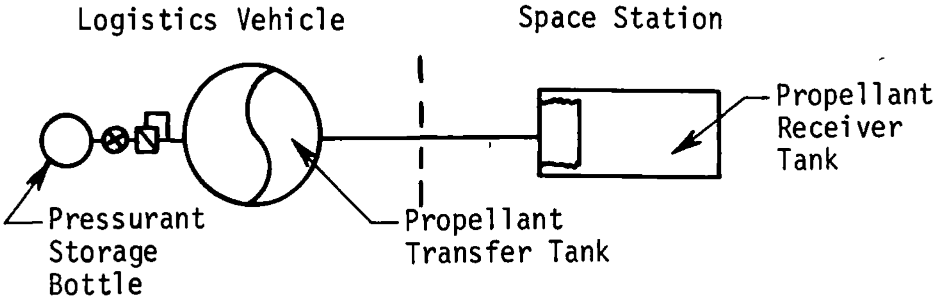


Fig. A-17 Separate High-Pressure Source as an Energy Source for Propellant Transfer

b) Blowdown Pressurization - Another approach is to provide pressurization by means of a conventional blowdown system illustrated in Fig. A-18. When compared to the previously discussed high-pressure systems, this approach has the advantage of eliminating the requirements for a pressure regulator and for extremely high storage pressures. Because of its inherent simplicity, the blowdown system provides maximum reliability and minimum maintenance requirements. Development, manufacturing, and operating costs should also be a minimum. Because of the relatively small pressurant requirement, development of a system which is competitive, in terms of weight, with the regulated system is also anticipated.

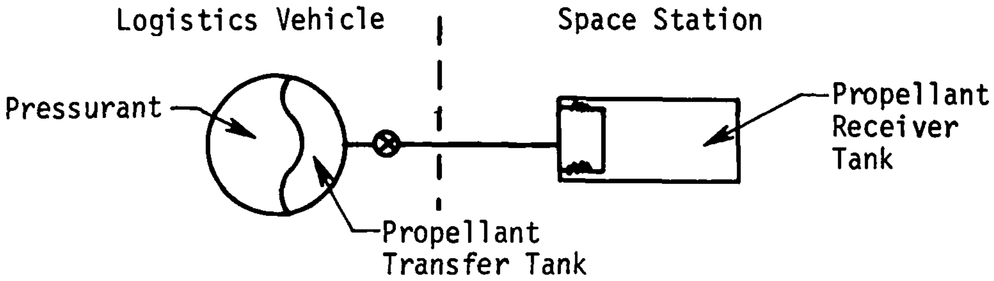


Fig. A-18 Blowdown Pressurization as an Energy Source for Propellant Transfer

A similar technique is illustrated in Fig. A-19. This approach is essentially a blowdown system that uses the residual ullage from the expended propellant tanks as the pressurant source. Operation of this system involves transferring the propellants by venting the first tank and allowing ullage from the second tank to pressurize the propellant transfer tanks of the logistics vehicle. This sequence is repeated until the last tank, which can be filled by simple blowdown of the transfer tanks. This system avoids the necessity of high-pressure gases and should be easily capable of transferring the required propellant quantities within 1/2 hr.

Several pressurant sources other than stored gas were also considered, e.g., heated liquids, evaporated propellants, and products of chemical reactions. Although each of these approaches is discussed in some detail in Ref A-7 and briefly described below, they have been eliminated from further consideration for a variety of reasons such as unwarranted complexity, excessive weight, possible propellant contamination, limited development experience, and/or potential safety hazards. Such factors are especially pronounced when these systems are compared to the simpler pressurization techniques previously discussed and when the relatively low pressurant requirements are considered.

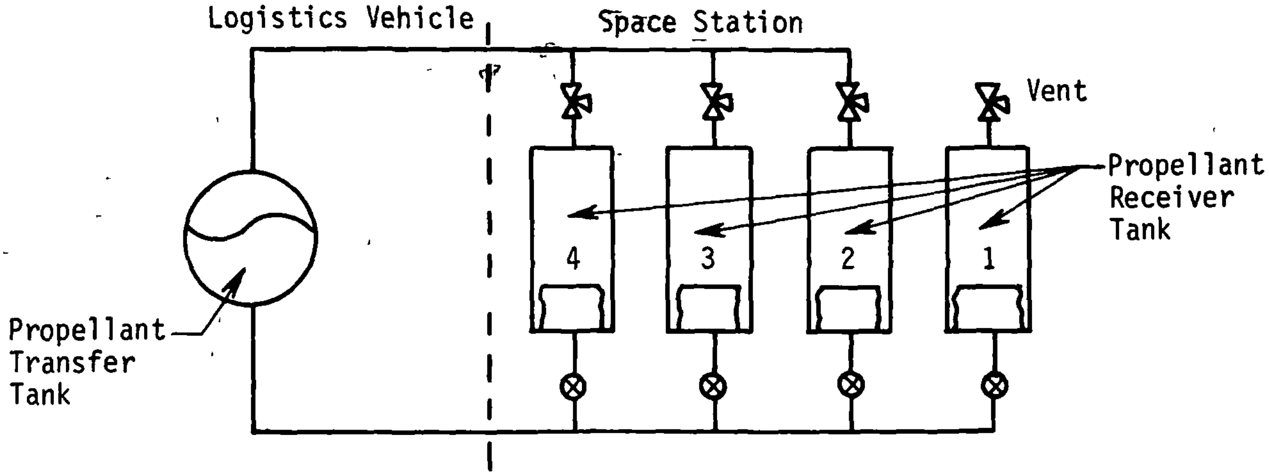


Fig. A-19 Residual Ullage as an Energy Source for Propellant Transfer

c) Heated Liquids - Pressurants can also be stored in a liquid state under their own vapor pressure, (subcritical) or under high pressure (supercritical). Using pressurants such as ammonia and certain Freons, subcritical storage can be accomplished at ambient temperature without the requirement for thermal conditioning. The conventional pressurants (nitrogen and helium) can be stored as cryogens. Nitrogen or helium can also be used in a supercritical cryogenic storage system. This system is similar to the subcritical storage system except that the pressurant is loaded as a cryogenic liquid and the container is sealed so that as heat is added, the pressure rises to a supercritical level. As pressurant is withdrawn, additional heat is required to maintain the high-pressure supercritical state.

d) Evaporated Propellant - Another means for using the liquid stored pressurant concept is to allow the vapor pressure of the propellants themselves to act as the transfer force. This can be done by conditioning the propellants to the temperature at which their vapor pressures are equal to the required transfer pressure. When a temperature other than ambient is desired, electric heaters or heat exchangers may be used. For short-duration missions temperature conditioning can be accomplished before launch, otherwise thermal conditioning equipment may be required by the logistics vehicle. For systems such as the WACS which employ hydrazine fuels and nitrogen tetroxide, secondary fluids such as NH_3 and NO may be mixed with the liquid propellants to increase the vapor pressure and reduce the required thermal conditioning.

e) Products of Chemical Reaction - Products of chemical reaction may also be used as pressurants. Combustion products may be generated inside the tank by injecting hypergolic liquids directly into the tank. This technique is often referred to as Main Tank Injection (MTI). Reaction products may also be generated outside the propellant tanks by gas generators employing liquid bipropellants, liquid monopropellants, solid propellants, or hybrid systems.

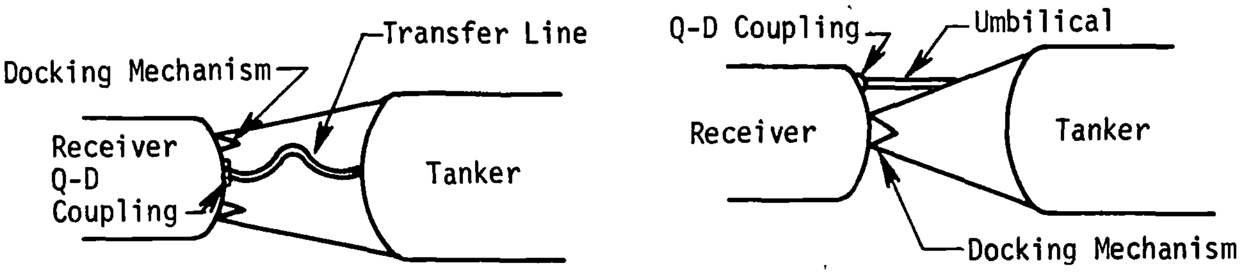
2) Pump Transfer - In addition to the pressurized transfer techniques outlined above, mechanical pumps were also considered for transferring propellant from the logistics vehicle to the Space Station. Although a variety of auxiliary power sources and types of pumping units are available for this application, the added complexity of a pumped transfer system is difficult to justify for the relatively low flow rates required for propellant resupply. Addition of a pumping unit and an electric or a turbine drive does not eliminate the requirement for ullage control or pressurization of the transfer tanks, since even assuming a minimum NPSH transfer pump, something on the order of 20 psia must be maintained in the NTO transfer tank to avoid vaporization in the lines.

3) Ullage Control Forces - In addition to pumping and pressurization systems, certain of the ullage control techniques such as capillary and acoustic pumps, dielectrophoresis, spray impingement, and vehicle acceleration were recognized as potential energy sources for propellant transfer. These approaches were eliminated from further considerations, however, based on their development status, limited performance capability, or excessive weight.

c. Transfer Line Coupling - In addition to the requirements for providing ullage control and fluid transfer energy, use of transfer lines for resupply of propellants will require that a suitable method of connecting the lines be developed.

Two basic methods are available for joining the logistics vehicle and Space Station. The first is docking of the two vehicles to form a rigid, combined control unit. The second method is to form the connection with a flexible line leaving each unit independently controlled.

For the rigid docking system, the propellant transfer line may be part of the docking structure and automatically coupled during the closure maneuver as in Fig. A-20(a). Another approach is for a separate umbilical to be used, as shown in Fig. A-20(b). The umbilical connection may be made remotely through use of a boom or similar mechanical device or by manual coupling.



(a) Docking with Direct Coupling (b) Docking with External Umbilical

Fig. A-20 Transfer Line Coupling by Docking of Vehicles

The second concept involves proximity rendezvous of the vehicles with mating using a flexible or semirigid umbilical A schematic of such a possible system is shown in Fig. A-21. The umbilical may be coupled by either remote control (extendable boom) or EVA. Only the rigid docking approach is considered applicable for the Space Station resupply function since transfer of personnel and packaged cargo already require this capability. It is also possible that safety considerations will demand that coupling of the transfer lines be made in an unpressurized area external to the access tunnel. Detailed aspects of the coupling mechanism must be considered as an integral part of the docking system, however, and as such were not considered in detail during this study.

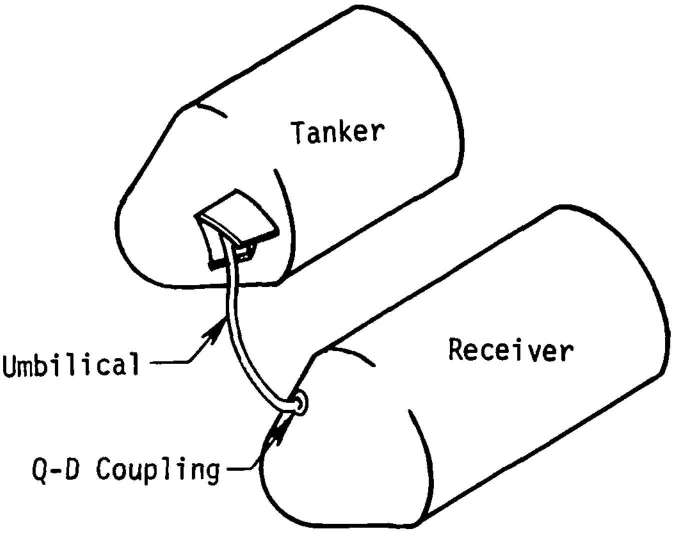


Fig. A-21 Transfer Line Coupling by Proximity Rendezvous

2. Modular Replacement of the Propellant Storage Tanks

A second fundamental approach to propellant resupply consists of a modular replacement of the propellant storage tanks. Expended propellant tanks can be replaced by loaded ones at each resupply cycle.

In general three requirements must be met if modular replacement is to be used as a resupply technique.

First of all a transporting mechanism must be provided, secondly a container design must be developed that will provide adequate protection against mechanical damage during the transfer process, and finally a means must be provided for isolating and removing the expended tanks from the remainder of the system and for recoupling the replacement tanks.

a. Transporting Mechanism - Propellant storage tanks as well as other packaged cargo can feasibly be transferred from the logistics vehicle to the Space Station by crew members using some form of auxiliary handling equipment. EVA can be avoided by transporting the packages through the docking port and access tunnel to the unpressurized consumables storage area within the Space Station structure. Judging from the results of Ref A-8, the present baseline propellant tanks are too large for efficient handling by one man without auxiliary handling equipment such as guiding tracks, harnesses, or other mechanical handling aids. However, since similar devices will surely be required for handling other packaged cargo, they should probably not be considered a serious penalty in the development of a modular propellant resupply technique.

b. Mechanical Protection - Another major factor in the development of a resupply system requiring movement of loaded propellant containers will be the packaging of the containers to preclude mechanical damage and subsequent propellant spillage. Although a number of design variations are possible, the most promising appear to be double walled designs of honeycomb or foam construction. With these devices protective provisions are incorporated as an integral part of the container design. Another approach might be to install removable protective shells during the transfer process only.

c. Tank Replacement - Self-sealing disconnects can be used to facilitate isolation, removal, and replacement of expended propellant tanks. As illustrated in Fig. A-22, disconnects can be installed in both the pressurant and propellant distribution lines to provide simultaneous isolation and disconnect of the replaceable module. Crew safety becomes a major factor when considering this approach, however. Since personnel will be in contact with pressurized tanks containing unvented residual propellants, this scheme relies heavily on foolproof operation of the disconnects to prevent exposure of the crew and adjacent equipment to hazardous propellants. Handling of damaged or malfunctioned tanks must also be recognized as a potential requirement.

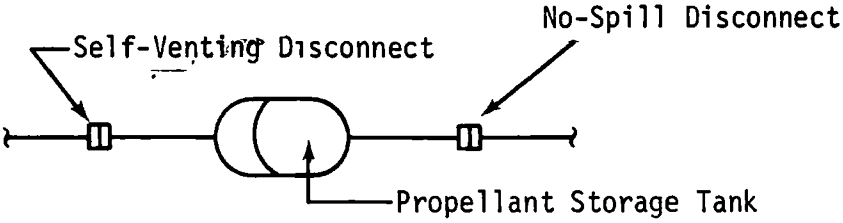


Fig. A-22 Modular Replacement of Tank Using No-Spill Disconnects

Handling hazards can be minimized by installing isolation valves as shown in Fig. A-23 to isolate, depressurize, and vent the tank modules. Purge and bleed-in is not anticipated since the propellant side of the tanks will be vented to a hard vacuum, and since entrapment of gases at the line connections will also be impossible, again due to the vacuum environment. Some means of capturing the vented vapor may be necessary, however, to prevent damage to the Space Station exterior, such as radiators and solar panels. Interconnects between tanks will also be required to transfer propellants from one partially expended tank to another. This is necessary to minimize handling hazards and residual propellant losses in the event that premature replacement of a tank is required.

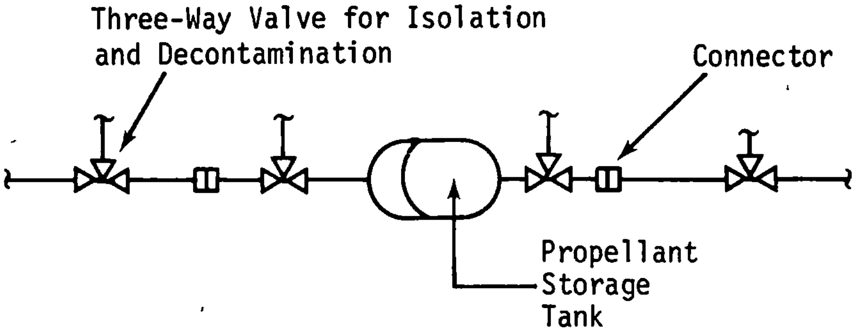


Fig. A-23 Modular Replacement of Tank Using Mechanical or Brazed Connectors

In spite of the above provisions, however, several design and system integration problems must be faced if this technique is to be used. These problems may be especially difficult to anticipate because of limited development experience in handling hazardous cargo in the operational environment of the Space Station.

Safety - Regardless of the design and procedural precautions taken to assure safe handling of propellant storage tanks, the requirement for routine and direct contact between personnel and the system represents a significant safety consideration.

Performance - The time required for propellant resupply is expected to be several times that required for the other techniques considered. This results from the number and complexity of operations involved in the resupply of a complete propellant load. Each expended tank must be checked out, depressurized, vented, and disconnected. It must also be transferred to the logistics vehicle and stowed. New tanks must be checked out and conditioned for transfer to the Space Station. They then must be installed and again checked out before they are put on line. Even assuming efficient and rapid handling techniques, the number of tanks involved may require an excessive amount of time.

Integration Potential - Simultaneous use of the access tunnel for transfer of personnel or other cargo will be prohibited. This must be compared to the fluid transfer technique that can be accomplished concurrently with bulk cargo transfer.

Cost - Since refurbishable or expendable tanks will be required for each resupply cycle, fabrication and refurbishment costs must be carefully controlled if this technique is to be economically competitive for a long-duration program.

It is also significant, however, that some of the design problems discussed above are probably unavoidable in that the capability of replacing malfunctioned or damaged tanks will almost certainly be a maintenance requirement. Use of a modular resupply technique will also have a significant impact on long-duration mission reliability. The extreme long-life requirement will be avoided.

Since empty weight of the propellant tanks (376 lb) represents a severe weight penalty for the baseline design, the opportunity for using a lightweight, limited cycle expulsion technique also represents an attractive design option. The necessity for such heavy tanks (47 lb/tank) arises primarily from the requirement for a long-life recycle capability. Even allowing for mechanical protection of the tank shell, tank weights could probably be reduced to less than one-half of their present weight if a minimum weight single cycle expulsion design were employed. Use of this technique might also reduce the logistics vehicle weight, although probably not to such an extent.

C. PRESSURANT RESUPPLY DISCUSSION

A number of approaches were evaluated for resupply of the baseline pressurization system. In addition, the feasibility of several modified systems was also evaluated to determine their potential effect on resupply requirements.

1. Baseline System

The baseline system uses high-pressure ambient temperature nitrogen as a pressurant source. This system can be resupplied by either of two basic methods: fluid transfer, or modular replacement of the gas storage spheres.

a. Fluid Transfer - Making use of fluid distribution lines, the gaseous nitrogen storage bottles of the baseline system can be resupplied by blowdown of high-pressure gas onboard the logistics vehicle or by vaporization or thermal compression of cryogenic nitrogen.

1) Blowdown - Gas can be transferred through fluid distribution lines by allowing pressures to equalize between the expended storage bottle and the charged resupply bottle. High-pressure blowdown represents a well-established, uncomplicated technique for transferring pressurant from one storage bottle to another, and as such should provide a highly reliable resupply system requiring a minimum of maintenance or replacement.

However, a major disadvantage does exist in that large pressurant residuals will be left in the logistics vehicle storage bottles. These residuals represent a severe weight penalty not only in terms of pressurant but more significantly in the volume and pressure level required by the storage bottle itself. A simplified analysis of this effect -- based on an initial transfer pressure of 6000 psi -- indicates that to transfer 30 lb_m of usable N_2 to the Space Station, from 80 to 120 lb of initial pressurant and from 70 to 100 lb of bottle weight must be carried by the logistics vehicle. To achieve the lower values (80 and 70 lb), transfer rates must be low enough to allow time for thermal equilibrium to be achieved between the residual pressurant and the ambient.

Several other methods were also considered for reducing or effectively using the residual pressurant. As discussed during the evaluation of propellant resupply techniques, high-pressure stored gas represents a most attractive energy source for propellant transfer. Use of residuals from the pressurant resupply operation would eliminate the requirement for a separate pressurant source for propellant transfer. The quantity required (20 lb including the bottle and miscellaneous hardware) is small compared to the available residual quantities, and consequently should not be considered a major factor in the selection of a pressurant resupply technique.

Other methods of reducing residuals such as compressors or heaters were also considered. A major disadvantage associated with these techniques is that they greatly compound the problem of compressive heating of the transferred pressurants. Rapid loading of the Space Station receiver tanks will result in severe compressive heating of the pressurant, with resultant temperatures as high as 300 to 400°F. This condition can be accommodated by oversizing the receiver tanks or by controlling the servicing rate so that sufficient time is allowed for thermal equilibrium to be achieved. Reducing residuals using a compressor or by installation of heating elements in the logistics vehicle transfer tanks will further add to the thermal problem by demanding either increased transfer time or possibly thermal conditioning of the transferred pressurant. Since free convection inside and outside the receiver bottle will not occur because of the lack of atmosphere and buoyancy forces, heat transfer will be greatly reduced in the environment of the Space Station. Close control and monitoring of the resupply process will also be required to "top-off" the receiver tanks without exceeding their design pressures or temperatures. Nevertheless, use of such devices may be expected to reduce the weight penalty associated with residual pressurant by as much as 50 lb_m.

2) Supercritical Cryogenic Nitrogen - The logistics vehicle storage bottle can be loaded with liquid nitrogen and heat added to raise the pressure to a supercritical condition. As fluid is removed, additional heat is then required to maintain a supercritical state. Compared to storage at ambient temperatures, the primary advantage of this technique is that the combination of high pressure and cryogenic temperature results in a pressurant density even greater than that of liquid nitrogen and thus decreases the required storage volume and resultant bottle weight. An overall system weight reduction can be expected when compared to the blowdown system. Since the pressurant remains at a supercritical state during withdrawal, liquid/vapor separation is not required as in the case of a subcritical storage system.

Opposed to the expected weight advantage, however, are several problem areas resulting from the sophisticated components required for cryogenic storage and operational control of the fluids. To accommodate anticipated standby requirements without excessive venting of pressurant, an extremely effective insulation system will be necessary, such as evacuated annular jackets with multiple radiation shields. Effective methods of suspending the pressure vessel, such as tensile wire supports, insulation pads, or rods will also be required. Precise monitoring of operating conditions and control of electric heaters and heat exchangers is required to prevent overpressurization and subsequent venting of pressurant or excessive pressure decay. Design of components is also complicated by the wide range of operating temperatures and pressures.

The above characteristics will have a major effect on reliability, cost and maintenance requirements. These factors in conjunction with the required complexity of ground servicing equipment and procedures will also be a significant handicap in the development of a low-cost logistics system.

3) Subcritical Nitrogen - Nitrogen can also be stored onboard the logistics vehicle as a cryogenic liquid and vaporized by an electric heater or heat exchanger when transfer to the Space Station is required. Although high-pressure transfer can be accomplished using a compressor instead of by heating the liquid to supercritical conditions, the relatively small storage volume required -- approximately 1 cu ft -- does not allow a significant weight reduction by lowering of the bottle operating pressure. Consequently, weight of the storage bottle as well as complexity of the heat exchanger/vaporizer and associated control equipment is comparable to that of the supercritical cryogenic storage system discussed previously. Because liquid/vapor separation is required in the subcritical design and is not required for supercritical storage, the latter approach is clearly preferable for this application.

b. Modular Replacement of Pressurant Storage Bottles - As in the case of propellants, a second fundamental approach to resupply of pressurants is that of modular replacement of the storage assembly. Although in both cases common requirements exist for development of transportation, mechanical protection, and installation techniques, the reduced number, size, and mass of the pressurant spheres makes modular replacement much more feasible.

1) Transporting Mechanism - Based on the empirical results of Ref A-8, the reduced dimensions and mass of the pressurant bottles will allow simultaneous transfer of at least two modules. This can be accomplished efficiently by one man using a minimum of auxiliary handling equipment, probably a simple guide cable or hand rail.

2) Mechanical Protection - Protection is of course absolutely essential since rupture of a loaded storage bottle would likely be catastrophic. This factor must be viewed from a realistic perspective, however. One must consider the possibility of failure of a pressurant bottle during handling as compared to the same possibility resulting from alternative servicing techniques and operational hazards. It seems probable that development of a lightweight foolproof design for mechanical protection during transfer will be easier than the development of corresponding servicing and operational procedures.

3) Tank Replacement - Tanks can be replaced using conventional disconnects and three-way valves to depressurize and remove the expended bottle and to isolate and install the replacement unit. Since hazardous vapors or bulk propellants are not involved, provisions for vapor recovery or transfer of fluid from one vessel to another will not be necessary.

4) Safety - Development of lightweight protective devices to prevent mechanical damage during transfer seems entirely feasible. The charged replacement bottles can be packaged, isolated, and checked for overpressurization or damage before transfer; thus minimizing the hazard during handling.

5) Performance - Although modular replacement affords a potentially minimum weight design, current development experience is limited. Efficient handling techniques must be developed if this approach is to be competitive with fluid transfer techniques in terms of resupply time.

Assuming timely development, however, modular replacement can be expected to provide a very reliable approach. Since inspection and refurbishment of storage bottles should be relatively simple, reuse of expended tanks will reduce operating and maintenance costs to a minimum for both the Space Station and logistics craft.

c. Recompression of Ullage - Routine resupply of pressurant can be avoided by recompression of the ullage gas, thus reducing resupply requirements significantly. Leakage makeup can be supplied by the N_2 source from the EC/LSS. The complexity of such a system, as illustrated in Fig. A-24, represents a major handicap, however. To be competitive with other resupply techniques the compressor system would almost certainly be integrated with a common coolant loop, radiator, and power source. In this event resupply must be scheduled to avoid periods of peak power and coolant demands. To maintain power requirements below 1 or 2 kw, operating durations of at least 1 hr should be anticipated. The number and complexity of mechanical components will also significantly effect reliability and increase maintenance requirements. Initial launch weight of the Space Station will be increased by the weight of a coolant pump, partial coolant loop, heat exchanger, and compressor. Safety considerations will also demand that provision be made to assure that mixing of propellant vapors cannot occur. Assuming a low cost logistics supply capability (on the order of $100/lb of payload) and a yearly resupply cycle, development and operating costs for such a system would clearly exceed the cost saving due to a reduced resupply requirement.

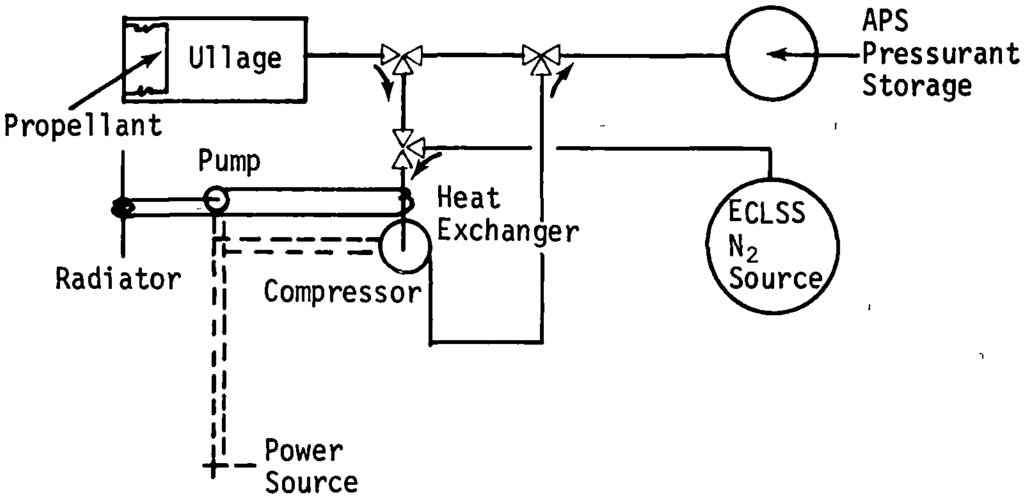


Fig. A-24 Recompression of Ullage as a Means of Pressurant Resupply

2. Modified Baseline Systems

The requirement for high-pressure gaseous storage of pressurant also can be eliminated from the baseline design by incorporating heated liquid, evaporated propellant, chemical reaction, or blowdown systems. These systems, previously described under the Pressurization section of the Propellant Resupply discussion, represent major modifications to the APS, however, and with the exception of volatile liquids and blowdown pressurization none of them are suitable for the Space Station APS.

Cryogenic systems are generally unsuited for APS-type duty cycles that demand high periodic flow rates followed by prolonged periods of relative inactivity. Such duty cycles require excessive heat input during engine activity to maintain required operating pressure and extremely effective insulation systems to avoid venting or overpressurization during standby.

Evaporated propellant systems are also unsuited for duty cycles requiring multiple restarts and prolonged standby times because thermal losses will result in condensation of the pressurant during periods of engine inactivity.

Systems using products of chemical reactions are also considered inapplicable for pressurization of the Space Station APS because efficiency of these systems depends heavily on elevated temperatures to provide pressurant gases with a high specific volume.

The foregoing thermal considerations are relatively unimportant when the mission duty cycle consists of a single firing because the temperature remains at a relatively high constant value throughout operation of the system. For APS applications, however, thermal effects become extremely significant -- particularly for systems using reaction products for the pressurant -- because condensation of the pressurant results in potential contamination of the propellant and/or hardware.

Volatile liquid pressurization represents a potential improvement over the baseline system for application to the Space Station APS. As illustrated in Fig. A-25, pressurization results from vaporization of a volatile liquid pressurant by controlled addition of heat. Operating characteristics of such a system are discussed in some detail in Ref A-9. The potential of this approach results primarily from two fundamental characteristics, namely the elimination of high-pressure gases and an inherent recycle capability that avoids any requirement for resupply of expended pressurant.

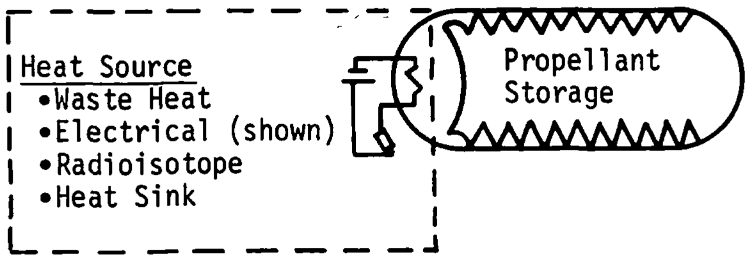


Fig. A-25 Volatile Liquid Pressurization

The major disadvantages of this approach are associated with integration requirements and an early development status.

To maintain propellant tank operating pressure during standby, a waste heat source can probably be used to avoid unnecessary use of electric power. During periods of high flow demand, the penalty for power consumption will probably be unavoidable unless a heat storage material is used.

Compression and condensation of the pressurant vapors during propellant resupply may also require a coolant loop or heat sink to minimize resupply time without overpressurizing the tanks.

Since these factors are extremely sensitive to duty cycle requirements, a quantitative evaluation of their effects is difficult at this stage of Space Station development. They do represent a recognized limitation in flexibility and growth potential, however.

Present estimates of cargo delivery costs also indicate that development costs of such a system would exceed the savings in logistics resupply expense.

The variations in propellant tank operating pressures inherent with this approach will also degrade APS performance, since engines of the baseline type are sensitive to these effects, particularly any pressure difference between fuel and oxidizer tanks.

Use of a blowdown pressurization system, rather than high-pressure regulated gas for the baseline APS, offers another technique for eliminating the requirement for scheduled resupply of pressurant. As illustrated in Fig. A-26, this approach would allow recompression of the ullage during propellant resupply and would thus avoid the necessity of a separate pressurant resupply system. The reliability and safety aspects of a resupply system

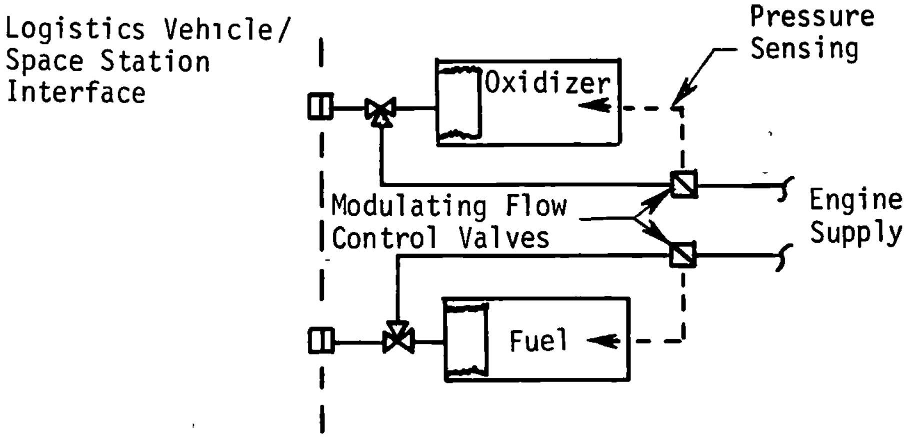


Fig. A-26 Bipropellant Propulsion System Using Blowdown Pressurization

of this type are also expected to be good, the major disadvantage being the development risk associated with developing a blowdown bipropellant APS that will perform satisfactorily. A reasonable development effort should be anticipated for a propellant and pressurization system which, over the complete operating cycle, will maintain suitable engine inlet condition, particularly during the pulse mode of operation.

Nevertheless such development is considered entirely feasible at this time.

Integrated nitrogen storage for the EC/LSS and the APS may afford another means of reducing overall Space Station and resupply weights by common use of resupply and storage equipment for both systems. The considerable nitrogen quantities required by the EC/LSS will clearly dictate that cryogenic storage be used by such a system. Although average EC/LSS nitrogen usage may be an order of magnitude greater than that required by the APS, peak flow demands will likely be established by the APS rather than by the EC/LSS. The question then becomes whether or not the additional heat exchange capability demanded by the APS outweighs the advantages resulting from an integrated system. Resolution of this question will require a rather detailed definition of system duty cycles, and as a result, any quantitative evaluation of this approach is premature at this time. Generally speaking, however, the tradeoff will be primarily between integration problems and potential weight savings.

D. INTEGRATED RESUPPLY CONCEPTS

The requirement for replenishing expended propellants and pressurant can also be incorporated into an integrated consumables resupply system. Three basic approaches have been identified. These are replacement of the propulsion modules, continuous supply from a docked logistics vehicle, or continuous supply from an attached consumables module.

1. Replacement of Propulsion Modules

Replacement of the propulsion modules represents one fundamental approach to the resupply of propellants and pressurant. As illustrated in Fig. A-27, the propulsion modules may be replaced by external mounted booms, handling arms, or by docking and attachment operations employing a tug or logistics vehicle.

(a) Docking Attachment (b) External Handling Equipment

Fig. A-27 Resupply by Replacement of Propulsion Modules

2. Docked Logistics Vehicle

As schematically illustrated in Fig. A-28 propellant and pressurant requirements can also be supplied by a logistics vehicle that is continuously docked between resupply intervals. Although such a system could be designed to supply propulsion commodities only, maximum use would suggest an integrated resupply system that provides the complete consumables requirement for the Space Station. In either case, the propulsion resupply system can also be integrated with the auxiliary propulsion requirements for the logistics vehicle.

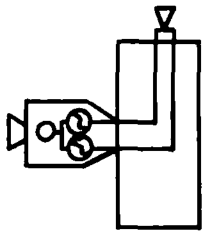


Fig. A-28 Resupply by Docked Logistics Vehicle

3. Attached Consumable Module

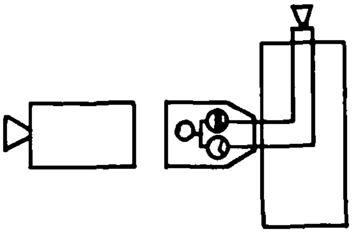


Fig. A-29 Resupply by Attached Consumables Module

The requirement for a continuously docked logistics vehicle can be avoided by providing a detachable consumables module as illustrated in Fig. A-29. Such an approach would allow immediate return of the logistics vehicle with an expended module or standby as an emergency return vehicle.

Several significant advantages can be realized by the use of an integrated consumables resupply system. Since major portions of the APS and/or EC/LSS would be included as part of the replaceable module rather than as an integral portion of the Space Station, requirements for inflight maintenance would be significantly reduced. This will allow design and development effort to be directed toward providing operationally optimum systems and will avoid the possibility of compromises in design to provide the additional capability for inflight servicing and repair. This effect should reduce subsystem development costs by a significant amount. Ground servicing and maintenance will also make Space Station personnel available for other potentially more productive activities.* Safety and reliability considerations should also be improved by minimizing the necessity of handling and processing hazardous fluids as well as by reducing crew/system contact. Growth potential will be improved in that additional total impulse capability can be provided by modifying or enlarging the resupply module rather than the Space Station itself.

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*The value of this effect depends, of course, on program objectives; for example whether the Space Station mission is directed more toward scientific experimentation or toward training of personnel and development of techniques for prolonged space compatibility. Use of replaceable consumables modules would to a large extent avoid the issue of inflight repair and resupply; when in fact, development and demonstration of this capability may be a major objective of the Space Station program.

Although total resupply weight is expected to be nearly equal for the modular resupply approaches and the consumables transfer techniques, a significant reduction in Space Station liftoff weight could be realized by a modular system, since much of the system hardware and all of the required consumables would be carried by the logistics vehicle.*

The major disadvantage of integrated resupply approaches are associated with potential program and vehicle integration problems. Use of these techniques may place unacceptable operating and configuration constraints on the design of the logistics craft and Space Station. Since these factors affect major program elements, integrated consumable resupply systems will require evaluation at the program definition level.

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*The potential value of this effect again depends on program considerations and launch vehicle/payload integration factors. This approach would require placing an inactive unmanned Space Station into orbit and then activating it by attaching the propulsion module, logistics craft, or consumables module.

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