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STUDY OF DAMAGE CONTROL SYSTEMS FOR SPACE STATION

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Final Report

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16. Abstract

Promising damage control systems for detecting and locating overboard and onboard leak and damage modes on the Space Station were identified. These included a nitrogen use rate monitor, pressure wall-mounted transducer array, seal leak detectors, mass spectrometer, gas chromatograph and a portable leak detector. A hazard analysis, weight tradeoff analysis, and access and leak repair studies were conducted. It was concluded that damage control systems for Space Station are feasible and cost-effective.

Requirements for damage control systems should be reflected in future phases of the Space Station program.

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FOREWORD

This is the final report on the study of damage control systems for the Space Station performed under NASA contract NAS1-10184, Study of Damage Control Systems for Space Station and Preliminary Design of a Space Station Simulator. This study was conducted during the period from July 24, 1970 to October 24, 1971.

The final report on the preliminary design of a Space Station damage control simulator was published in March 1971.

The project was carried out for the National Aeronautics and Space Administration, Langley Research Center under the direction of Mr. Victor L. Vaughan, Jr. of the Structural Mechanics Branch, Structures Division.

The program was conducted by M. V. Scherb, Prinicipal Investigator and Study Manager for the McDonnell Douglas Astronautics Company.

This report was prepared by M. V. Scherb, E. S. Chambers, G. V. Colombo, D. C. Giedt, J. F. Harkee, G. P. Kazokas, T. J. Linzey, D. C. MacKallor, D. L. Magargee, K. E. Meadows, E. S. Mills, G. L. Murphy, Ph. D, E. R. Regis, J. S. Seeman, D. A. Tiede, M. M. Yakut, and J. A. Zelik, Ph. D.

Professor Anatol Roshko, Professor of Aeronautics, California Institute of Technology, acted as consultant to the program on the problem of noise sources from a choked orifice or crack.

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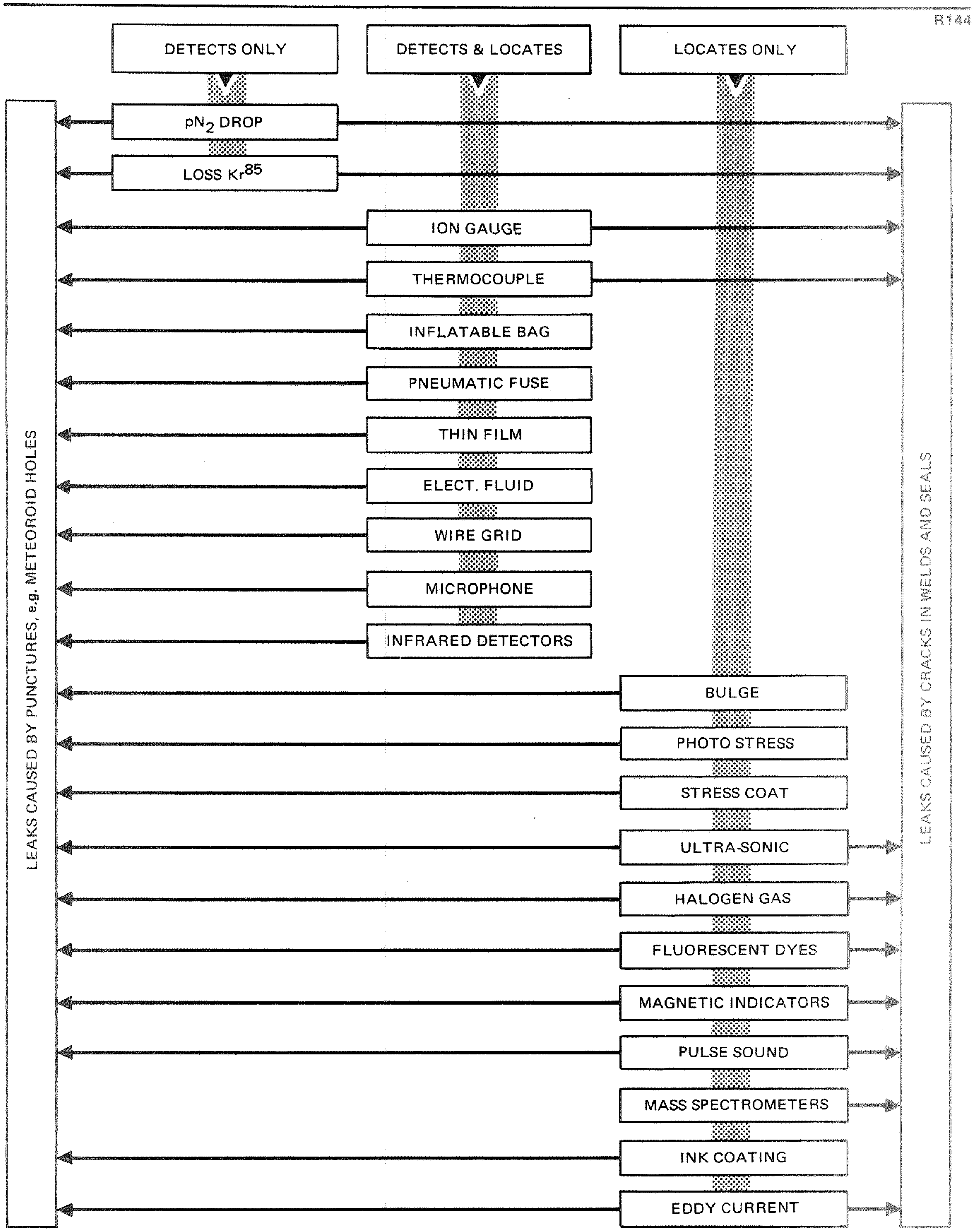
INTRODUCTION

Parallel Phase B definition studies of a 10.1-m-dia Space Station were recently completed by McDonnell Douglas Astronautics Company (MDAC) and the Space Division of North American Rockwell Corporation. The supporting research and technology plans from both studies (References 1, 2, and 3) identified the need for damage control systems on the station for the detection of leaks or significant damage modes conducive to leaks, such as meteoroid impact.

It was found that unplanned overboard leakage can threaten the safety of the crew, shorten the mission time, or pose a severe penalty in added weight for gas reserves. Onboard leaks from equipment, experiments, plumbing, and gas supplies can endanger crew safety by contaminating the Space Station atmosphere and presenting a threat of toxic gas or fire.

To minimize these hazards, a damage control system should be capable of sensing both onboard and overboard leaks, identifying and quantifying leaks. locating leaks, and indicating counteraction procedures by means of leak evaluation displays and crew warning systems.

Detecting overboard leaks or damage modes in the pressure shell of the Space Station under the vacuum conditions of space presents novel conditions for investigation. A recent state-of-the-art survey (Reference 4) lists 22 methods of detecting or locating overboard leaks. This survey, complemented by a review of current research on leak detection, served as a guideline for the selection of damage control systems for overboard leaks.



Summary of Overboard Leak Detection Methods

Section 1
SUMMARY

Results of the study indicated that an integrated overboard damage control system (DCS) should contain at least four independent sensor elements for maximum flexibility in identifying the presence and location of a leak and the precursor damage mode. These are:

A. A sensor which will monitor the pressurized compartment pressure and sense the rate of change of pressure as well as absolute pressure. For an oxygen-nitrogen atmosphere, nitrogen monitoring is preferable to total pressure since it eliminates variations due to metabolic consumption of oxygen by the crew. This type of sensor can detect and quantify a leak, but not locate it.

B. Sensors located on the pressurized compartment main wall in an optimum array to both detect and locate the source of a leak within a specific area. Ideally, the sensors will quantify the leak rate.

C. A sensor for monitoring the performance of seals. This sensor can detect, locate, and quantify the leak rate above the normal molecular diffusion (planned) rate of loss.

D. A portable leak detector to detect leaks to space from the interior of the pressurized compartment.

The basic pressure sensor for monitoring compartment atmosphere can be an independent sensor or the function can be integrated into the performance of a two-gas controller for the compartment atmosphere as part of the environmental control and life support (EC/LS) system.

Pressure wall sensor arrays preferably should be mounted internally to eliminate extra penetrations of the walls. However, sensors such as ion gages or thermistors could be mounted on the exterior in compartments formed by the main wall and a meteoroid bumper.

Wall damage mode detection techniques such as liquid crystals, Stresscoat, and such advanced nondestructive techniques as exo-electron emission, infrared radiometry, and holography (Reference 5) were not considered promising for space station. With the exception of a portable leak detector, the emphasis in this study was on sensing techniques which permit direct readout at a control center without the required presence of a man at the location of the damaged wall. This class of techniques does not readily supply remote readout.

Conventional portable leak detectors do not lend themselves to detecting an overboard leak from within a pressurized compartment. A promising detection technique for a portable leak detector to be operated inside of space station was identified in this study. The principle of operation is based on sensing the reduced pressure gradient which exists in the vicinity of an overboard leak to space.

Five detection concepts for overboard leakage show promise for further development in damage control systems for the Space Station. These are:

A. Nitrogen Use Rate Monitor—Detection accomplished by nitrogen channel of two-gas controller.
B. Passive Ultrasonics—Detection of impact stress waves produced by meteoroids, orbital debris, or docking impact. Detection of acoustic emissions generated by dynamic flaw or crack.
C. Active Ultrasonics—Pulse echo detection of flaw or crack.
D. Moisture Monitor (Seals)—Electrolytic hygrometry or capacitance.
E. Thermal Conductivity—Thermistor bridge technique as applied to seals and a portable leak detector.

For onboard leakage damage control systems, the most critical functions are: (1) to detect contamination of the crew compartment, (2) to sense incipient degradation of the EC/LS system, and (3) to monitor propellant storage tank lines and valving. An evaluation of onboard leakage contains many of the requirements for trace contamination and control. For onboard leakage detection, the emphasis is on sensors to monitor inventory depletion and system failures. Many of the sensors considered necessary are already under development for future manned space flights.

The following primary detection concepts show promise for integration into an onboard leakage damage control system for the Space Station.

A. Mass Spectrometer—Flight-type to allow measurement of high mass (molecular weights of 150 to 250) compounds.

B. Gas Chromatograph—Flexibility to use several column materials as well as detectors.

C. Flame Ionization Detector—Total hydrocarbon measurements.

D. Hydrogen Detector.

E. Infrared Analyzer.

Space Station parameters that have a major influence on the selection of damage control systems were evaluated. These included size of pressurized volume, station diameter, baseline-planned overboard leakage, noise background from onboard equipment, and crew safe time.

A mission hazard analysis was conducted to identify the type of leak or damage that each hazard may produce. Major mission hazards identified include loss of compartment pressure, loss of oxygen, collision with a meteoroid or space debris, docking collision, explosion, fire and smoke toxicity, and contamination.

A weight tradeoff analysis was carried out between the selected damage control systems and the weight of atmospheric supply reserves. The results of this study indicated that the weight penalty for the overboard damage control systems is rapidly exceeded by the weight of atmospheric reserves required to compensate for small overboard leaks from Space Station over time periods considered short compared to its projected 10-year life.

A study of methods and procedures for gaining access to the pressure walls of the Space Station emphasized that access should be designed into the Space Station for the least weight penalty. An evaluation study and ranking of various access methods indicated that the pivot and displacement methods were favored for a majority of conditions preventing access.

A parametric study of leak repair systems reveals that where practical, replacement of the defective component in the case of onboard leaks is preferred. Where replacement is not feasible, elastomeric sealants or epoxy adhesive patches are recommended repair methods for those fluids and containers permitting this approach. For remaining fluid-container combinations, an equally desirable method is the bolt and seal approach.

The preliminary design of selected onboard and overboard leakage damage control systems for the Space Station indicated that processing and storage requirements for the damage control systems represent about 10 percent of the total requirements for onboard checkout. Most of the damage control system sensor inputs can be monitored by the existing data acquisition system. Caution and warning signals as well as display and control requirements are compatible with the planned system for onboard checkout.

The final conclusion of this study was that Space Station damage control systems for both overboard and onboard leakage are feasible, cost-effective, and should be included in future design phases of Space Station.

Section 2
INFLUENCE OF SPACE STATION PARAMETERS

The baseline Space Station for this program is the Phase B definition Space Station as defined by the parallel studies of McDonnell Douglas Astronautics Company and the Space Division of North American Rockwell. This Space Station is a 10. 1-m (33-ft) dia four-deck structure with a volume of 850 m^3 (30, 000 ft^3). The original Phase B studies have been followed by current Phase B efforts on shuttle-launched modular Space Stations (Figure 2-1). For a modular Space Station, the basic module must be configured to fit the dimensions of the shuttle cargo bay which is 4. 27-m (14-ft) dia by 17. 5 m (58 ft) long. A typical crew module is a cylinder of 4. 1-m (13. 5-ft) dia by 9. 76-m (32-ft) length with a volume of 124 m^3 (4, 580 ft^3).

Basic parameters such as volume, diameter, and exposed area, which influence selection of damage control systems, can vary significantly between the extremes posed by the two types of Space Stations. The damage control systems (DCS's) selected at this stage must be versatile enough to adapt to any space station design. Two independent pressurized volumes with separate environmental control and life support systems are required in all Space Station designs. A key parameter, therefore, is the depressurization rate for an independent volume which can contain two decks—for example, in the 10. 1-m-dia Space Station—or one or more modules in the modular Space Station. Different volumes containing the same pressure and suffering identical size penetrations will undergo different pressure decay rates.

The depressurization rate, in turn, determines the available crew reaction time in that volume losing pressure due to a leak. This reaction time can be derived based on the pressurized compartment hole size and repressurization capability.

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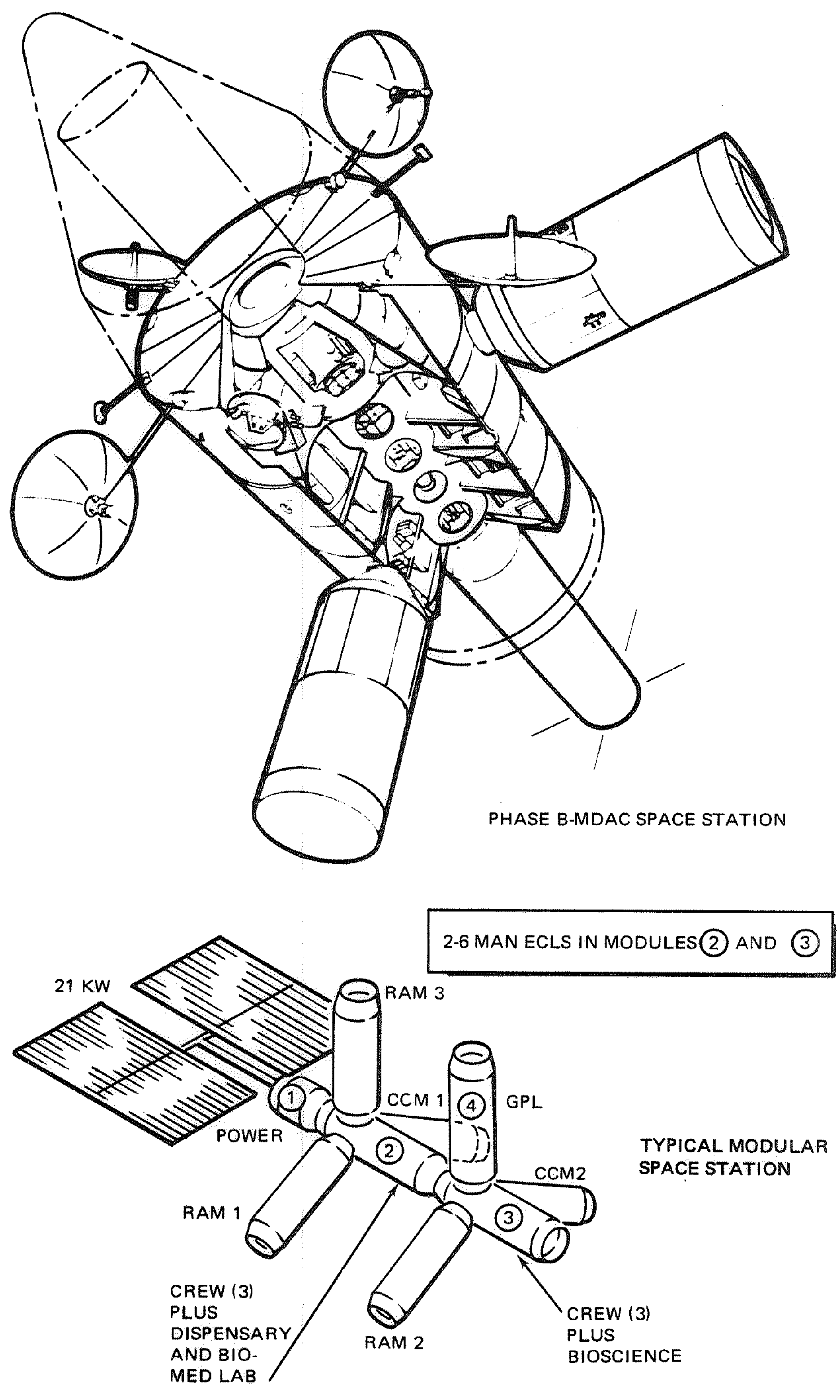


Figure 2-1. Space Station Configurations

Any surface area that is vulnerable to overboard leaks must be accessible to repair. Penetrations of the pressure shell are obvious sources of potential leaks. For example, meteoroid penetrations can occur anywhere. Where equipment cannot be moved in a short time, extra pressure wall protection (such as thickening the wall) can be provided.

Equipment mounted at the walls will provide added protection to the interior, but the area hidden must be accessible, and the equipment must be repairable or replaceable. Provisions for swinging the equipment out from the wall and other techniques for accessibility add weight to the vehicle. Tradeoff studies must be performed early in the design effort to consider the criticality of the equipment, additional weight of shielding, and meteoroid puncture probabilities.

Similar considerations apply to onboard leaks in that access must be provided to pressure vessels, pumps, and pipes to ensure that the leak can be located and repaired.

2.1 ACCESSIBILITY WEIGHT ANALYSIS FOR METEOROID HAZARD

Figure 2-2 presents a curve showing the minimum acceptable increase in accessible area per kilogram of added weight as a function of meteoroid penetration probability for a vehicle having a total vulnerable surface area of 500 m^2. This curve was derived as follows:

A. The requirement for the probability of no meteoroid penetration is established (e.g., 0.99 over a one-year period).

B. From the probability, the allowable risk is determined (1 - 0.99 = 0.01 per year).

C. The minimum value for the change in reliability per unit of added weight for design improvements is established (e.g., $\Delta R/\Delta W$ cutoff $\geq 33 \times 10^{-6}$ per kg). The cutoff value of $\Delta R/\Delta W$ is normally established in reliability studies during configuration selection. The goal is to obtain an optimum vehicle based on a weight distribution to obtain the greatest vehicle improvement for the least weight and cost penalty. The value 33×10^{-6} per kg was established for the Phase B space station.

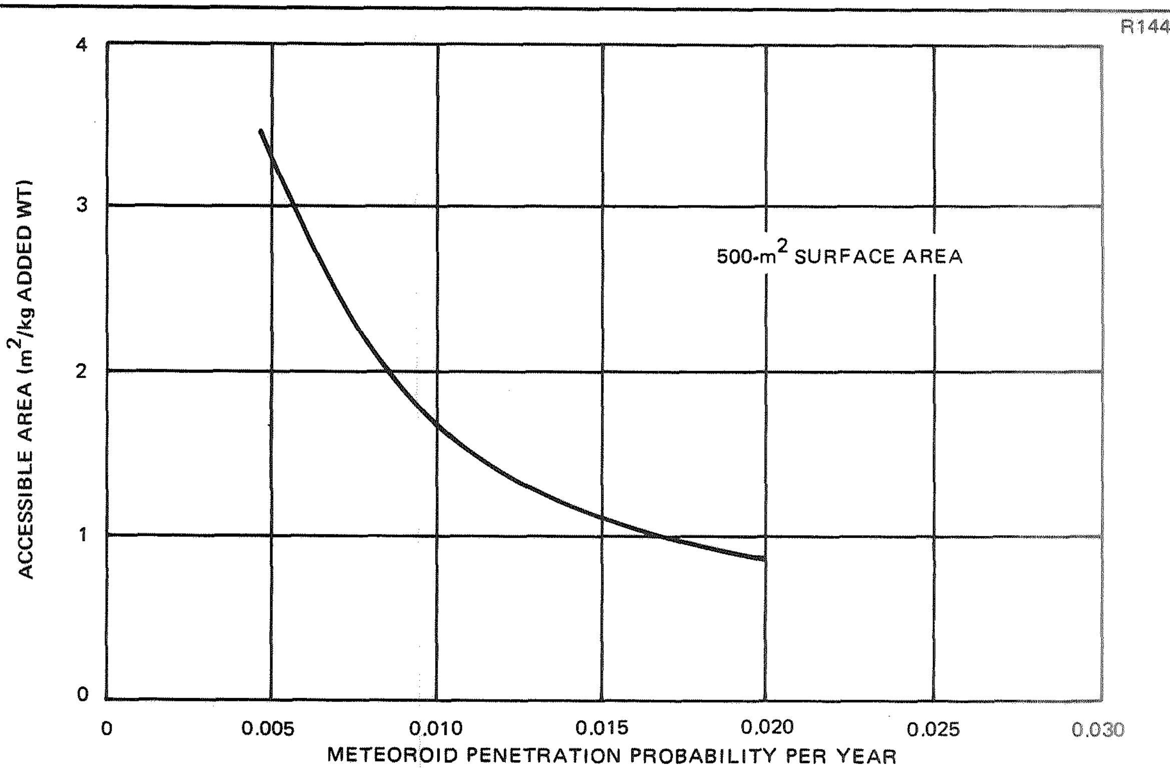


Figure 2-2. Accessible Area Weight Penalty vs Meteoroid Penetration Probability

D. The total weight allowable for accessibility at the above penetration probability level is derived ($0.01/33 \times 10^{-6}$ = 303 kg[665 lb]).

E. By dividing this last value into the total vehicle surface area, the minimum acceptable accessible area per kilogram of added weight is obtained. For 500-m^2 surface area, 500/303 = 1.65 m^2 of accessible area per kilogram would be acceptable to satisfy the reliability requirement.

The minimum acceptable accessible area per kilogram added weight increases as the probability of penetration decreases.

2.2 INFLUENCE OF SIGNALS FROM ONBOARD EQUIPMENT

Onboard noise or signals which may influence the selection of DCS can arise from subsystems (e.g., EC/LS, communications, power, and control moment gyros) or experiments.

Specific components include ventilation fans, rotating machinery, intermittent motion devices, fluid flow pipes, and pumps. A recent study to develop improved leakage detection methods for the Space Shuttle (Reference 6) emphasized the need for background signatures in order to attempt to apply ultrasonic techniques to detection of leaks from pipes and tanks. Even though the noise level on a Space Station might be acceptable to the crew, it could be a significant source of interference for damage control systems based on acoustic detection principles. Acoustic signatures have been obtained for a wide variety of components as part of an effort to apply acoustic signature analysis to predictive testing checkout systems (References 7 through 9).

Most of the signatures not involving impact techniques yield waveforms at frequencies less than 50 kHz with the greatest number below 10kHz. As an example, control moment gyros (CMG's) are a major source of potential noise. As many as eight CMG's would be required aboard a Phase B 10.1 m Space Station. Recent acoustic measurements (Reference 10) indicate that acoustic energy was generated over a bandwidth from 22 Hz to 45 kHz. The noisiest frequency range measured contained the fundamental rotor frequency of 8,000 rpm.

Under separate contract (Reference 11), MDAC carried out background noise measurements in its Space Station Simulator to determine the influence of prototype onboard equipment on potential leak detection techniques. Particular emphasis was given to obtaining the acoustic signatures of the EC/LS system which had successfully completed a 90-day run.

A general conclusion as to the influence of signals from onboard equipment is that the noise spectra are likely to present considerable interference to acoustic leak detection systems operating in the frequency range below 100 kHz. Specific data can be obtained only by actual measurements in simulated layouts with appropriate shielding.

2.3 SPACE STATION LEAKAGE

A vital Space Station parameter which strongly influences the selection of overboard leak DCS is the leakage of atmosphere from pressurized compartments. Atmospheric losses are of two types: planned and unplanned. Planned losses are losses from air lock evacuation, ullage dumps, and the like. By definition, allowance is made for this class of leaks in the design of the atmospheric supply and control subsystem. Unplanned losses result from leaks through sealed pressure shell penetrations (leaks greater than molecular diffusion), cracks, and meteoroid penetrations. A leakage allowance must also be provided for unplanned leaks.

The basic relationship between equivalent hole size and atmospheric mass loss per unit of time for atmospheric pressure of 1.01×10^5 N/m^2 (14.7 psia) is shown in Figure 2-3. Leak rates represented by molecular diffusion through seals can be expected to be in the range of milligrams/sec (pounds/day). Leaks in the viscous flow range, as permitted by structural design or produced by unplanned events, can be significant and bear directly on the design of the DCS. For example, a sonic flow leak equivalent to a hole of diameter 2.54×10^{-4}m (10 mils) will produce an atmospheric weight loss of ~16 mg/sec (3 lb/day). A hole of diameter 7.6×10^{-4} m (30 mils) will produce a weight loss of $\sim 10^2$ mg/sec (20 lb/day). The figure shows that a small change in equivalent hole size will result in an unacceptable leakage that could not be economically compensated for by gas reserves. In an analysis of the atmospheric overboard leakage of the MDAC 10.1-m-dia Space Station design, Charhut et al (Reference 12) concluded that the planned leakage would be on the order of $\sim 10^{-2}$ mg/sec (2×10^{-3} lb/day). If the actual Space Station planned leak rate is close to this value, the probability of detecting leaks in the equivalent 10^{-4} m-dia hole size is enhanced.

2.4 HAZARD ANALYSIS

This analysis identified potential mission hazards and failure events leading to the particular hazard along with their possible causes and denoted controlling features required to offset these causes.

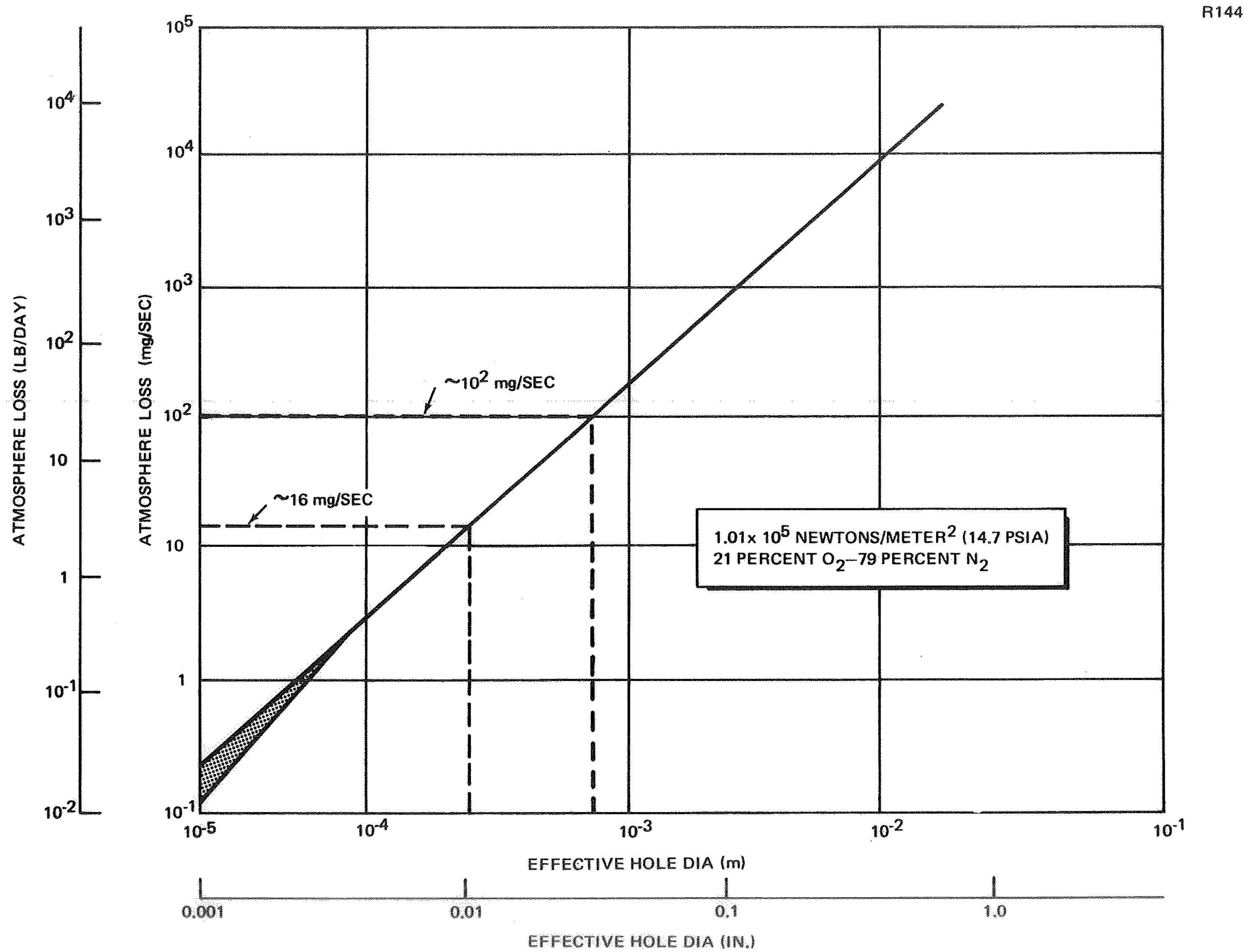


Figure 2-3. Atmosphere Leakage vs Hole Diameter

This analysis was performed for the NASA Space Station Phase B definition study. Failure modes and effects analyses were reviewed for input as were safety analyses. Additionally, the Space Station design was reviewed separately to determine possible damage from internal and external sources.

Figure 2-4 depicts gross hazardous events that could lead to vehicle loss or flight crew fatality. Analyses for these gross hazards are presented in Tables 2-1 through 2-7. First, a hazard is identified, then failures which could lead to the occurrence of the hazardous event and their possible courses are identified. Finally, design and procedural controls that can eliminate or significantly reduce the failure event occurrences are noted.

2.5 DESCRIPTION OF HAZARDOUS FUNCTIONS

Some specific potential hazards that have been identified as applicable to a Space Station type vehicle are further discussed below. These hazards, should they occur, can be expected to test the effectiveness of damage control systems and procedures.

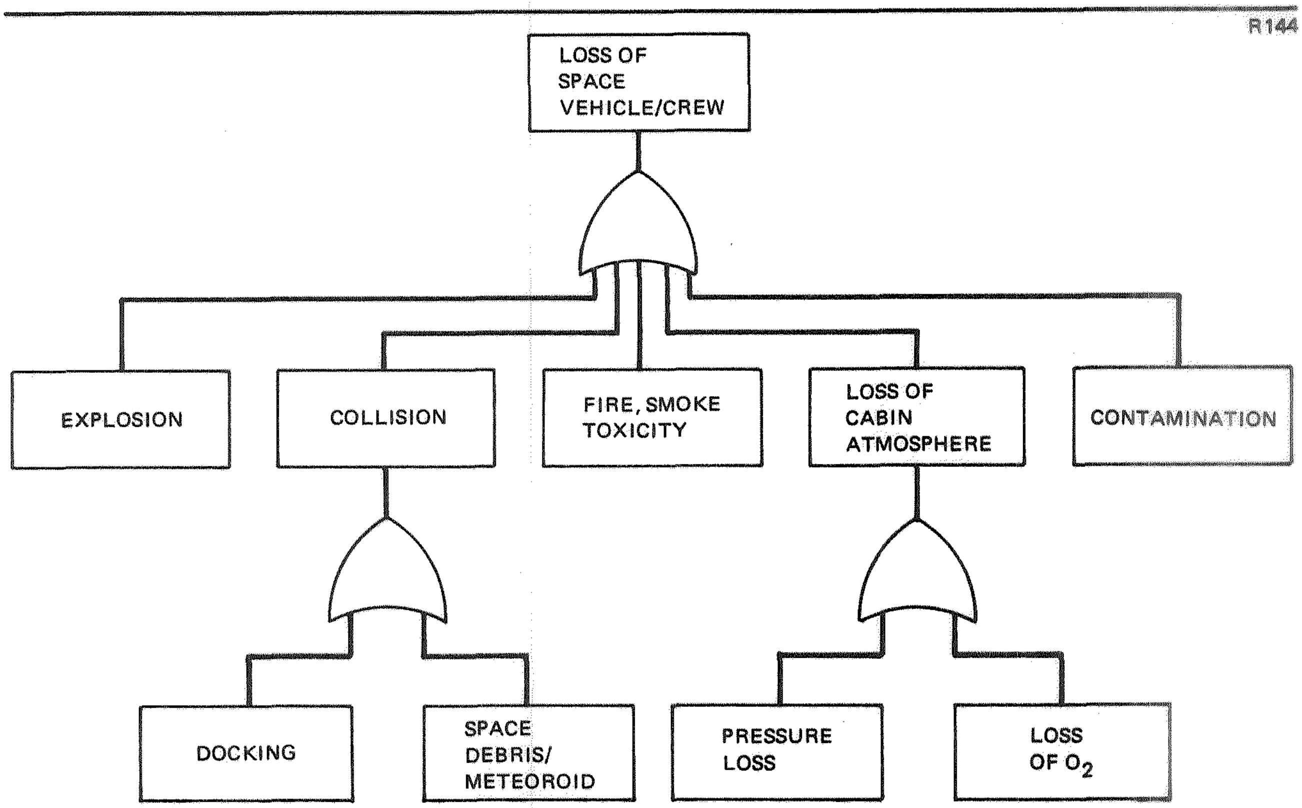


Figure 2-4. Mission Hazard Potential

Table 2-1

LOSS OF COMPARTMENT PRESSURE

Failure Event	How Occurring	Controls Recommended or Required
Dump and relief valves fail open or are opened, exposing compartment to space environment	Human error. O-Seal failure. Seat contamination. Fatigued springs.	Provide capping or fail-safe design for valves which can open to space environment. Provide capability to replace embrittled seals. Provide contingency procedure in the event valves fail open (e.g., seize masks, open hatch, and get out).
Propellant pressure vessels rupture or leak	Relief valves fail to open. Burst disks fail to rupture. Pressure vessels scratched or dented during production testing. HX fails. Lines blocked. Filters clogged.	Provide shielding in immediate vicinity of pressure vessels to absorb impact of shrapnel from pressure vessel rupture. Provide backup for failure of relief valves to open. Reinspect all pressure vessels for dings, and pressure test prior to launch. Provide capability and accessibility to repair or replace pressure wall. Provide for scheduled replacement of filters. Design to high safety margin for operating through burst pressure.
Docking collision*	Thruster failure. Pilot error. Optics failure. Communication failure. Radar failure.	Fail-safe thruster design. Completely independent braking thrusters. Redundant docking optics. Automatic shutoff of propellant flow to thruster if duration exceeded. Human engineering review of pilot thruster selection to eliminate error.

*Covered separately.

Table 2-1

LOSS OF COMPARTMENT PRESSURE (Continued)

Failure Event	How Occurring	Controls Recommended or Required
Docking collision* (Continued)		Require contingency (backup) if communications fail during docking. Manual override capability. Contingent pressure source.
Viewport seals, EVA hatches docking ports, etc. fail	Seals degrade and embrittle; antennas, solar panels, etc. are knocked off;hatch actuating or locking mechanism jams.	Provide redundant seals. Provide for scheduled replacement of seals. Provide contingency procedure for closing off compartments in event of severe leaks. Monitor total cabin pressure and flow. Provide audible or visual alarm if pressure deviates from certain limits. Provide sensors to detect leakage of pressure through seal and pressure shell. Monitor N_2 usage rule. Provide detectors to locate puncture. Provide patch kit. Provide sensor to locate hole. Develop contingency procedure which enables crew to egress rapidly from compartment in event of large hole, and rapid venting to space.
Equalization valve to airlock is opened, fails open, or leaks.	Human error. Seat contamination or deterioration. Galling or solenoid failure.	Provide fail-safe design. Provide redundant valves. Provide capability to replace valve.

*Covered separately.

Table 2-1

LOSS OF COMPARTMENT PRESSURE (Continued)

Failure Event	How Occurring	Controls Recommended or Required
Electrical circuit failure causing valve to open inadvertently	Short, part failure, open, bad connection, or circuit tolerance drift.	Provide manual override or bypass capability for all valves associated with pressurization. Use voting logic/redundancy in electrical circuitry. Design to wide tolerances.
Leakage of cabin atmosphere via feed-through assemblies	Seal embrittlement or degradation.	Provide sufficient backup gases. Provide seal replacement capability. Use double seals.
Loss of pressure control features so that too rapid use of pressurant occurs	Pressure control regulators or valves fail open (relief valves function properly).	Provide fail-safe design. Provide redundancy and manual backup. Provide overpressure alarm.
Collision with space debris*	Communications failure. Radar failure. Thruster failure.	Provide redundant critical components. Provide manual override.
Micrometeoroid penetration		Provide detectors to locate puncture. Provide patch kit. Provide contingency procedure to enable crew to egress rapidly from compartment in event of large hole and rapid venting to space.
Structural penetration	Hostile action.	Provide patching capability. Provide shielding. Provide contingency procedure for crew.

*Covered separately.

Table 2-2

LOSS OF OXYGEN

Failure Event	How Occurring	Controls Recommended or Required
Leakage	Fittings/valves, etc. leak	Provide shutoff valves Redundant O_2 storage tanks Monitor cabin O_2 level and provide alarm when not within certain limits
O_2 tank rupture	Relief valves fail Dings in tank Meteoroid hit	Isolate or shield tanks so rupture of one will not rupture other
Excessive usage	Regulators fail Leakage	Provide redundant components which control and regulate O_2 pressure

Table 2-3

SPACE DEBRIS, LARGE METEOROID COLLISION

Failure Event	How Occurring	Controls Recommended or Required
Communications failure	Loss of communications with the ground backing radar	Provide redundant communications capability
Radar failure	Component failure	Provide redundant critical components
Thruster failure	Failure to fire when collision course is determined	Redundant system
Multi-wall structure fails to stop meteoroid	Structural penetration	Locate equipment so as to minimize effects Provide repair capability including compartment evacuation by flight crew

Table 2-4

DOCKING COLLISION

Failure Event	How Occurring	Controls Recommended or Required
Optical failure	Optical tracking failure during final docking	Redundant optical reflectors Redundant angle tracker sensors and electronics Backup visual and audio contact High-reliability parts Provide manual override
Thruster failure	Fail to cease or start firing, or wrong thrusters activated High thruster fires prematurely	Fail-safe thruster design, redundancy Require contingency procedure Require crew training Require visual backup Automatic shutoff of propellant flow to thrusters if thruster duration is exceeded Manual override by docking safety officer up to point of impact.
Communications failure	During final docking maneuvers, a communications failure could be catastrophic if misalignment of docking ports occurred or the approach velocity is too great and dependence on voice contact is required for docking and latching	Provide active redundancy for critical components such as power amplifier, transmitter, and antenna to eliminate reaction time Use closed-circuit TV as backup Provide contingency procedure in event of communication loss during docking

Table 2-4

DOCKING COLLISION (Continued)

Failure Event	How Occurring	Controls Recommended or Required
Pilot error	Pilot pushes wrong thruster selection Highly probable, likelihood increases as number of dockings increases	Provide fail-safe design for thruster selection Require human engineering review of all docking operations and procedures Provide redundant docking lights and power source Use automatic docking
Radar failure	Very remote, since radar would not likely be used as distances become relatively small between Space Station and docking vehicle	Not prime during final docking maneuvers. However, a failure during approach could be propagated into a nonrecoverable collision course Provide redundant critical components and contingency procedures. Provide visual or audible alarm if velocity exceeds certain approach limits
Gyro failure	Gyro failure during final docking maneuver could cause momentary instability and impact	Evaluation of vehicle instability if gyro failure occurs, examine mass unbalance of both Space Station and docking vehicles, and provide necessary controls

2.5.1 On-Orbit Equipment Replacement – EVA and IVA

Due to the effects of zero gravity, provisions must be made to ensure that equipment being removed and installed does not damage other elements by collision (bumping) during the removal or replacement activity. During EVA repair, loose equipment must not be allowed to bump into the vehicle or externally mounted equipment. Protection will require thorough motivation of the flight crew and proper equipment design.

Table 2-5

EXPLOSION

Failure Event	How Occurring	Controls Recommended or Required
Rupture or burst of the following components located in Space Station, cargo module, or experiment module causing destruction of the Space Station structural integrity: Propellant tanks Pressurant tanks Pressure lines Pressure regulator Emergency O_2 tanks Freon accumulator Portable life support system	Relief valves fail to open Ding in tanks creates high stress point Human error—crewman hits tank with tool during EVA or maintenance function Docking shock Meteoroid puncture Poor weld joint Metal or weld fatigue Break in lines Tank heater fails on	Establish burst-to-operating pressure safety factor in excess of that required Use redundant relief devices Identification as mission-critical items and subject components to (1) special handling and shipping controls, (2) double inspection, (3) labeling, and (4) tight test controls Shield or place pressure vessels to avoid chain reaction if one bursts or design anti-shrapnel pressure vessels Locate in forward compartment, design blowout panel in pressure shell Provide redundancy and manual backup for heater controls
Premature activation of ordnance devices	RF energy present from RF filter failure	Fail-safe filter design Minimum use of ordnance
Batteries or black boxes rupture	Internal short results in overheating	Provide double stainless steel cases for battery and relief devices for black boxes
Thrusters explode	Thrust chamber overheats in presence of explosive mixture	Monitor thruster temperature

Table 2-5

EXPLOSION (Continued)

Failure Event	How Occurring	Controls Recommended or Required
Combustible gases or powders in presence of ignition source	Static charge builds up on IVA-suited crewmen and arcs to ground Hydrogen leakage from fuel cell plus the availability of an ignition source	Protect against any potential ignition sources Provide means to constantly ground crewmen during IVA Ensure that all hazardous experiments are conducted in controlled area Provide gas monitoring capability Provide purge capability of any areas where gas could accumulate
Structural breakup	Hostile action	

Table 2-6

FIRE, SMOKE TOXICITY

Failure Event	How Occurring	Controls Recommended or Required
Battery fluid or gas leakage	Overheating or internal shorting could cause outgassing and leakage of KOH or hydrogen	Require smoke, heat, and fire sensors in vicinity of batteries Need contingency procedure to get rid of KOH if leakage occurs
Electrical initiation	Power distribution wires short Electronic equipment explodes	Protect with circuit breakers or fuses Design boxes to prevent overpressure Use fire and smoke detectors near potential fire sources

Table 2-6

FIRE, SMOKE TOXICITY (Continued)

Failure Event	How Occurring	Controls Recommended or Required
Electrical initiation (Continued)		Provide automatic or readily accessible fire extinguishers
		Require contingency procedure for fire or toxicity
		Require redundant cooling circuits around boxes if cooling failure cannot be tolerated
Static electricity	Metal tools, etc. in contact with equipment	Arc proof tools or coated tools. Ground all equipment that can arc
	Charge buildup in clothing	Require procedure to ground crewmen before metal contact
	Inadequate grounding of equipment	
Combustible material and ignition source present together	Hydrazine flow piping connection leakage into a pressurized area	Provide shutoff capability and the capability to purge affected area
		Provide sensors to detect pressure of fuels
		Provide fire detection sensors and a fire suppressant system
		Mimimum use of combustible materials
Toxic fluid leakage	Piping breaks, piping connector leakage	Provide sensors and warning devices
		Provide shutoff capability and a capability to purge potentially affected areas
External explosion	Hostile action	

Table 2-7

CONTAMINATION

Failure Event	How Occurring	Controls Recommended or Required
High toxicity buildup	Materials outgas and removal devices fail or are inadequate	Provide redundant contamination removal capability
	Caution and warning unit fails to indicate buildup	Provide escape procedures and capability
		Provide redundant caution and warning capabilities
		Use strict materials control during design
		Provide temporary (masks, etc.) emergency provisions
Propellant leakage into cabin	Connection leakage where propellant transfer piping passes into or through the cabin	Weld all connections
		Provide monitoring and alarm capability, and crew escape procedures
CO_2 buildup	CO_2 removal device fails or becomes inadequate, and monitor and alarm unit fail to indicate buildup	Provide redundant monitor and alarm
		Provide redundant CO_2 removal capability

2.5.2 Propellant Storage and Distribution

In a large space vehicle, it frequently is necessary to transfer propellant from its storage location to its usage point, possibly through different compartments within the vehicle. Vehicle design must provide protection against potential leaks and breaks in the piping and provide damage control features.

The NASA/MDAC Space Station uses hydrazine (N_2H_4) for one of its propellants. Hydrazine has an auto-ignition temperature of 270° C (518° F). It is stored in tanks under pressure in the forward end of the vehicle and is piped to thrusters at the aft end. The most probable source of ignition is a spark in the vicinity of a leak. To prevent a spark, all electrical leads are physically separated from any propellant lines. Propellant-carrying lines are routed inside of ducts that are vented overboard and the area containing the storage tanks is vented. Additionally, brazing or welding of connections will minimize connection leaks.

2.5.3 Experiment Facility Failures

Facilities provided for the performance of potentially hazardous experiments should be isolated from the primary vehicle. Protection must be provided to shield the primary vehicle from potential experiment-created hazards.

The NASA/MDAC Space Station design provides an isolated facility with shielding provisions. Detailed attention is given to experiment design so as not to jeopardize the station itself.

2.5.4 Docking Port Collisions

Low-energy collisions during docking of two space vehicles, especially repeatable occurrences, can cause metal indentations, seal puncture, and other minor events that, after a significant period of time, can become leak points. Repair features and docking port isolation capability must be provided. Thorough wearout analysis must be incorporated into the design activities and periodic inspection of the mating surfaces and seals must be incorporated into the operational procedures.

High-energy collisions during docking operations can cause immediate puncture of the vehicle's protection. Procedures must be developed to allow for contingency operations. These could include compartmentization in design, the requirement that personnel facing possible vacuum exposure be suited for EVA, and additional protective features. Surfaces and equipment exposed to potential collision should be designed for easy repair or replacement.

2.5.5 Space Debris or Meteoroid Collision

Space vehicles with long-duration missions must provide protection against collisions with other space bodies including self-generated debris. The hazards due to self-generated debris were analyzed in a recent study of space rescue operations (Reference 13). Protection can include collision-avoidance features and shielding to preserve vehicle integrity. Further protection includes compartmentization and a damage control design.

2.6 TYPE OF LEAK OR DAMAGE PRODUCED BY HAZARDS

Typical mission hazards and the type of leak or damage that each event can cause are shown in Table 2-8.

Table 2-8

IDENTIFICATION AND DESCRIPTION OF MISSION HAZARDS

Hazardous Event	Cause	Damage Effects
Meteoroid penetration or partial penetration (orbital debris)	Impingement	Crack propagation Dimple or perforation Fire
Onboard failures - seal	Deterioration, improper installation, scratch in striker	Leak (replace seal), leak (replace seal), leak (repair)
-internal explosion	Relief valve failure, fatigue failure	Localized damage, pressure-wall perforation, injury to personnel, irreparable, leave station
Excessive vibration of the vehicle	Attitude control malfunction, equipment off balance, excessive engine irregularity	Distort seal and jamb, crack initiation, abort mission
		Damage of hatch seal
Collision with another space vehicle	Operational error, accidental operation	Hole or ding in pressurized wall
Hostile action	(Unknown)	Hole in pressure shell, destruction of Space Station

The damage caused by micrometeoroids is projected as a rare experience due to protection provided by the micrometeoroid shield about the Space Station. This projection is based upon a population of sizes and velocities. Nevertheless, the Space Station may be hit by a meteoroid causing a large hole in the pressure wall. For example, a hole 5.08 cm (2 in.) in diameter would be characterized by a ragged, tear-type opening. Smaller micrometeoroids that penetrate the shield can cause dimples and spalls on the inner surface of the Space Station wall. These will not produce immediate leaks, but could result in weakening the wall so that sustained stress on the wall could develop crack growth resulting in a leak. Cracks in this category are small, being equivalent to hole sizes from 2.54×10^{-5}-m (0.001-in.) dia to 2.54×10^{-4}-m (0.010-in.) dia, causing leakage of atmosphere up to ~16 mg/sec (3 lb/day). Early detection of the cracks will permit repair to prevent continued growth. Repairs of these cracks will be from the inside of Space Station, since the outside of the wall has thermal insulation and micrometeoroid bumpers inhibiting access to the pressure wall.

The hatch and view port seals nominally have very low leakage resulting from molecular diffusion through the seal. In the hatch it may be possible to have damage caused by disorientation of the seal, damage to the seal, or a scratch in the jamb at the seal contact region. Leakage from these types of damage can be from miniscule to very large (several hundred kg/day). The seals in hatches and windows can deteriorate after long periods of installation (2 to 5 years) resulting from shrinkage and cracking. This condition is progressive and minute leakage should be detected early in this deterioration cycle. This deterioration in view port seals may be less rapid than for hatches, due to the protection provided by the metal jamb about the seal and lack of exercising the seal.

Onboard leakage from equipment can occur at joints, through cracks due to fatigue in tubing, and at seals about rotating shafts. Another leak source could be cracks caused by pressure buildup in closed systems from malfunction of the pressure regulator or blockage in the system.

If the Space Station is exposed to excessive vibration, it is possible that leaks can be initiated through bolted joints and at seals due to seal damage or separation of the seal from metal contact surface. Such excessive vibration, if it persists, could result in evacuation of the Space Station because of potential injury to personnel. In this instance, the leakage should be sufficiently low so that evacuation can be successfully accomplished. Vibration can also cause cracks to be propagated through the wall of the Space Station, resulting in loss of atmosphere.

Damage from collision with another space vehicle may occur during docking maneuvers. Damage could occur also during buildup in orbit of Space Station modules. The momentum and location of the collision impact will determine the type of damage and the amount of leakage.

Damage from hostile action can range from small holes to complete demolition of the Space Station. Such damage modes cover the complete range from repairable leaks to catastrophic depressurization.

2.7 CREW SAFE TIME

An important parameter in damage control is identifying the time available for the crew to accomplish repairs. When atmospheric pressure decay is slow, repairs can be accomplished without the use of pressure suits. Conversely, when leak rates are high and atmospheric pressure decay is rapid, personnel should don pressure suits before attempting any repair of the leak. Safe time for the crew depends on vehicle volume, initial and final atmospheric pressure, and the size of the hole through which the atmosphere is being lost. The flow rate through a hole in a vehicle wall can be expressed mathematically in two different ways.

$$\dot{\omega} = 60(S)\ (A)\ (\rho)\ (C_G) = N\rho \qquad (2\text{-}1)$$

where:

$\dot{\omega}$ = flow rate (kg/min)

S = sonic velocity (m/sec) = 344

A = hole area (m^2)

ρ = gas density (kg/m^3)

C_G = coefficient of flow = $C_D\left[\gamma\left(\frac{2}{\gamma+1}\right)\frac{\gamma+1}{\gamma-1}\right]^{1/2}$ = 1.0

N = 60 (344) (1) A = 20640A

C_D = coefficient of discharge (Reference 14)

and

$$\dot{\omega} = V\frac{d\rho}{d\theta} \qquad (2\text{-}2)$$

where:

θ = time (min)

V = vehicle volume (m^3)

equating (2-1) and (2-2) produces

$$N\rho = V\frac{d\rho}{d\theta} \text{ and } d\theta = \frac{Vd\rho}{N\rho} \qquad (2\text{-}3)$$

$$\theta = \int_{\theta}^{0} d\theta = \frac{V}{N}\int_{\rho 2}^{\rho 1}\frac{d\rho}{\rho} = \frac{V}{N}\ln\frac{\rho_1}{\rho_2} \qquad (2\text{-}4)$$

since ρ is proportional to P

$$\theta = \frac{V}{N}\ln\frac{P_1}{P_2} \qquad (2\text{-}5)$$

returning to N:

$$N = 20640A = 20640\ (0.7854)D^2 = 16,200D^2 \qquad (2\text{-}6)$$

where

D = hole diameter (m)

substituting for N in equation (2-5) yields:

$$\theta = \frac{V}{16200D^2} \ln \frac{P_1}{P_2} \qquad (2\text{-}7)$$

or

$$\theta = 6.16 \times 10^{-5} \frac{V}{D^2} \ln \frac{P_1}{P_2} \qquad (2\text{-}8)$$

The normal partial pressure of oxygen is 2.07×10^{-4} N/m^2 (155 mm Hg) for all cabin pressures between 4.83×10^4 N/m^2 (7 psia) and 1.012×10^5 N/m^2 (14.7 psia). This oxygen partial pressure can be allowed to decrease to about 1.22×10^4 N/m^2 (91 mm Hg) before the cabin occupants will become concerned with the ability to perform tasks. This value then becomes the minimum allowable oxygen partial pressure. Since the composition of the residual gas in the spacecraft compartment will remain constant during leakage, the values 155 and 91 may be substituted for P_1 and P_2, respectively in Equation (2-8). Therefore, Equation (2-8) reduces to:

$$\theta = 6.16 \times 10^{-5} \frac{V}{D^2} \ln 1.71 \qquad (2\text{-}9)$$

Up to this point, a coefficient of flow of 1.0 has been used. Reference 14 presents detailed information on experimental bleed-down determinations.

Using the data from Reference 14, a realistic value of C_G of 0.46 was obtained from the relationship:

$$C_G = C_D \left[\gamma \frac{2}{\gamma + 1} \; \frac{\gamma + 1}{\gamma - 1} \right]^{1/2}$$

where

$C_D = 0.67$ and $\gamma = 1.4$

When the realistic value of C_G is applied to Equation (2-9), the equation reduces to

$$\theta = 7.13 \times 10^{-5} \frac{V}{D^2} \qquad (2\text{-}10)$$

Figure 2-5 depicts the available crew reaction time for a variety of vehicle volumes and equivalent hole diameters. Figure 2-6 shows similar information for a wider variety of conditions in a nomogram format. Using as an example a Space Station compartment of 424 m^3 (15,000 ft^3) and a 2.54 cm (1 in.) dia equivalent hole, the crew would have about 45 minutes to take corrective action before the atmosphere in the vehicle decays from 1.01×10^5 N/m^2 (14.7 psia) to 5.9×10^4 N/m^2 (8.6 psia). This is probably adequate time for the crew to locate and repair a readily accessible hole. If, however, the hole is not accessible or if the safe time is shorter, the crew would retire to another compartment of the Space Station, don pressure suits, and reenter the compartment to effect proper repairs.

The safe-time calculation presented here assumes that the leak is detected as soon as it starts. For large leaks, this is probably a true condition. For small leaks, the calculations presented here are pessimistic because the atmosphere control system will be adding gas as leakage occurs to maintain proper composition and pressures. Part of the damage control system function will be to calculate the safe time for the crew to correct leakage problems. When a leak is detected, it will be monitored and a gas loss rate

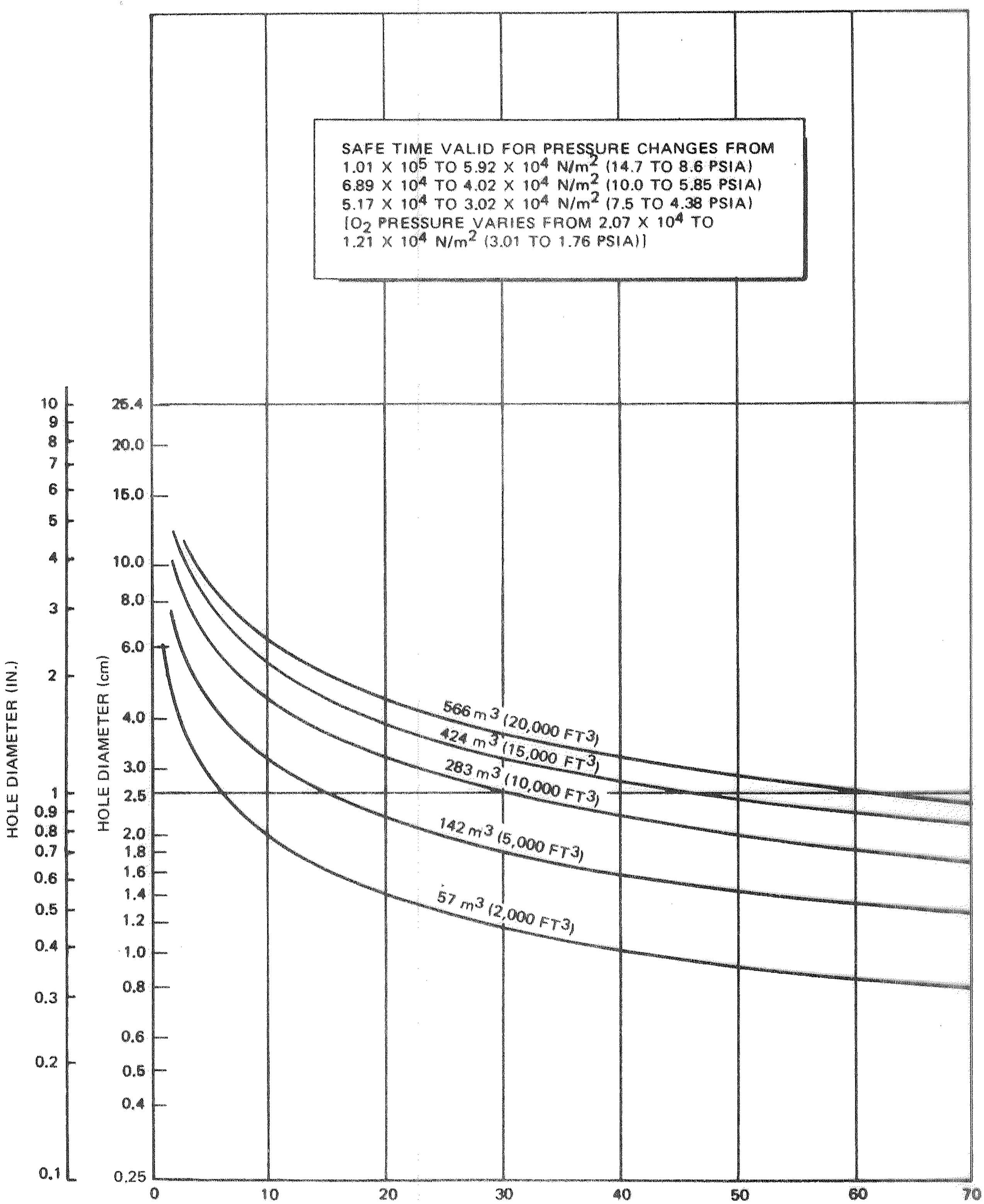


Figure 2-5. Safe Time for Crew Activities After Determining Leakage

THIS ALIGNMENT CHART VALID FOR PRESSURE CHANGES OF
1.01 X 10^5 TO 5.92 X 10^4 N/m^2 (14.7 TO 8.6 PSIA)
6.89 X 10^4 TO 4.02 X 10^4 N/m^2 (10.0 TO 5.85 PSIA)
5.17 X 10^4 TO 3.02 X 10^4 N/m^2 (7.5 TO 4.38 PSIA)
[O_2 PRESSURE VARIES FROM 2.07 X 10^4 TO 1.21 X 10^4 N/m^2
(3.01 TO 1.76 PSIA)]

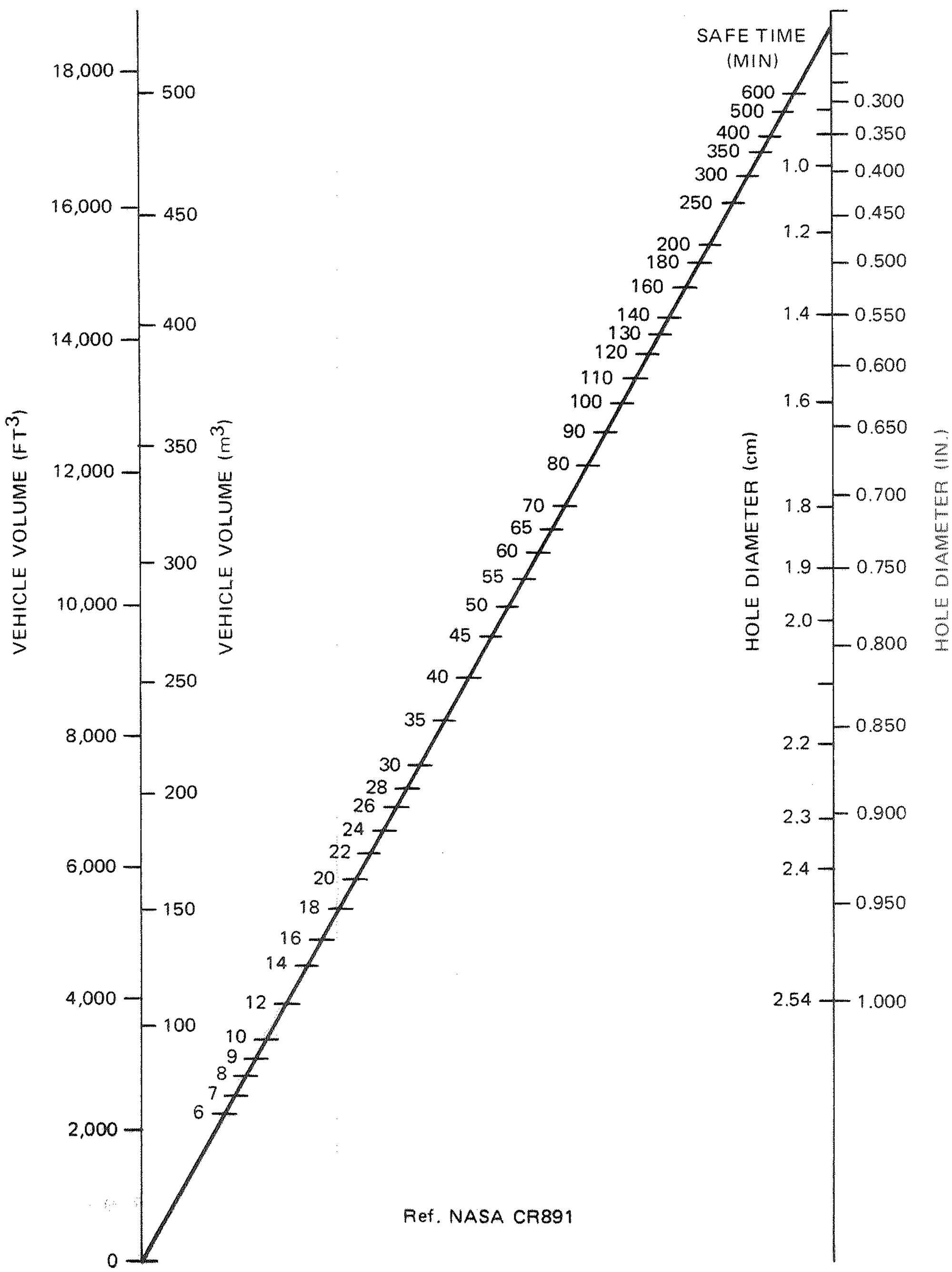


Figure 2-6. Nomogram of Crew Safe Time After Leakage Determinations

calculated. This can be converted to equivalent hole size, which can then be converted to safe time. These calculated values can be displayed on the various warning and display panels in the vehicle. During the period the crew is effecting the repair, the DCS computer can upgrade the calculations at regular intervals to keep the crew informed of how much time remains before they should leave the compartment and don pressure suits to complete the repair.

Figure 2-7 shows atmosphere lost in kg/day versus size of equivalent overboard holes for three nominal design pressures considered for space vehicles. These plots are independent of the volume of the vehicle.

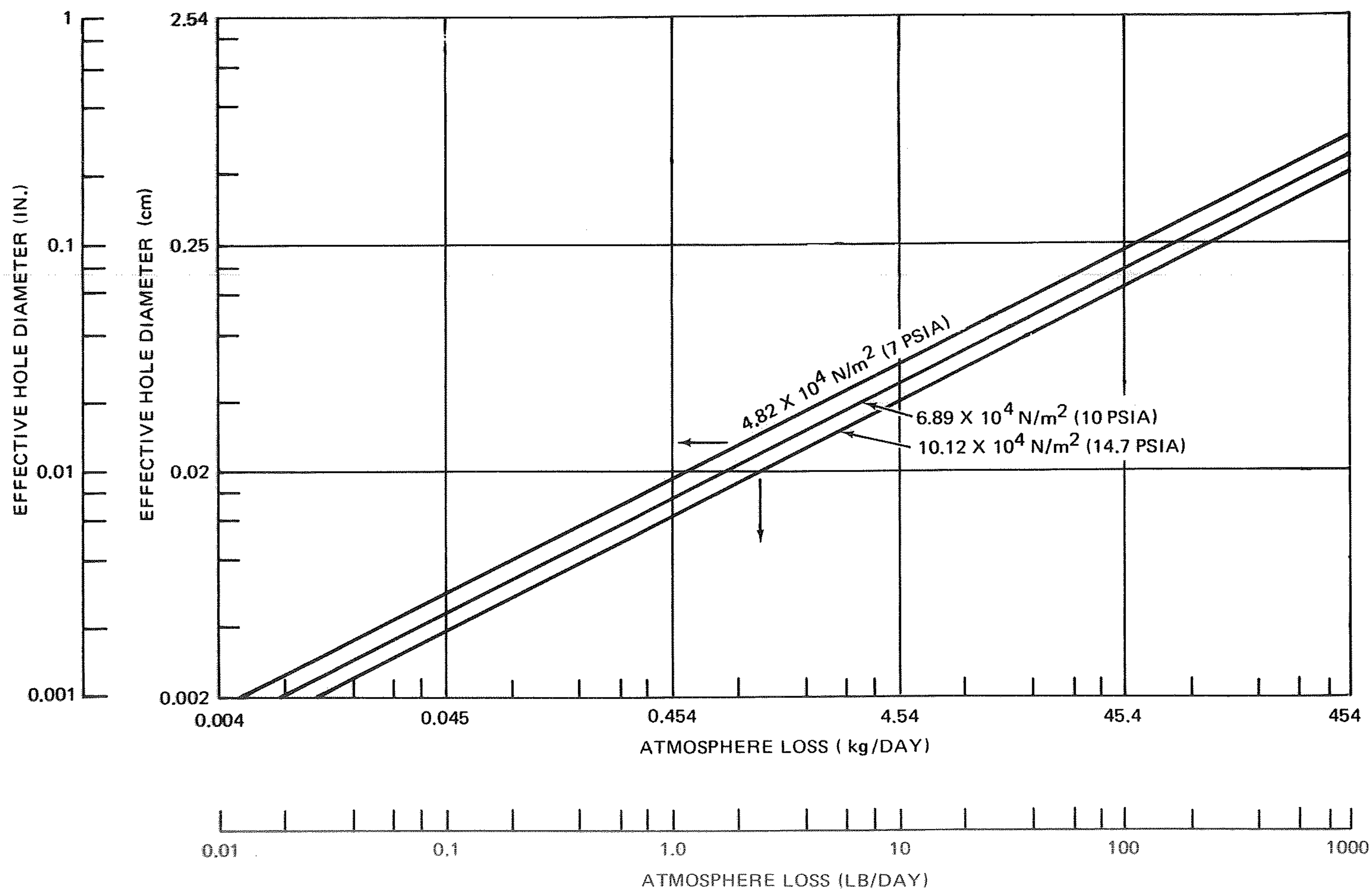


Figure 2-7. Atmosphere Loss vs Hole Size

Section 3
DAMAGE CONTROL SYSTEMS FOR OVERBOARD LEAKS

3.1 DEFINITION OF OVERBOARD DAMAGE MODES AND LEAKS

The function of damage control systems for overboard leaks is not only the detection and location of leaks, but also of pressure wall damage and defect modes which can be precursors to leaks. Such damage modes include dimples, bulges, cracks, and spall associated with meteoroid/orbital debris impact and the general class of static and dynamic cracks. Continuous surveillance monitoring of the pressure shell for both damage or defect modes and leaks will enhance the prospects for safe life of the Space Station structure over long-duration missions.

3.2 DESCRIPTION OF SELECTED OVERBOARD DAMAGE CONTROL SYSTEMS

A prime criterion for an overboard damage control technique is that it provide a remote readout at the command and control center. With the obvious exception of a portable leak detector, this criterion has been met.

The guidelines set forth in Section 1 recommended four independent sensor subsystems for maximum flexibility in identifying the presence and location of a leak or precursor damage mode. These are:

A. A sensor which will monitor the pressurized compartment pressure and sense rates of change of pressure as well as absolute pressure. For an oxygen-nitrogen atmosphere, nitrogen monitoring is preferable to total pressure since it eliminates variations due to metabolic consumption of oxygen by the crew. This type of sensor can detect and quantify a leak, but not locate it.

B. A sensor array which will be mounted on the pressure walls of the Space Station. By triangulation techniques, information can be obtained as to the presence and location of a leak or damage mode. Ideally, this system will quantify the damage mode.

C. A sensor which will monitor the performance of seals. This sensor can detect, locate, and quantify the leak rate above the normal molecular diffusion (planned) rate of loss.

D. A hand-carried portable leak detector to detect leaks to space from the interior of the pressurized compartment.

A two-gas atmosphere, pulse-rate-modulated controller was chosen as the compartment pressure sensor for monitoring gas leakage. In addition to its primary function of regulating the partial pressures of oxygen and nitrogen in the compartment, the controller supplies nitrogen pulse rate data as a measure of overboard or onboard leakage. This system has had extensive operational experience, most recently during the 90-day simulator test conducted at MDAC.

A transducer array mounted on the pressure walls consists of piezoelectric elements dispersed to ensure that a damage mode or leak will be detected and located by triangulation techniques. Three modes of operation were considered: (1) active ultrasonics (2) passive ultrasonics, and (3) a combination of both. Active ultrasonics involves a pulse-echo technique in which pulses are propagated through the pressure wall and ultrasonic reflections from cracks or holes are detected. This transducer array can also provide the function of a passive meteoroid impact gage system. It has been demonstrated at MDAC that typical wide-band active ultrasonic transducers such as PZT and lead metaniobate will readily respond to simulated meteoroid impacts.

Conceptually, a pure passive array can detect meteoroid impacts and acoustic emissions from dynamic flaws. In the meteoroid impact case, crack propagation may be directly related to the primary debris impact on the pressure wall. Although signal amplitudes differ in magnitude and frequency distributions, signal conditioning techniques can handle the dual passive function.

Three sensor concepts showed promise for the seal leak detector: (1) electrolytic hygrometry to measure moisture, (2) capacitance to measure moisture, and (3) a thermal conductivity approach based upon the use of thermistors.

A hand-carried portable leak detector based on the thermistor detection principle has been identified as a promising sensor. Experimentally, the thermistor sensor has demonstrated great sensitivity in detecting small leaks. A portable detector is especially useful as sensor to back up the damage control system in pinpointing the location of the leak. Further, it serves as an emergency sensor if the other systems fail.

3.3 OVERBOARD LEAK DETECTION AND LOCATION CONCEPTS

3.3.1 Measure of Overboard Leakage by Two-Gas Atmosphere Controller

Spacecraft life support systems for extended-duration missions require the use of two-gas atmospheres for physiological and safety reasons. Basically, the two-gas system provides the measurement of oxygen concentration in a gas mixture and a method to control the concentration of the oxygen and diluent. An evaluation and comparison of several methods of sensing and controlling the composition of two-gas space cabin atmospheres is contained in Reference 15.

The function of the two-gas controller is to maintain the correct oxygen and nitrogen partial pressures and, therefore, total pressure at the preset level. Oxygen is sensed by a partial pressure sensor (i. e., a mass spectrometer or a polarographic sensor) and added when the oxygen pressure is low. The nitrogen or other diluent is sensed by the total pressure sensor or by the mass spectrometer, and added only when the oxygen partial pressure is within a specified limit and the total pressure is low. Oxygen is consumed by the crew members for metabolic functions as well as lost by leakage overboard. However, nitrogen is lost only by leakage. The nitrogen makeup rate can therefore be considered a measure of the total leak. If the vehicle leakage increases above normal, the amount of increased nitrogen supplied to maintain pressure levels should be an indication of the size of the leak. A decrease of nitrogen usage could also indicate an onboard leak of nitrogen, or with total pressure being monitored, some other stored gas.

3.3.1.1 Pulse-Rate Modulated Two-Gas Systems

Several pulse-rate modulated systems of two-gas atmosphere control have been developed over a period of years and tested in extended-duration manned space simulations (References 16 and 17). The advantages of this type of system are (1) the dead-band operation, which results in a fairly wide range of controlled variables, is eliminated; (2) the system retains the simplicity inherent in pressure regulators and solenoid valves for the mechanical components; (3) the amount of gas used is easily measured by counting pulses; and (4) rate changes in gas makeup, which may be indicative of either onboard or overboard leaks, can be detected.

3.3.1.2 Description of the Flightweight Two-Gas Controller

The two-gas control system utilized in the 90-day manned space simulation test (Reference 18) consisted of the following:

A. The primary sensor—a mass spectrometer developed under NASA contract by Perkin-Elmer, Aerospace Division, Pomona, California. This equipment measures the partial pressures of four gases: nitrogen, oxygen, water vapor, and carbon dioxide. The partial pressures of interest in the two-gas controller are those of oxygen and nitrogen.

B. Backup sensors including a Beckman polarographic sensor which measures oxygen partial pressure and a Statham total pressure transducer.

C. Oxygen and nitrogen stored gas supply.

D. Two pressure regulators (oxygen and nitrogen).

E. Two control solenoids.

F. The supply lines and fittings required to connect C, D, and E to inlet orifices designed to admit gas at sonic flow when the solenoids are actuated.

G. The electronic controller.

The two-gas atmosphere controller assembly (Figure 3-1) contains the control electronics for the atmosphere control system. The electronics are

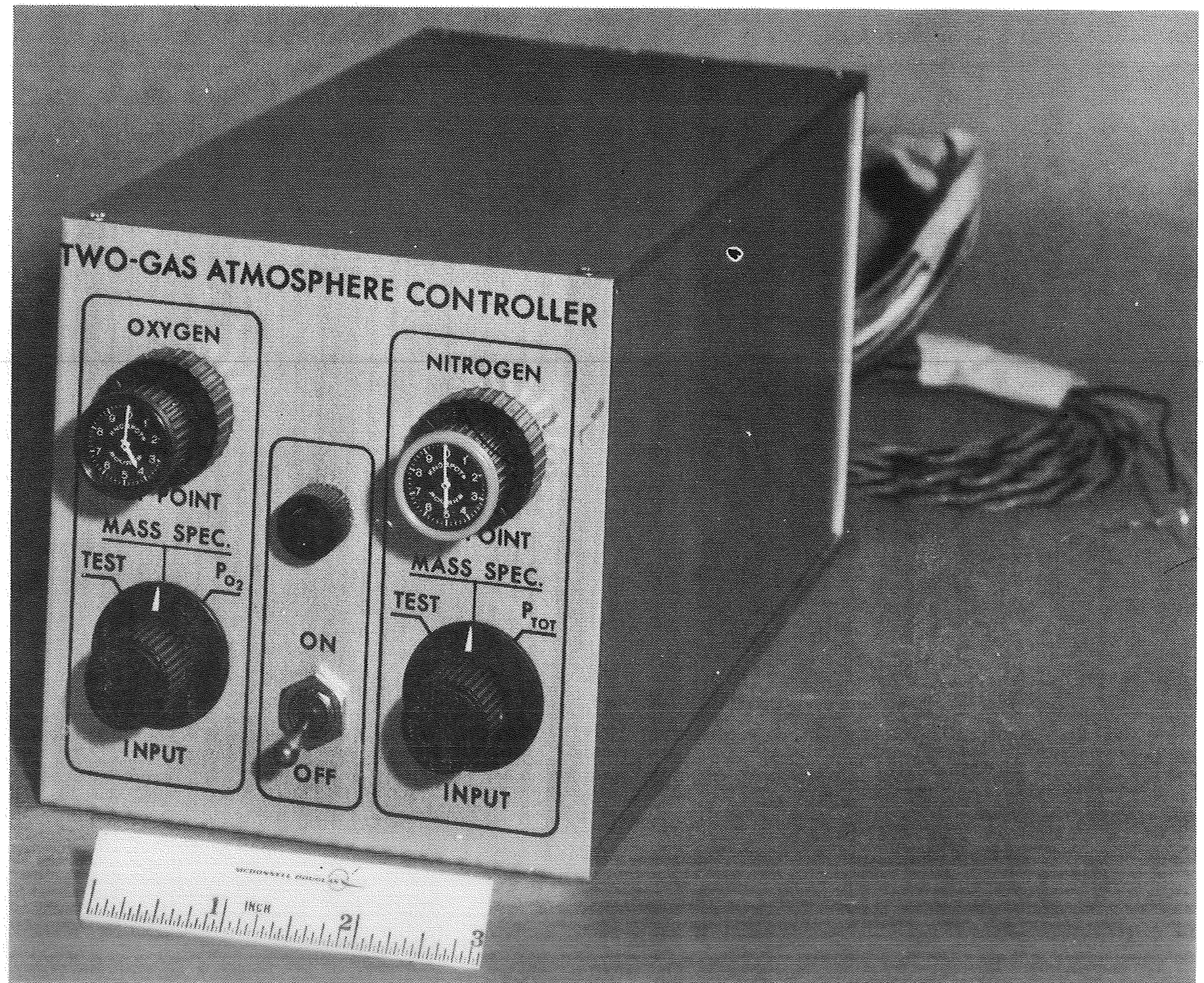


Figure 3-1. Two-Gas Atmosphere Controller

designed utilizing integrated circuits and discrete components and are contained in a 2.85 x $10^{-3} m^3$ (175 in.^{3}) package weighing less than 1.6 kg (3.56 lb).

The operation of this system is described by the block diagram of Figure 3-2. Input signals from the mass spectrometer or from the backup sensors are selected by means of panel controls. Each input signal selected is summed with a reference set-point signal at the input of an operational amplifier integrator circuit. If the absolute value of the set-point voltage exceeds the absolute value of the sensor signal, the different voltage (error signal) is integrated by the circuit. If the converse occurs, the output of the integrator is clamped to prevent the integrator from going to positive saturation. When an error signal occurs, as defined above, the output of the integrator circuit is compared to a reference voltage at the level detector. When the output voltage equals the reference voltage, the detector circuit resets the integrator and provides a pulse output whose repetition rate is proportional to the input error signal amplitude. These pulses are summed in a 4-bit binary counter. At the 16th pulse, an output pulse from the binary counter circuit, called a terminal count, is used to trigger a 10-sec one-shot multivibrator circuit. The 10-sec one-shot circuit in turn controls the solenoid valve and admits a fixed pulse of gas to the cabin atmosphere.

The nitrogen and oxygen channels operate in a similar manner. The primary difference in the two channels is that the oxygen channel terminal count is also used to reset the nitrogen binary counter. The reason for this reset is to prevent the addition of nitrogen (diluent) to the controlled atmosphere until most of the oxygen deficiency is made up.

Figure 3-3 presents the nitrogen addition during the 90-day manned test. The leaks were due to improper sealing of various equipment interfacing with space vacuum. The nitrogen pulses during these periods were above average. The equipment was systematically checked and resealed, and the pulse count was then monitored to ensure the leak was corrected. Although the design of this unit was not optimized for leak detection, it is apparent from these data that it can be effectively used for this purpose.

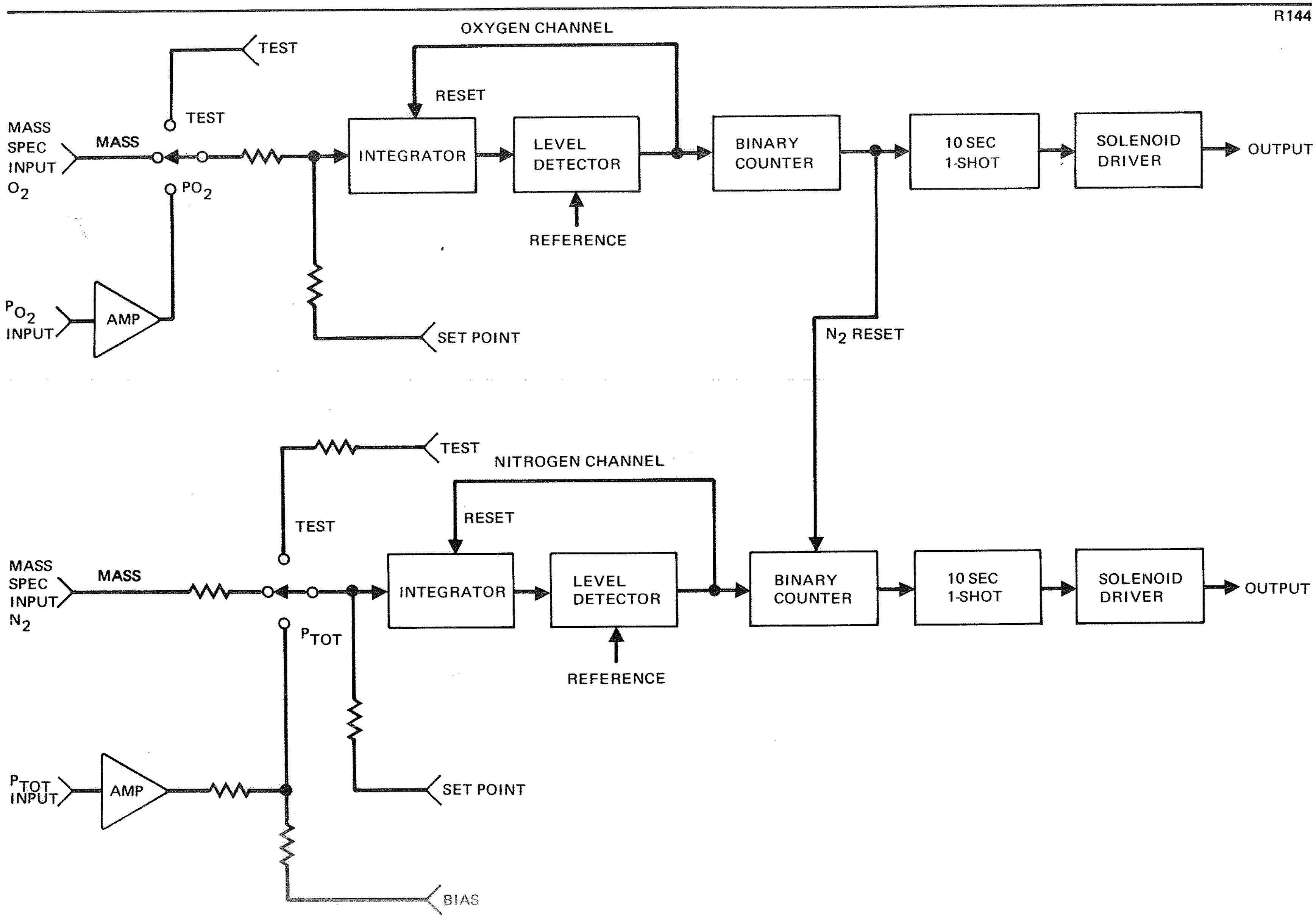


Figure 3-2. Two-Gas Atmosphere Controller Block Diagram

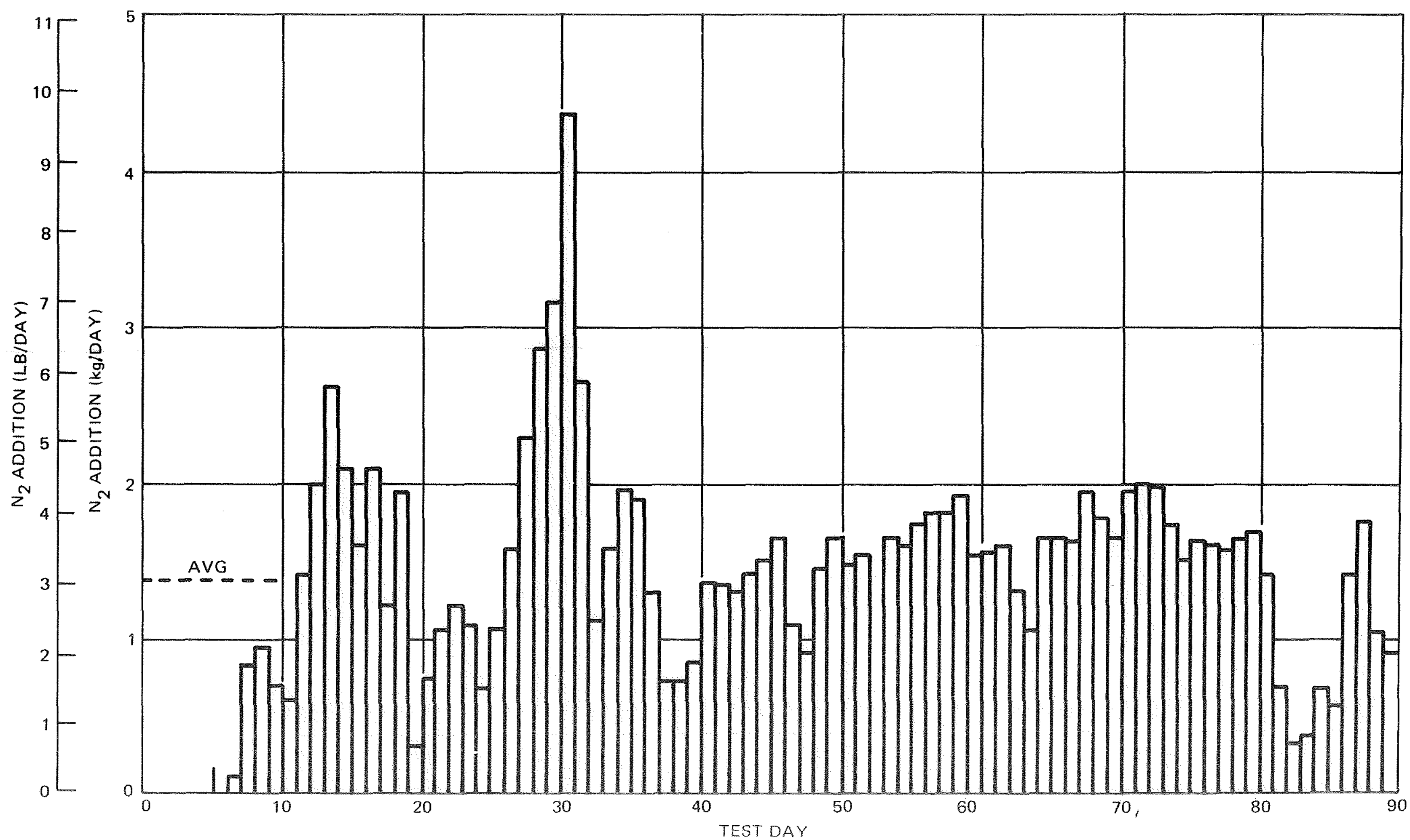


Figure 3-3. Nitrogen Addition During 90-Day Manned Test

3.3.1.3 Analysis of a Typical Dead-Band Two-Gas Controller (Ideal Case)
The two-gas controller utilizes a signal from an oxygen partial-pressure sensor and a total-pressure sensor to determine requirements for gas inputs to the cabin. If the oxygen partial pressure is in the correct range, a low total-pressure signal will activate the nitrogen solenoid valve. A specific volume of gas will be admitted to the cabin for each pulse of the nitrogen solenoid valve. This is accomplished by regulating the supply pressure and passing the gas to the cabin through a fixed orifice for a set solenoid-open time. The two-gas controller has a pulse frequency modulator which determines the time between pulses. The greater the signal error, the more frequent the pulses. The control characteristic assumed for this study is shown in Figure 3-4.

The pulse must be capable of meeting normal leakage, yet be large enough to make up for an abnormal leak. The size of the nitrogen pulse for the recent 90-day manned simulator run was 0.00172 kg (0.0038 lb). The normal leak rate of 9.6×10^{-6} kg/sec (1.8 lb/day) caused 474 pulses per day (almost 20 per hour). This pulse rate was too small to keep up with abnormal leaks.

R144

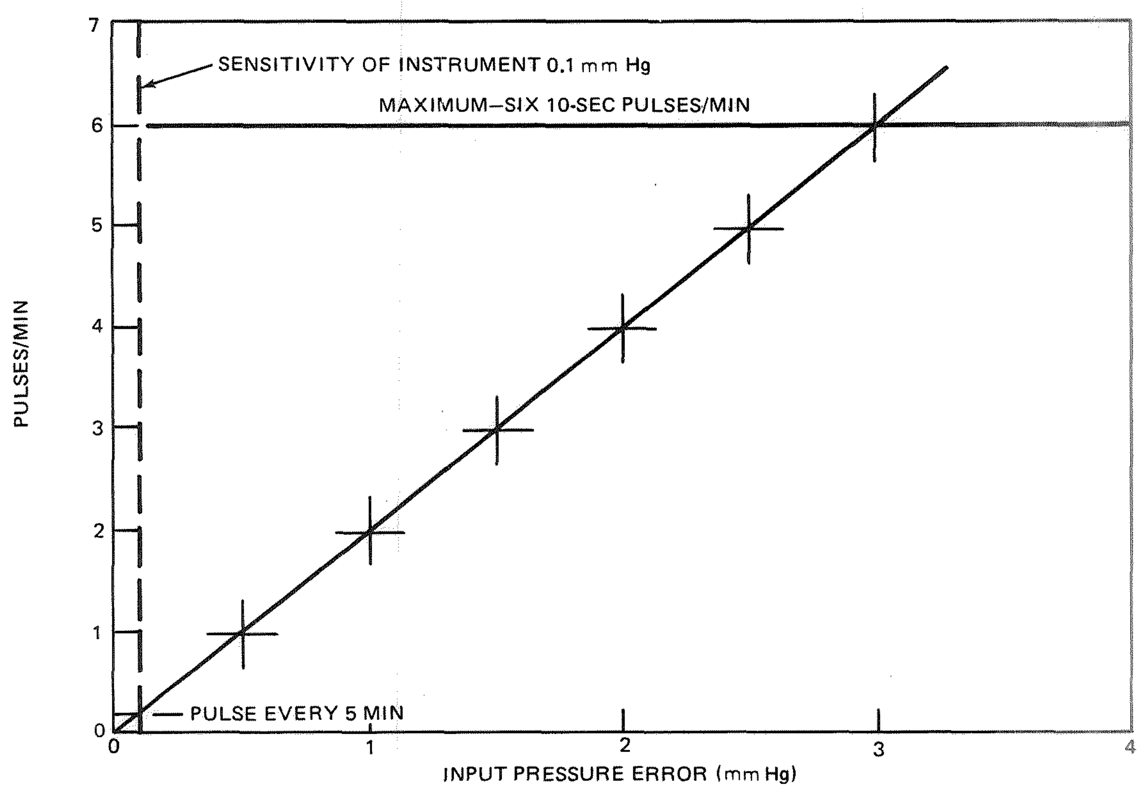


Figure 3-4. Two-Gas Atmosphere Controller Pulse Rate vs Pressure Error Signal

Therefore, a pulse size larger by a factor of 10 (i. e., 0.018 kg [0.04 lb]) and of 10-sec duration was chosen for this study. (The 10-sec duration was the approximate time used on the 90-day run.) The maximum nitrogen input with this design is 1.83×10^{-3} kg/sec (345 lb/day), two orders of magnitude above nominal. Figure 3-5 shows average time between pulses versus pulse size for various leak rates.

Sensitivity of the total pressure signal is a significant design parameter. In a 4.54×10^{2} m^{3} (16,000 ft^{3}) vehicle, for example, a pressure decrease of 13.3 N/m^{2} (0.1 mm Hg) means that 0.068 kg (0.15 lb) of nitrogen must be added. Figure 3-6 shows the relationship of vehicle volume to nitrogen weight for various error sensitivities. This study assumes a sensitivity of 13.3 N/m^{2} (0.1 mm Hg) can be achieved by incorporating the most accurate transducer available. Figure 3-7 shows the amount of nitrogen in various size vehicles for the three design pressures used in the study. The

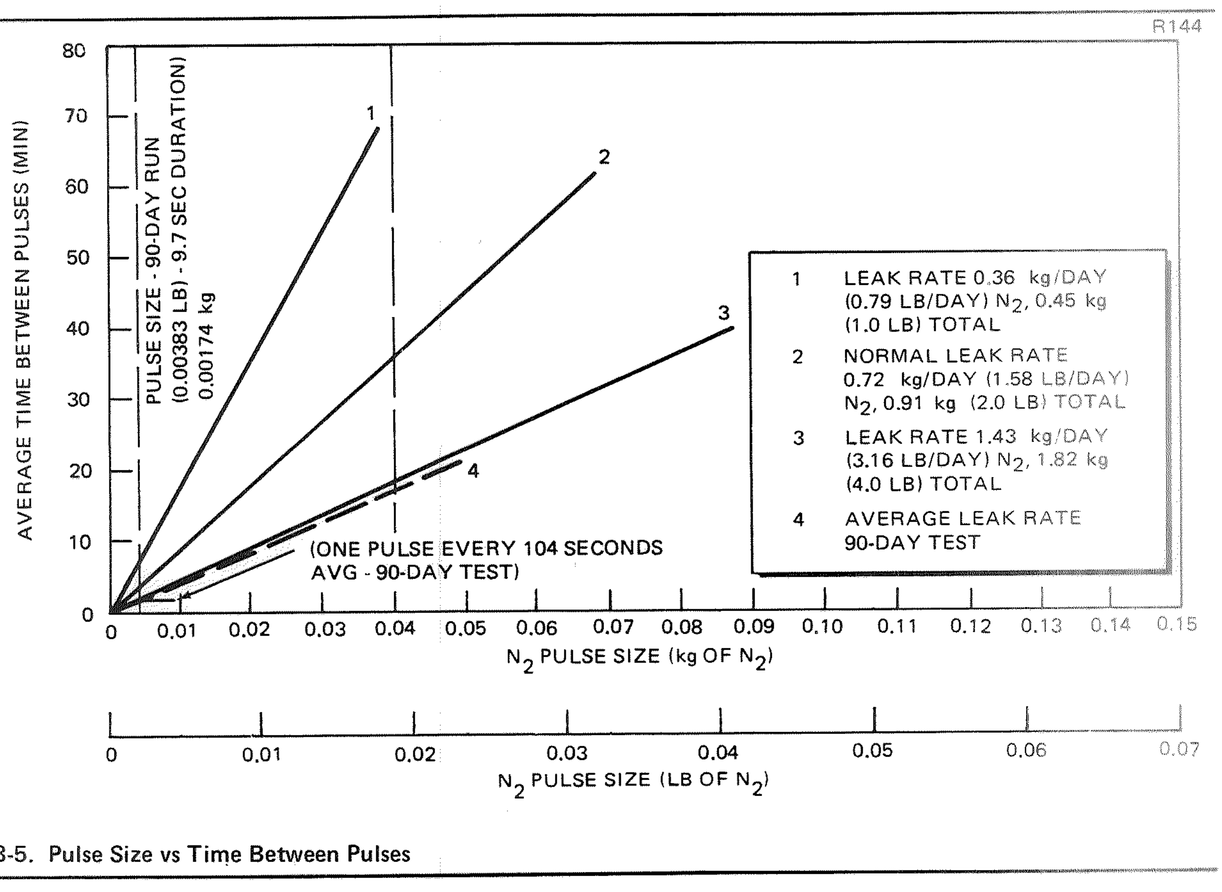


Figure 3-5. Pulse Size vs Time Between Pulses

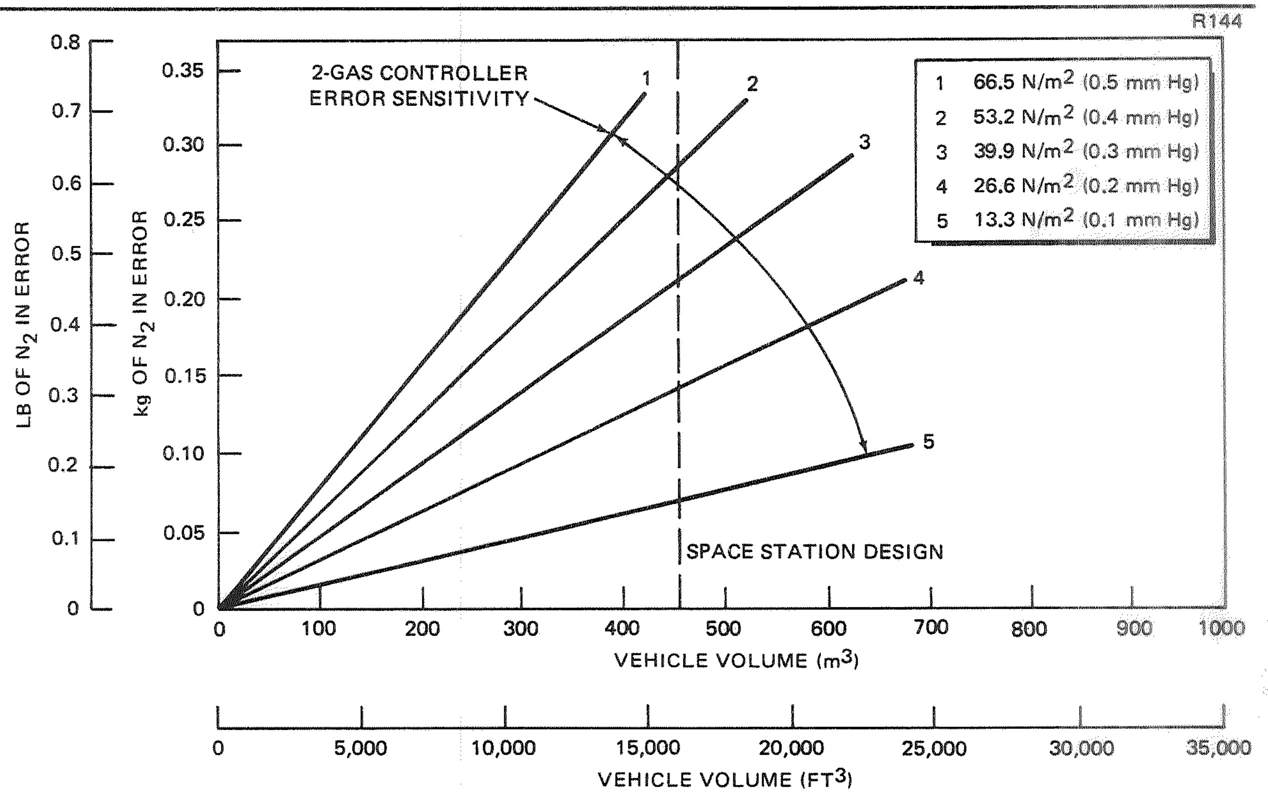


Figure 3-6. Error Sensitivity vs N_2 Required to Correct Error (Independent of Total Pressure)

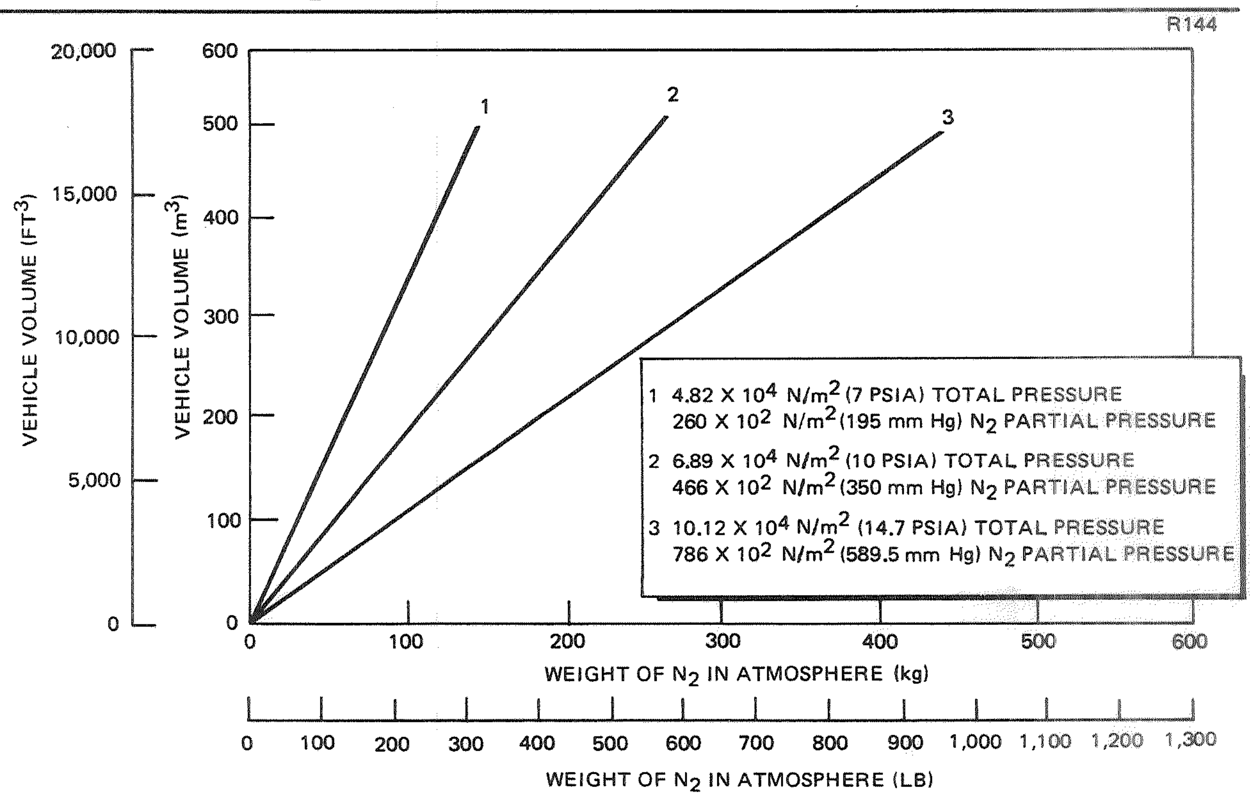


Figure 3-7. N_2 Weight in Atmosphere vs Pressure and Vehicle Volume

control function assumed for this portion of the study actuates the gas solenoid valve whenever the pressure transducer signal is 13.3 N/m^2 less than the preset level, and continues to add "pulses" of gas until the preset pressure level is attained.

The onboard checkout-data management system can count the number of pulses and maintain a continuous record of nitrogen usage versus time. These data can be displayed continuously or on crew demand. The computer could subtract from this count the amount of nitrogen lost overboard via planned compartment decompression, thereby assuring that only the uncontrolled (leakage) nitrogen losses are included in the count. More counts than normal in a given time would indicate abnormal leakage. Fewer counts than normal would indicate a leak in the nitrogen or oxygen supply system upstream of the two-gas controller or gas buildup of an unplanned nature. In this case, the mass spectrometer would be consulted to determine atmosphere constituents and their levels.

The times required for vehicle pressure to decay across the dead band for various size vehicles, hole sizes, and pressures are shown in Figures 3-8, 3-9, and 3-10.

Normal Operation Pressure Maintenance

The following assumptions were made in this analysis:

Vehicle volume	326 m^3 (11,500 ft^3)
Nitrogen pulse size	0.018 kg (0.04 lb)
Pulse duration	10 sec
Control characteristic as in Figure 3-4	
Sensor total pressure sensitivity	13.3 N/m^2 (0.1 mm Hg)
Temperatures and other atmospheric constituents and pressures constant.	

Case I—Vehicle pressure of 4.82 x 10^4 N/m^2 (7.0 psia). Nominal nitrogen leakage is 0.48 kg/day. The controller will not actuate until the lower limit is reached and will continue to pulse gas into the vehicle until

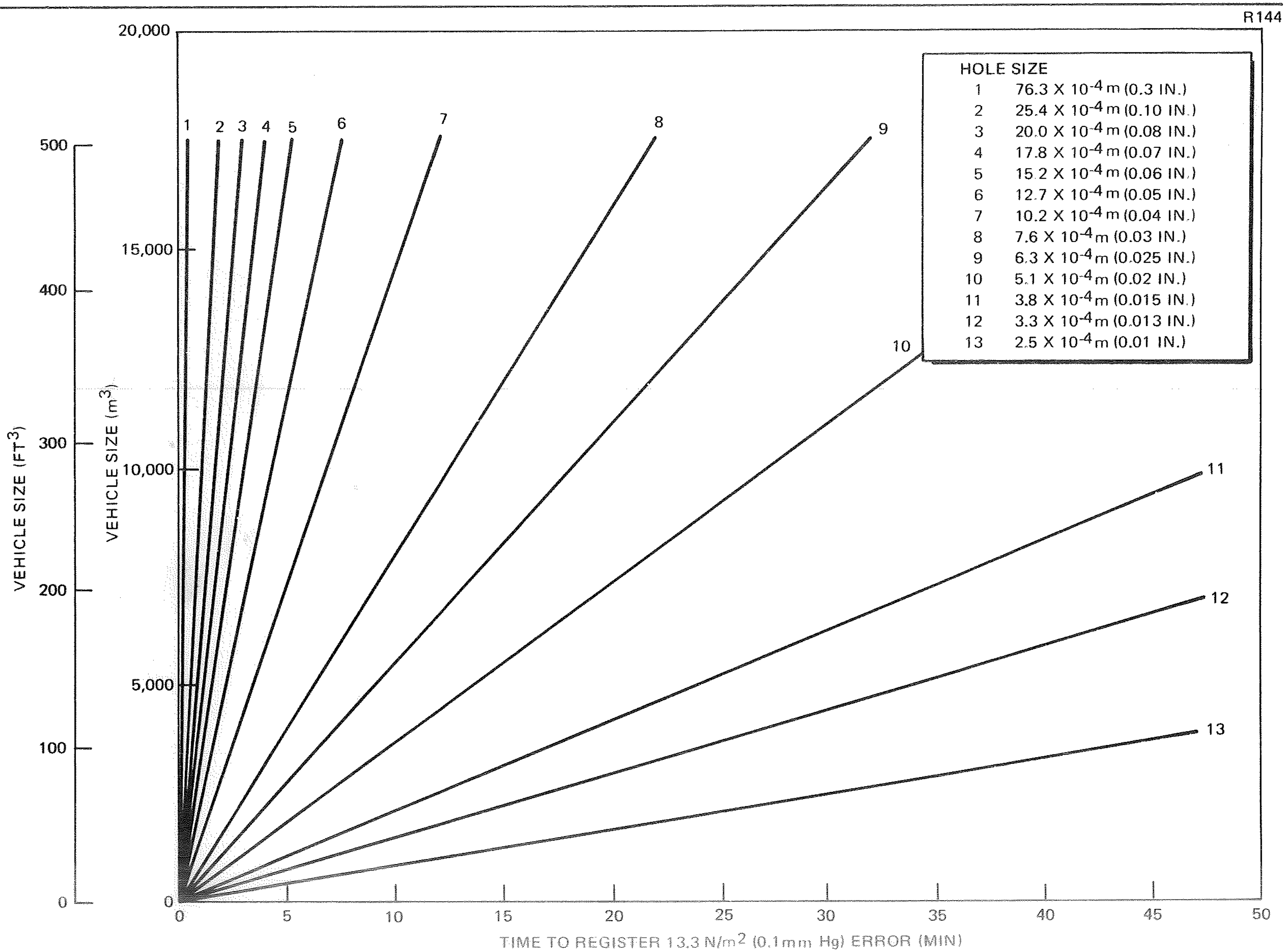


Figure 3-8. Time to Detect Hole at 4.82×10^4 N/m^2 (7.0 psia)

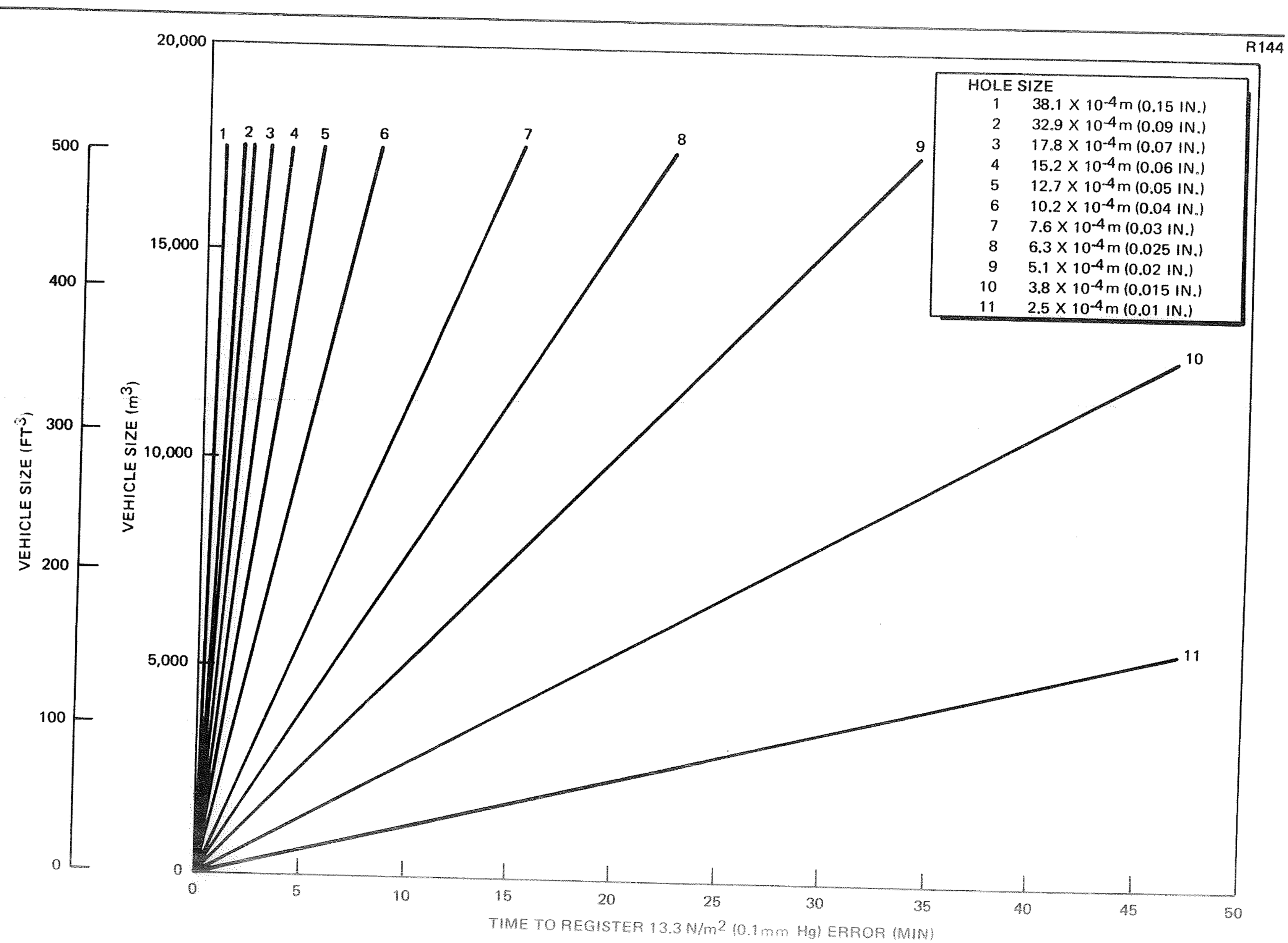


Figure 3-9. Time to Detect Hole at 6.89×10^4 N/m^2 (10.0 psia)

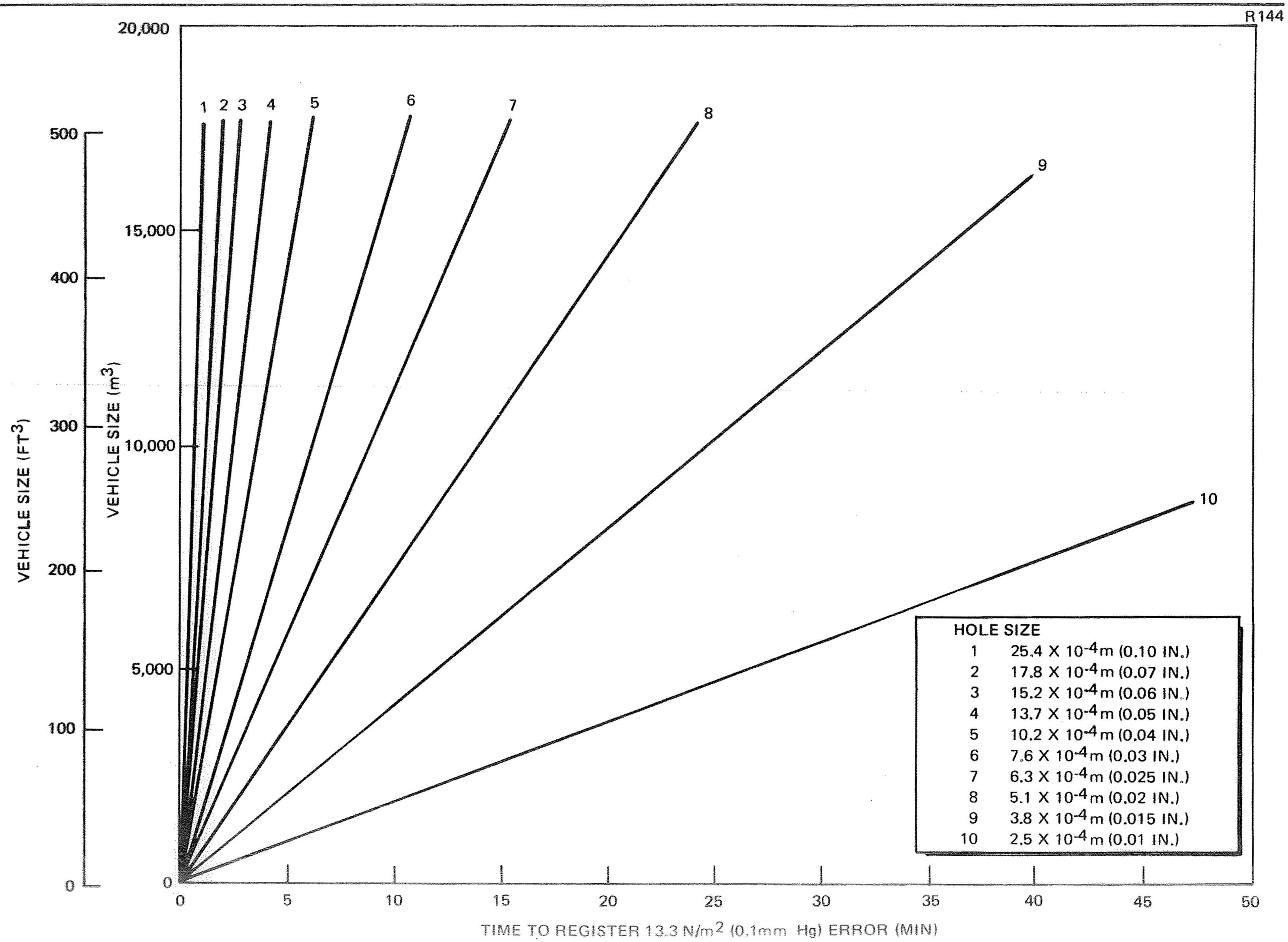


Figure 3-10. Time to Detect Hole at 1.01×10^5 N/m^2 (14.7 psia)

the 13.3 N/m^2 dead band is reached or exceeded. The mathematical expression for this action is:

(Number of pulses) (pulse size) ≥ Dead band (from Figure 3-6)

and

$$(\eta)\,(0.018\ \text{kg}) \geq 0.049\ \text{kg},\quad \eta = 3 \tag{3-1}$$

This indicates that each time the pressure decays to the lower limit, the controller will add three pulses (0.054 kg) to reach or exceed the preset pressure. The time between control actions is then:

$$\frac{0.054\ \text{kg}}{0.48\ \text{kg/day}} = 1.125 \times 10^{-1}\ \text{day} = 164\ \text{min} \tag{3-2}$$

The normal nitrogen makeup will be three nitrogen pulses or counts occuring within a 15-min period followed by an inactive period of 164 min. Any significant decrease in the inactive period would be symptomatic of abnormal leakage.

<u>Case II</u>— Vehicle pressure of 6.89×10^4 N/m^2 (10 psia). Nominal N_2 leakage is 0.59 kg/day.

Using the same calculation method as in Case I, the control action will be three nitrogen pulses or counts occuring within a 15-min period followed by an inactive period of 132 min. Again, a decrease in the inactive period would indicate abnormal leakage.

<u>Case III</u>— Vehicle pressure of 1.01×10^5 N/m^2 (14.7 psia) and a normal leak rate of 0.695 kg/day. For this case, the control characteristics will be three nitrogen counts occuring within a 15-min period followed by an inactive period of 114 min.

Abnormal Operation Pressure Maintenance and Leakage Detection

The following cases are similar to the three cases previously described except that an additional gas leak is considered which is equivalent to a 7.63×10^{-4}m (0.03 in.) diameter hole.

Case IV—Conditions are similar to Case I except that total leakage has increased because of the hole. The controller characteristics for this condition are five pulses occurring within a 20-min period, followed by an inactive period of 30 min. Figure 3-11 presents a comparison of Cases I and IV. It is of interest to note that a significant amount of gas is lost between pulses in the latter case so that an additional two pulses are required to raise the vehicle pressure above the dead band. Also, the leak has decreased the inactive period from 164 to 30 min.

Case V—Conditions are similar to Case II, except that nitrogen leakage has been increased to 0.55×10^{-4} kg/sec. For this condition, the control characteristics would be 25 N_2 pulses continuously for a 120-min period followed by a 15-min inactive period. A comparison of Cases V and II is shown in Figure 3-12.

Case VI—Conditions are similar to Case III, but with increased leakage. The controller characteristics for this case are continuous pulses of nitrogen at periods of less than 5 min between pulses. Since the leak is of a magnitude greater than the controller can supply with the 5-min intervals associated with the dead band, vehicle pressure will decrease causing the pulse rate to increase, as shown in Figure 3-4. Pressure stabilization will occur at a pressure level where the leak rate and addition rate are equal. A comparison of Cases VI and III is shown in Figure 3-13.

Table 3-1 is a summary of the six cases described, listing conditions and factors relating to normal and abnormal leakage. This analysis illustrates the change in control characteristics as a function of leak rate; however, it does assume an unrealistic measure of accuracy and sensitivity with regard to pressure measurement. All present methods of pressure measurement such as

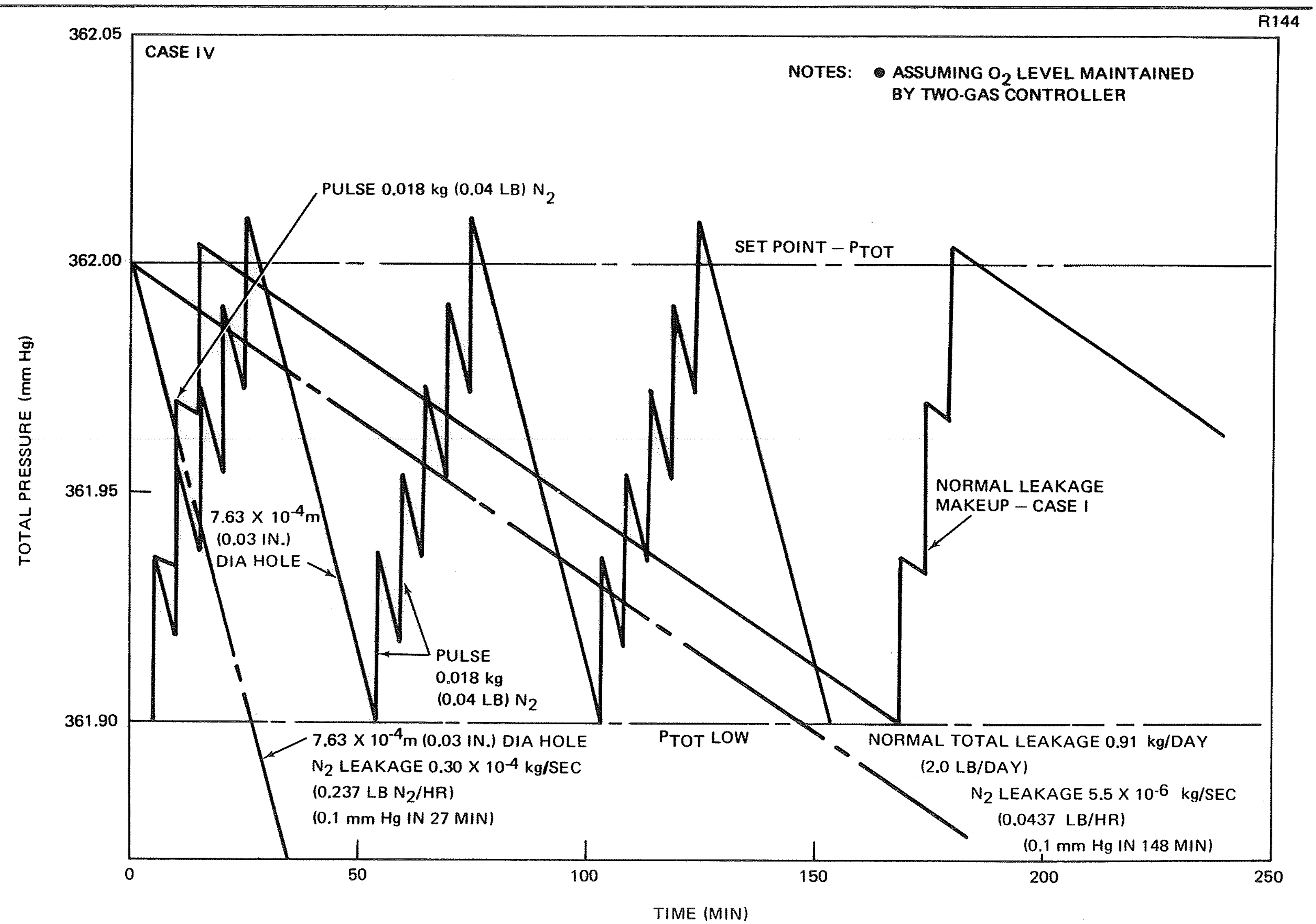


Figure 3-11. Two-Gas Controller Performance Characteristics [4.82 x 10^4 N/m^2 (7 psia)]

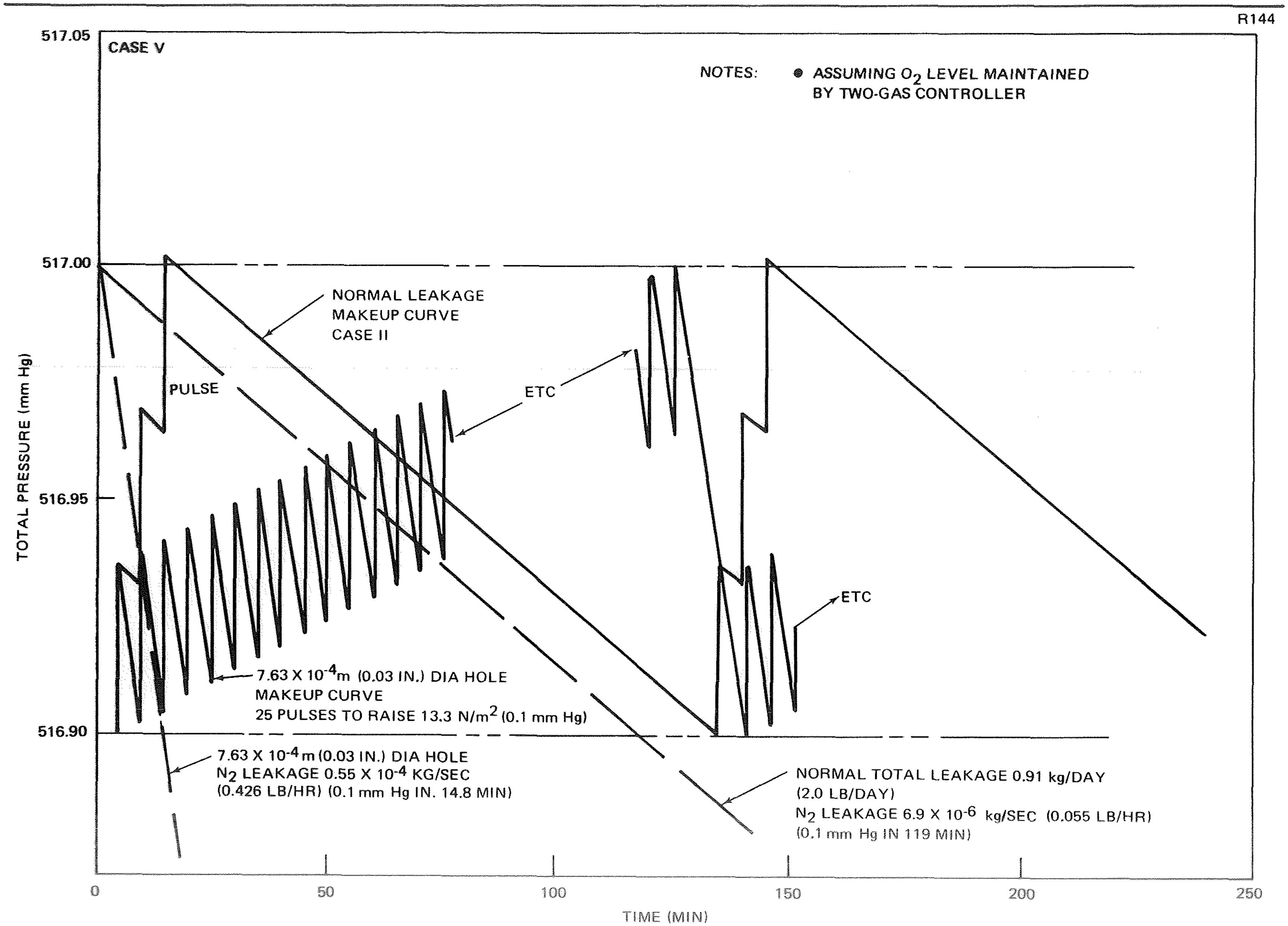


Figure 3-12. Two-Gas Controller Performance Characteristics $[6.89 \times 10^4 \ N/m^2 \ (10 \ psia)]$

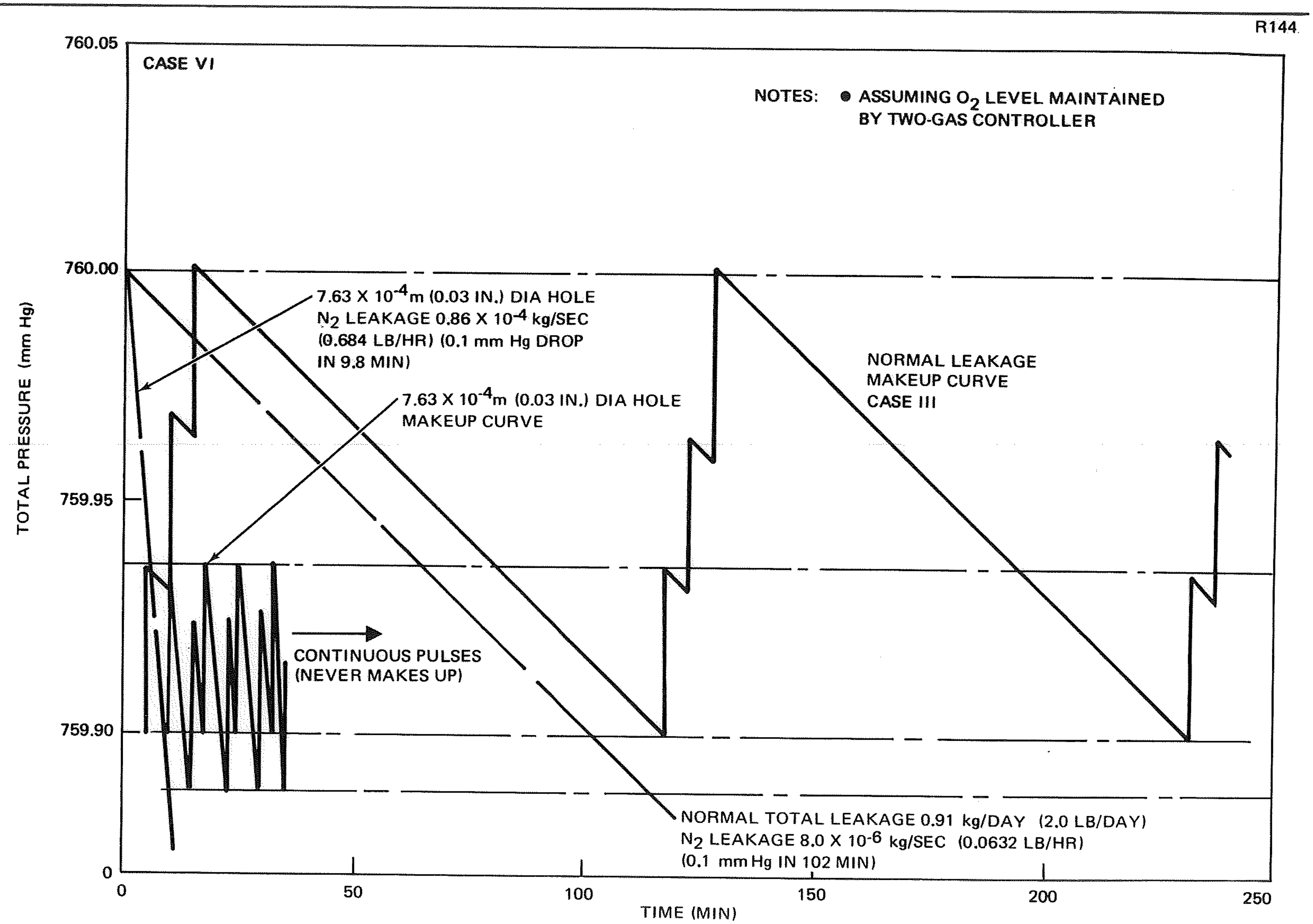


Figure 3-13. Two-Gas Controller Performance Characteristics [1.01 x 10^5 N/m^2 (14.7 psia)]

Table 3-1
PRESSURE MAINTENANCE SUMMARY

	Normal Operation			Abnormal Operation		
	Case I	Case II	Case III	Case IV	Case V	Case VI
Total pressure						
N/M^2	4.82×10^4	6.89×10^4	10.12×10^4	4.82×10^4	6.89×10^4	10.12×10^4
(psia)	(7.0)	(10)	(14.7)	(7)	(10)	(14.7)
N_2 leakage						
kg/day	0.48	0.59	0.69	2.6	4.7	7.6
(lb/day)	(1.05)	(1.3)	(1.53)	(5.63)	(10.44)	(16.7)
Equivalent hole size dia						
mm	0.33	0.27	0.23	7.6	7.6	7.6
(in.)	(0.013)	(0.0105)	(0.0090)	(0.03)	(0.03)	(0.03)
0.1 mm Hg error of N_2						
kg	0.049	0.049	0.049	0.049	0.049	0.049
(lb)	(0.108)	(0.108)	(0.108)	(0.108)	(0,108)	(0.108)
Time to drop 0.1 mm Hg (min)	145	119	102	27	14.8	9.8
Pulses to raise pressure to normal	3	3	3	5	25	∞
Time before next series of pulses (min)	164	132	114	30	14.8	Pressure stabilizes at lower set point
Factors indicating abnormal leakage	Pulses less than 5 min apart	Pulses less than 5 min apart	Pulses less than 5 min apart	Pulses less than 5 min apart	Pulses less than 5 min apart	Pulses less than 5 min apart
	More than 3 consecutive N_2 pulses	More than 3 consecutive N_2 pulses	More than 3 consecutive N_2 pulses	Five consecutive N_2 pulses	≈25 consecutive N_2 pulses	Consecutive pulses continuously
		More than 3 N_2 pulses in 132 min	More than 3 N_2 pulses in 114 min	Five pulses in 20 min, then 30 min later 5 more pulses	≈25 pulses in 125 min, then 14.8 min later 25 more pulses	Pressure stabilizes at lower level

mass spectrometers and pressure transducers exhibit electronic performance characteristics of noise and drift. These characteristics are random in nature, but are processed by the controller as if a real pressure transient were occurring. This would result in significant variance of the control characteristics previously described. Since variance in control characteristics is symptomatic of vehicle leakage, it would be difficult to distinguish between real leaks and short-term sensor drift. The next section presents an analysis which considers the random cyclic changes in the output of a sensor.

3.3.1.4 Response of Two-Gas Controller to Vehicle Leaks (Functional Case)

A number of parameters and characteristics must be considered to optimize the atmospheric control of a space vehicle. The control must provide the proper partial pressure of oxygen at a rate to match the metabolic demand of the crew over a broad band of activities. In addition, nitrogen must be provided and controlled to maintain a total pressure of atmosphere in which man can function comfortably.

Since the sensor-controller must continuously analyze the vehicle atmosphere with regard to the above gases and make corrections by adding known weight increments of gas, the gas addition rate can be utilized to detect and analyze vehicle leaks. This is especially true of nitrogen, because it does not undergo any metabolic or system processing. The mass spectrometer is the best developed sensor for measuring nitrogen concentrations (partial pressure). Unfortunately, knowing the partial pressure of a gas in a container does not give complete definition of its mass quantity. This can be illustrated by considering a fixed volume container of pure gas, where the partial pressure and total pressure are synonymous. If the gas is slowly vented as the container is warmed, the pressure can be kept at a constant value. In this case, the partial pressure has not changed but the gas quantity has. Therefore, the partial pressure should be adjusted to compensate for any changes in temperature.

Another consideration is the amount of control damping for variations caused by normal events. Such events as oxygen demand during an exercise period or increased leakage from a malfunctioning seal result in small rates of pressure change because of the relatively large size of the vehicle. An overresponsive controller could cause undesirable oscillation of oxygen partial pressure on both sides of the predetermined value without seeming to approach it. This type of operation would place undue demands on the electrolyzer furnishing the oxygen. In contrast, an underreactive controller will demand only small changes in oxygen output from the electrolyzer, but since the response lags behind the demand, information concerning abnormal usage can be seriously delayed. To summarize, the controller response should not cause hunting around the control point or overdemand from the gas supply, but should allow a rapid indication of abnormal gas usage. The design parameter of the controller which determines response is called the scale factor. This defines the number of gas pulses per hour that will be added to the vehicle for each mm Hg unit of partial pressure of error below the reference value.

Since nitrogen is usually provided from high-pressure storage, large demand rates do not seriously affect its design. Therefore, leak detection can best be accommodated by including it in the design of the nitrogen control channel. This may be enhanced by making the nitrogen control channel more responsive than the oxygen channel. In this way, the overboard leak can be detected before oxygen demand overload conditions are placed on the electrolyzer. The effect of scale factor on leak detection time is presented in Figure 3-14. The basis is a 113 m^3 (4,000 ft^3) vehicle having a normal N_2 leak rate of 0.43 kg (0.95 lb) per day and the solid line represents the normal leak pulse count as a function of time. The dashed lines represent the pulse count of controllers with scale factors of 4 and 40 to an overboard N_2 leak of 0.23 kg (0.5 lb) per hour occurring at time 0. Figure 3-14 illustrates that a higher scale factor will allow an earlier detection of a leak. The oxygen scale factor should be about one-fifth that of the nitrogen channel so that its response is much slower, thereby protecting the oxygen electrolyzer in case of a leak.

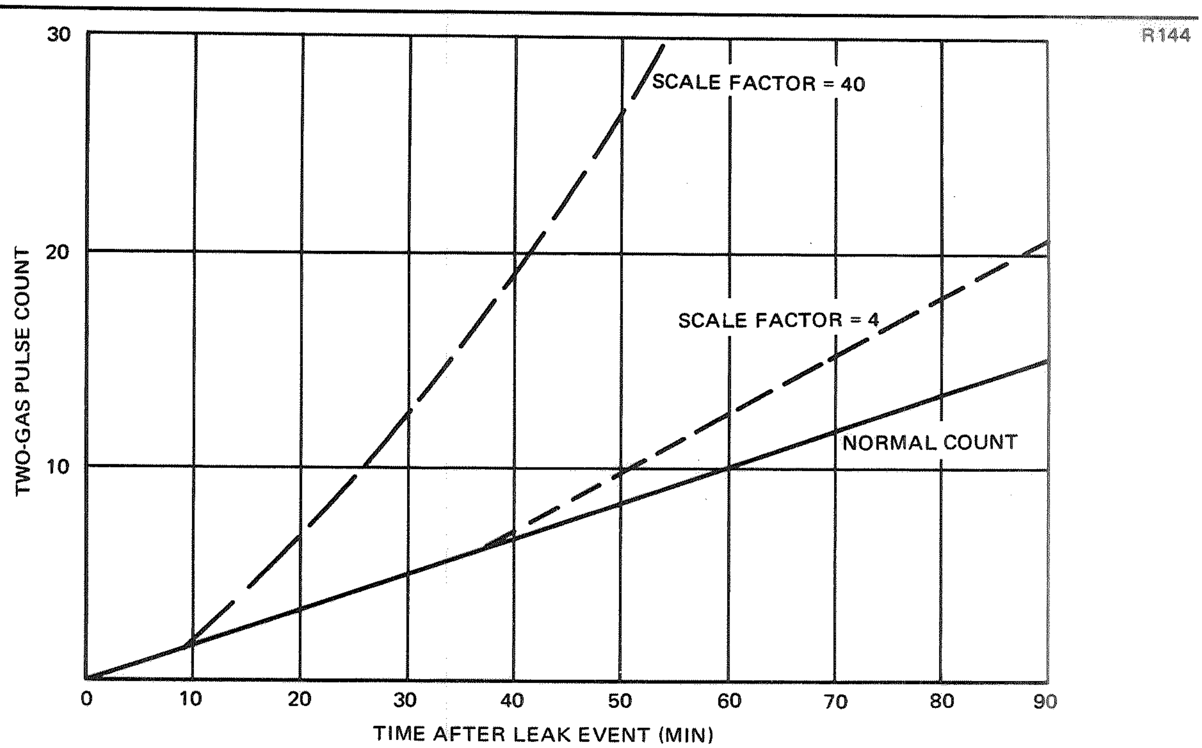


Figure 3-14. Pulse Count vs Time After Leak Showing Effect of Controller Scale Factor

Figure 3-14 is an ideal case, as each count could not be expected to occur at precisely the time indicated on the plot. Instead, the pulse rate would have a distribution above and below the values shown. This is because the transient variations in the output signal (nitrogen partial pressure) of the mass spectrometer are not completely counteracted by the effect of the controller integrator in smoothing the signal. Too much smoothing by the integrator is not desirable as it would delay the controller's response to a leak.

Data concerning instanteneous nitrogen partial pressure error and two-gas controller integration rate over 1 second were taken on an hourly basis during the 90-day manned test (Reference 17). These data were analyzed to establish a significant sample of points when the chamber was at a "normal" leakage condition with the nitrogen use rate essentially constant for long periods of time. This was accomplished by selecting four test days, during which the daily total quantity of nitrogen supplied by the two-gas controller was approximately the same. The four days selected are shown below.

Test Day	Date	Kg N_2	Pounds N_2
41	7-13-70	0.65	1.43
42	7-24-70	0.63	1.38
49	7-31-70	0.73	1.60
53	8-4-70	0.65	1.42

Conditions on the selected test days included:

A. The total amount of nitrogen supplied by the two-gas controller on each of these days was approximately the same.

B. No unusual pressure excursions occurred during these days.

C. No known events occurred at a precise rate that would affect the hourly N_2 partial pressure data.

From these conditions, it was assumed that the hourly data obtained was a representative sample of the statistical population of values for the N_2 partial pressure error (ΔP) and the resulting 1-sec integration rates (R_1). Approximately 90 data points were used to calculate a mean ΔP and R_1, and resulting standard deviations ($S_{\Delta P}$ and S_{R_1}) which were:

$$\overline{\Delta P} = 4.85 \text{ mm Hg}; \; S_{\Delta P} = 1.03 \tag{3-3}$$

$$R_1 = 0.0860 \text{ volts/sec}; \; S_{R_1} = 0.0180 \tag{3-4}$$

These distributions must be in the same units for a comparison. Thus, assuming that an integration rate of 0.0860 represents an error signal of 4.85 mm Hg, the standard deviation of the 1-second average integration rate ($S_{\Delta P_{R_1}}$) becomes:

$$S_{\Delta P_{R_1}} = 0.0180 \; \frac{4.85}{0.0860} = 1.01 \text{ mm Hg} \tag{3-5}$$

Comparing this value to $S_{\Delta P}$ indicates that if one assumes the difference between 1.01 and 1.03 to be significant, a slight smoothing of the signal was accomplished by the integration over one second. The question which now becomes of interest is the effect integrations over longer periods of time will have on smoothing the data.

Another important assumption was made: a group of values obtained by averaging a number of one-sec values, taken at different times, were assumed to have approximately the same degree of scatter (standard deviation) as a set of rates taken over the same number of seconds. In other words, it is assumed that a group of points obtained by averaging five 1-sec points will have the same standard deviation as a group of points representing rates calculated over 5 sec. Carrying out this process, the mean rate, of course, is the same since the same data are being averaged. However, the standard deviation for the 5-sec average is 0.0145 and that for a 15-sec average is 0.0134 v/sec. Converting these to equivalent partial pressure units yields 0.816 and 0.755 mm Hg, respectively. This shows, as expected, that measuring the rate of change over a longer period of time yields a more precise value.

Carrying this philosophy further, the daily nitrogen usage during days 40 through 80 of the 90-day test was examined, as shown in Figure 3-3. These data indicate that no significant perturbations occurred during this period, and the standard deviation of a "normal" error signal calculated from these data should be even smaller than the 1, 5, and 15-sec averages since these are 24-hr average rates. The resulting standard deviations of these 40 data points is 0.115 kg (0.25 lb) per day. Converting this to partial pressure error units results in 0.356 mm Hg. One may observe from Figure 3-3 that the total nitrogen usage on the original four days was approximately 1.56 kg (3.44 lb) per day. The values shown earlier which were used to select the four days were for nitrogen added by the two-gas controller only, and did not include other sources such as the solid amine valve actuators.

A plot of standard deviations reduced to nitrogen partial pressure error units versus averaging time is shown in Figure 3-15. For purposes of leak detection, it is desired to have a sample with a minimum standard deviation; however, the time required to obtain the sample must also be reasonable. If one hour is chosen for an averaging time, the order of magnitude of the resulting standard deviation may be estimated from Figure 3-15.

An interesting illustration of the effect of sample time, as represented by normal distributions around the mean, derived from the standard deviations calculated above is shown in Figure 3-16. The two extremes—the instantaneous values and the one-day averages—are based on reasonably large samples of experimental data, 90 and 40 points, respectively, and thus are good representatives of real behavior. The intermediate curves, although based on a few assumptions, appear to be representative of the precision one would expect from averaging rate-of-change data over increasingly longer periods of time.

R144

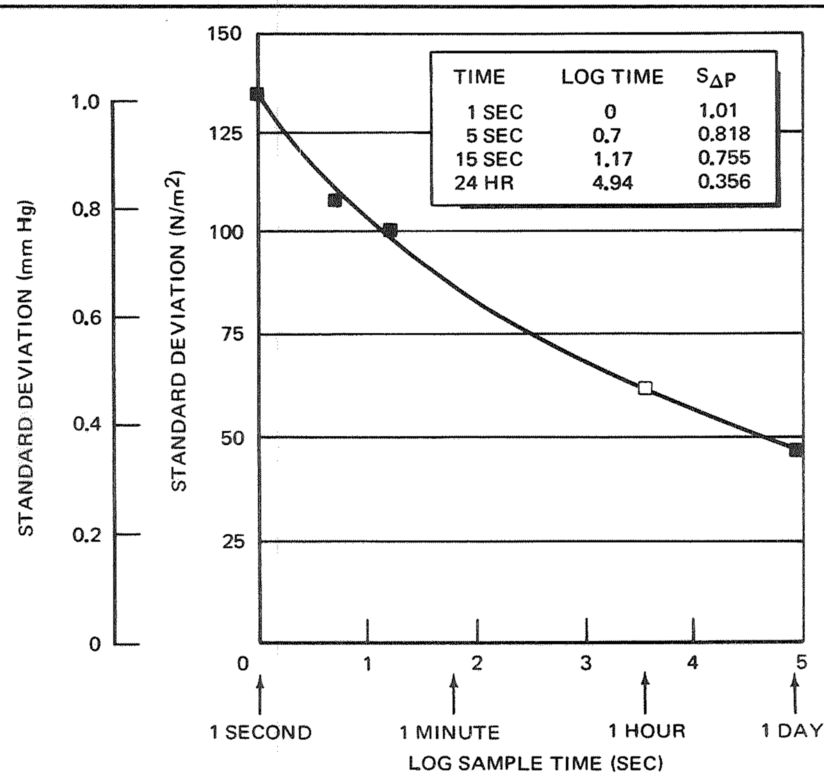


Figure 3-15. Standard Deviation vs Sample Averaging Time

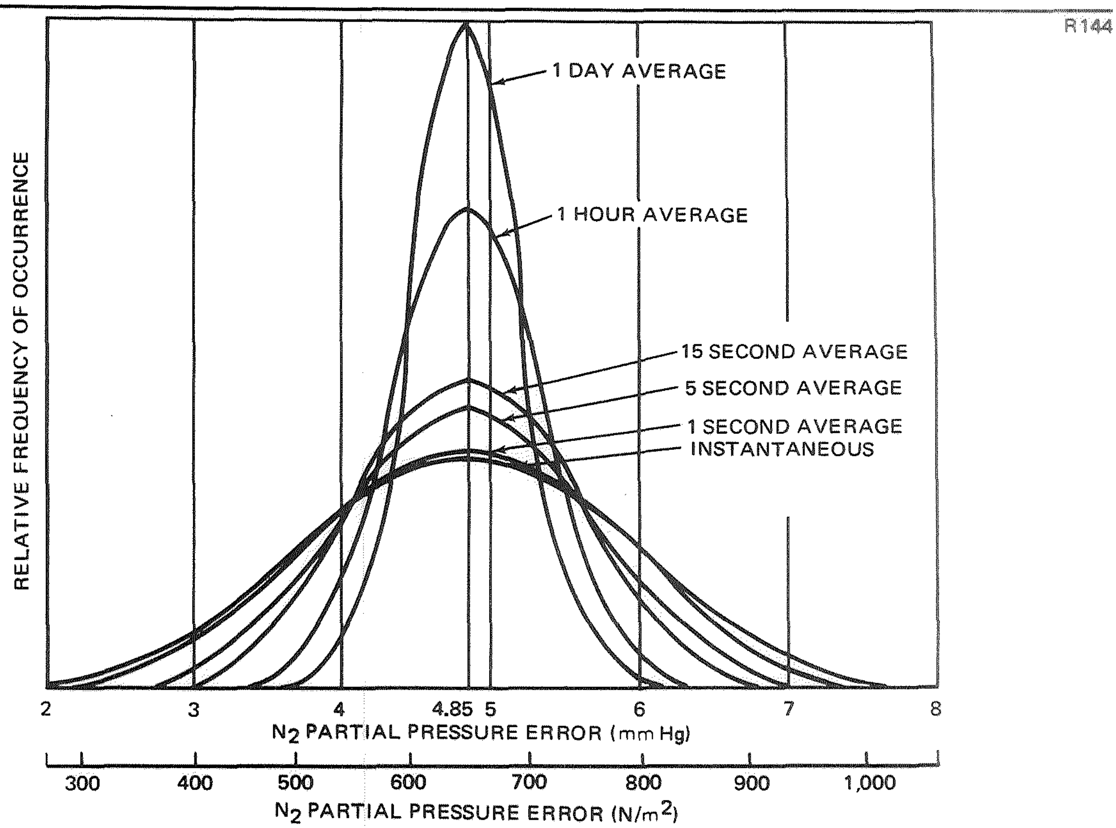


Figure 3-16. Normalized Error Signal Distributions

These distributions can be extremely useful in the design of a leak detection system. They show the expected scatter of data one can expect from a "normal" or baseline signal. The question now arises as to where one wishes to place the leak indication points, or how much sensitivity one is willing to sacrifice to minimize false alarms. For example, a reading of 7.0 mm Hg from a one hour or one day average signal would indicate approximately 99 + percent chance of leak; however, if it comes from an instantaneous or 15-sec average, there would be false alarms approximately 5 percent of the time.

To eliminate false alarms, the error signal must deviate from a mean by 3σ or greater, permitting alarm points to be established to identify a leak for the different signals. The time, however, depends on the vehicle volume.

The measurable parameter which is to be used to detect leaks is the partial pressure of nitrogen in the cabin. Likewise, the size of the leak may be estimated by the time required for the partial pressure of nitrogen to decay a given ΔP. The following expression was derived from the mass balance of the MDAC 90-day manned operating and pressurized chamber test and gives the dynamics of the system, including the effects of addition by the two-gas controller.

$$1 - \frac{K\Delta P}{r} = e^{-(KP_o/M_o)t} \qquad (3\text{-}6)$$

where

- r = Nitrogen leak rate
- P_o = Initial nitrogen pressure
- M_o = Initial mass nitrogen at P_o
- ΔP = Change in nitrogen pressure
- K = Two-gas controller addition rate ($kg\ N_2$/min, mm Hg)
- t = Time required to reach ΔP

A plot showing the time required for the nitrogen partial pressure to drop versus leak rate is presented in Figure 3-17. As shown, the addition rate factor, K, is quite important for very small leaks, and if it is large enough, the pressure will not drop at all. This may be seen by examining the above expression. As $K\Delta P$ approaches r, t must become infinitely large. At the other extreme, when r becomes very large, e^{-x} approaches 1. However, in expanding e^{-x} in a Taylor series for very small x, e^{-x} becomes equal to 1-x. Thus, the expression reduces to

$$\frac{\Delta P}{r} = \frac{P_o}{M_o}t \qquad (3\text{-}7)$$

which is the case with no addition. A similar treatment assuming K becomes zero yields the same result.

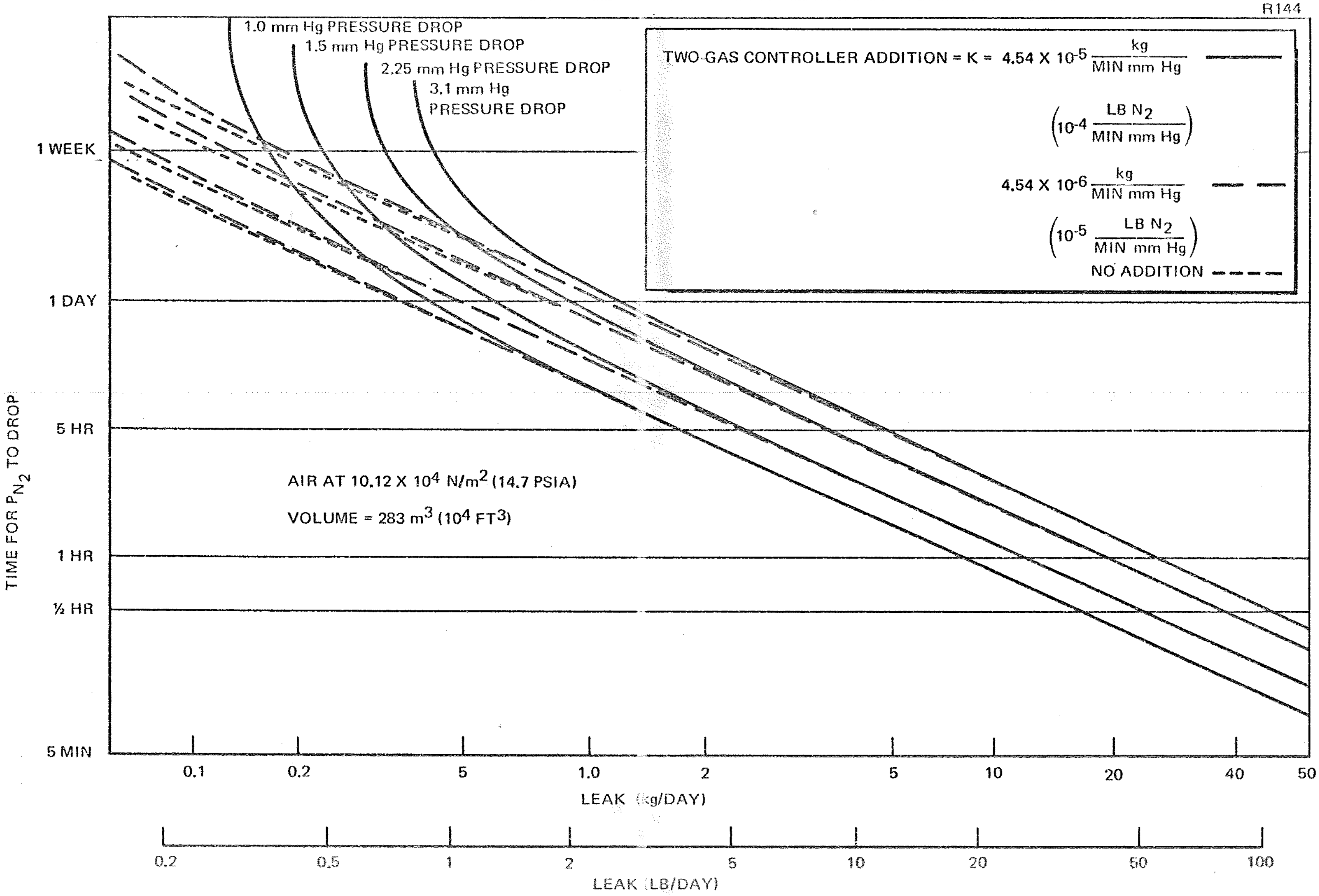


Figure 3-17. Time for Partial Pressure Nitrogen to Drop vs Leak Size

These figures and calculations provide a method to select the two-gas control addition rate factor for a given vehicle. One may see that 10^{-4} is the largest factor which will allow detection of leaks less than 0.45 kg (1 lb) of air per day. Thus, this is the largest practical factor for this size vehicle if leak detection is desired. However, this factor provides an equilibrium pressure error of 5.5 mm Hg for a one pound per day air leak. This means that a leak much larger than one pound per day would produce a proportionately larger equilibrium pressure error if not corrected. Thus, it may be concluded that a nitrogen addition factor small enough for small leak detection is unsatisfactory for long-term pressure control with significant changes in leak rate.

The leak detection and size estimation procedure may be explained by the representation shown in Figure 3-18. Since the nitrogen partial pressure signal is known to have a ± 3.09 mm Hg variation for a 3σ certainty, a one-hour average signal with a 3σ variation of ±1.5 mm Hg is arbitrarily selected for leak detection purposes. This signal is represented as the shaded band, with the shading intensity corresponding to increasing probability of occurrence.

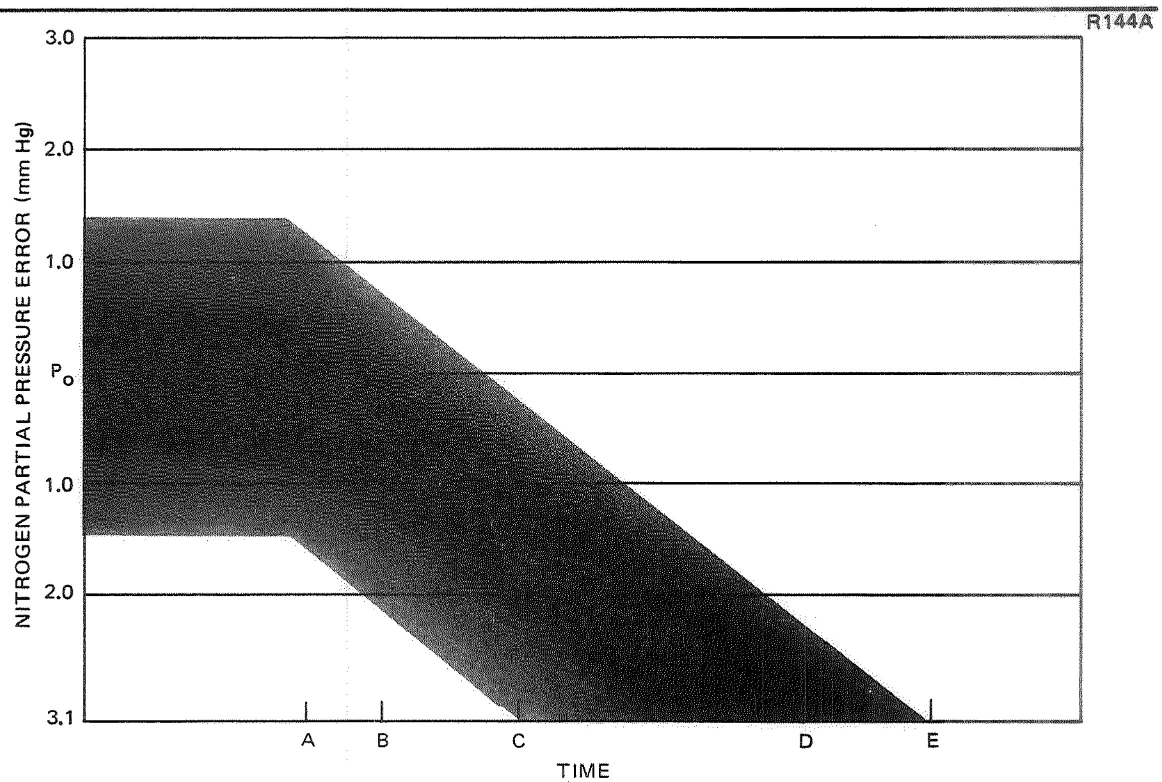


Figure 3-18. Decay of 1-Hour Average Signal Through Alarm Points

Normal conditions were then assumed up to time A, when a leak occurs. The pressure signal (using a 1-hr average) now begins to decay along a path described by the previously presented expression. If the leak detector computer has a level discriminator set at 2.25 mm Hg error, this alarm will be set off between time B and time D. In any case, this will alert the crew to a leak situation. A second discriminator set at 3.1 mm Hg will now be activated between time C and time E. The computer may now assume that the time between the first and second alarms actually represents the nitrogen partial pressure decay rate, and calculate the most probable leak rate. It may also calculate the uncertainty of the calculated value. The leak rate calculation will be based on Figure 3-17, i.e., the difference in times required to decay from 2.25 mm Hg and 3.1 mm Hg error. Although the lines are parallel, one must remember that the scale is logarithmic, thus producing increasing times for smaller leaks.

The preceding development, providing a method of estimating the actual leak size, permits a modification of the two-gas control design for detection of small leaks without sacrificing system control at relatively large "normal" leak rates. This concept can be illustrated by the system behavior during a hypothetical situation, shown in Figure 3-19. Begin by assuming the fanciful case of a vehicle with a zero leak rate. At time t_o, a leak occurs. The nitrogen partial pressure decays as shown in the figure with the 2.25 mm Hg alarm being set off, followed by the 3.1 mm Hg alarm.

If nothing is done at this point, the pressure would decay as shown by the dashed line to the equilibrium error. (This is defined by $\frac{r}{K}$.) However, from Figure 3-17, the time between the first and second alarms indicates the estimated leak rate and consequently the equilibrium ΔP. Increasing the set point of the controller by an increment equal to equilibrium ΔP will cause the system to return to P_o along a readily predictable route. This sequence may now be repeated for any size leak (within limits) without changing K and thus retains good resolution. The limit to this process is determined by saturation of the two-gas controller or more specifically by the length of the nitrogen pulse. Since it has been determined that a 10-sec pulse is about the

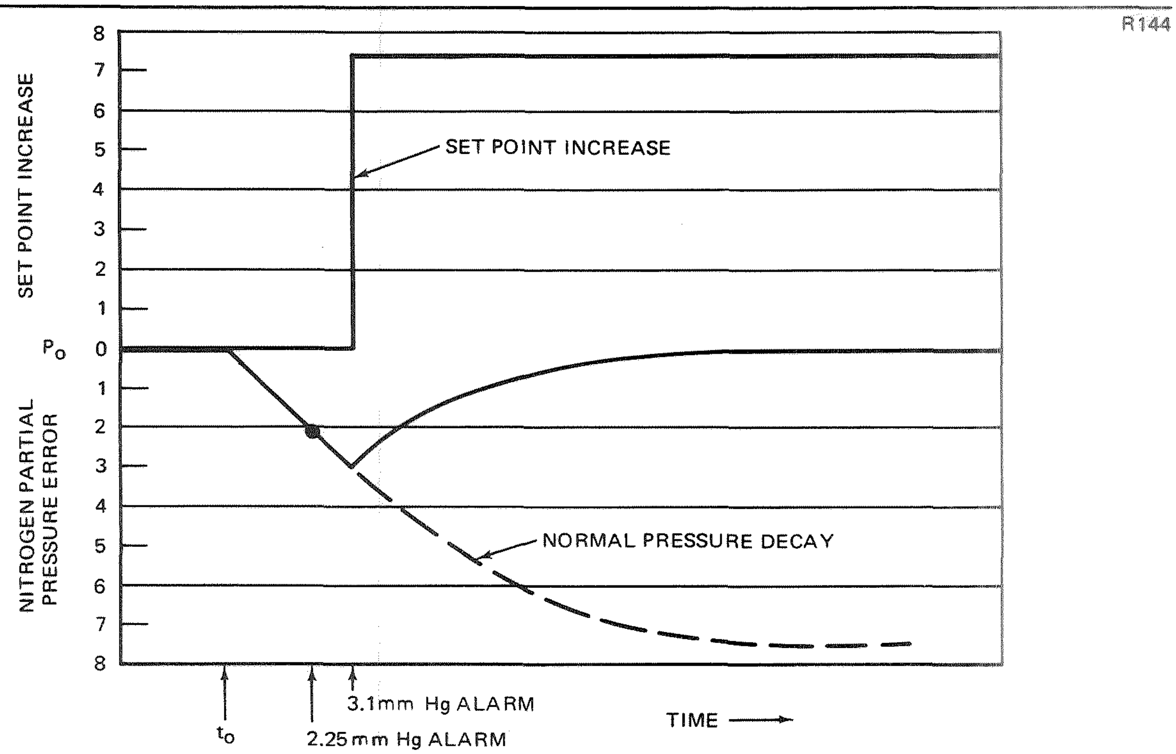


Figure 3-19. Effect of Set Point Adjustment When Leak Size Established

minimum solenoid valve pulse that is reasonably reproducible, 360 pulses per hour would correspond to controller saturation. If 10 pulses per hour are arbitrarily selected to correspond to a 0.454 kg (1 lb) per day leak, we find that the system can handle up to a 16.4 kg (36 lb) per day leak with less than 0.454 kg (1 lb) per day resolution. When saturation is reached, K is increased (probably by a factor of 5), which would then increase the leak size capability of the system with a somewhat reduced resolution (maximum of 77 kg (170 lb) per day leak with 2.3 kg (5 lb) per day resolution). A major advantage of this modification is that the "normal" or baseline leak rate of the vehicle need not be known ahead of time, and the system finds its own baseline with the appropriate K. In addition, the system always approaches P_o regardless of the leak rate.

Figure 3-17 confirms that a large leak can be found much quicker than a small one. Another useful item which may be deduced from Figure 3-17 is that the amount of gas lost prior to detection of the leak is nearly constant for all leak sizes. This indicates a detection sensitivity of 0.91 kg (2 lb) in 340 kg (750 lb) or 0.3 percent.

Translating this concept into hardware is the next logical step of development as the concept includes pressure error integration circuitry with a well-tested background. Four additional circuit functions are required. These are:

A. A temperature compensator to vary the pressure error integration rate inversely with temperature.

B. A bilevel integration limit check to allow the pressure decay or rise rate to be measured between two discrete levels. The upper limit tripout actuates a leak warning device.

C. A clock circuit to determine the time interval between the pressure limit levels.

D. A function generator to synthesize a set point feedback voltage $\cong \Delta P(\text{limit}) / (\text{time interval})(K)$. This voltage resets the integrator set point so that the gas addition rate is equal to the leak rate, and the vehicle pressure will equalize at P_o.

The principle of operation is more completely illustrated in Figure 3-20, which is a plot of nitrogen partial pressure vs time. An overboard leak event is experienced at time A. The nitrogen partial pressure falls to the upper integration limit (point C) which actuates a leak warning and starts an electronic clock.

The crew is now aware that an overboard leak exists and can initiate leak searching procedures. If the impact gages, for example, have indicated an impact event prior to the leak warning, the combined information could simplify the searching effort. The pressure continues to fall until the lower level integration limit is reached (point D), which stops the electronic timer. The function generator based on the time interval between the limit events first computes—Figure 3-19 illustrates this computation—and then displays an estimate of the leak rate, which gives the crew information as to the size of the hole to be found. In addition, the function generator computes the pressure level at which equilibrium will occur. This level is related to the control scale factor and the mass of gas added per pulse. The function

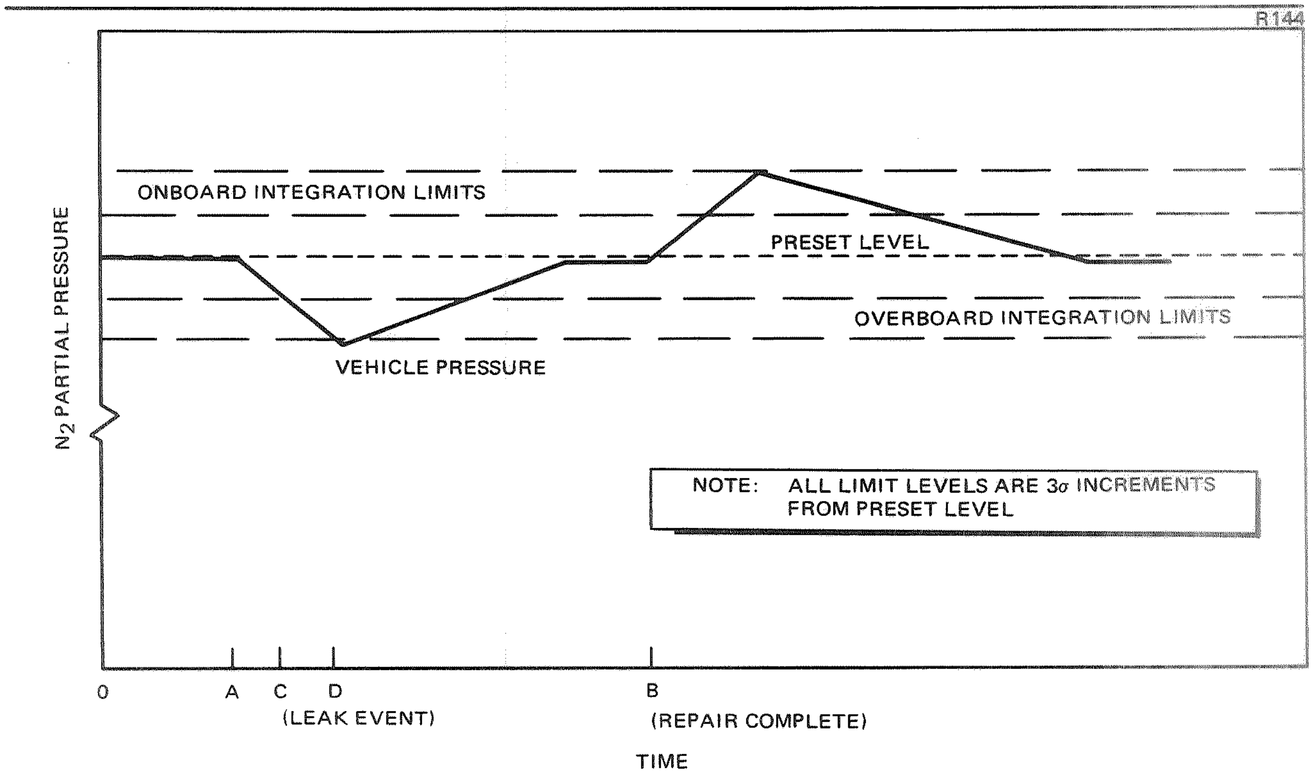


Figure 3-20. Two-Gas Control/Leak Detection Principle

generator issues a bias signal to the controller, which effectively increases the preset pressure level and increases the gas addition by the amount of the leak. Since an error signal also exists because of the pressure difference to the preset level, the actual gas addition is slightly higher than the leak and the vehicle pressure starts to increase, as shown in Figure 3-20. As the pressure approaches the preset level, the pressure error and the addition rate reach an equilibrium so that the addition rate and leak rate are equal.

To further illustrate actual events, assume that the hole is repaired at time B. Vehicle pressure will increase above the preset level and eventually reach the lower onboard integration limit, which will actuate the electronic timer and issue an onboard leak warning. Since the crew is previously aware of the leak event, the onboard leak warning serves as confirmation that the repair activity has been effective. The vehicle pressure will continue to increase until the upper onboard integration level limit is reached. At this point, the function generator again computes the leak rate and displays it. This quantity can be compared with the initial leak valve to evaluate the success of the repair activity. The function generator then decreases the bias level of the controller set-point to decrease the gas addition rate by an amount equal to the effective onboard leak rate. The pressure error is now negative and inherent leakage will cause the vehicle pressure to slowly decrease to the preset level. A major advantage of this application is that the "inherent" or baseline leak rate of the vehicle need not be known ahead of time as the system will adjust to any leak rate between 0.45 and 45 kg (1 and 100 lb) per day and maintain a near constant pressure level.

3.3.1.5 Two-Gas Controller Design to Accommodate Damage Control Function

The key to vehicle leakage detection is the control and management of the vehicle nitrogen inventory. The single function of nitrogen is to control and maintain vehicle pressure, and any change in cabin inventory must result from onboard or overboard leakage. This inventory exists in the storage containers and in the vehicle. In the case of high-pressure gas storage, storage pressure and temperature need to be measured. These parameters can be processed by a computer utilizing stored compressibility data to monitor stored inventory with acceptable accuracy. The remainder of the nitrogen inventory exists as a complex mixed cabin atmosphere. Results of the 60- and 90-day manned tests conducted for NASA by MDAC indicate the major species of vehicle atmosphere gases to be oxygen, nitrogen, carbon dioxide, and water vapor. While other gas species exist in trace quantities (e.g., hydrocarbons, NH_3, NO_2, and CO), their concentrations do not change at a rate to warrant real-time monitoring.

To monitor the quantity of nitrogen in the vehicle, the parameters which must be measured are nitrogen concentration, temperature, and pressure. Nitrogen concentration can be measured by several methods, including mass spectrometer and gas chromatograph, and indirectly by determining the concentrations of CO_2, H_2O, and O_2 and subtracting these from the total pressure. The indirect method has been utilized by NASA (Reference 15) to develop a flight-type sensor system with a maximum theoretical error of 5 percent. While no set criteria regarding accuracy requirements have been established, a 5 percent error is considered to be somewhat excessive. Five percent of the cabin nitrogen in the previous example would amount to a possible uncertainty of 8.6 kg (19 lb) of nitrogen. Gas chromatography possesses acceptable accuracy, but has disadvantages with regard to real-time information and flight development. Flightweight mass spectrometers have been developed and tested. The unit developed by NASA was successfully used to monitor and control the atmosphere during the 90-day manned test and is recommended for application to leak detection. The reported accuracy of this instrument is ± 1 percent for N_2 and O_2.

To determine the cabin gas quantities accurately, the temperature must also be determined. Since various locations within the cabin exist at significantly different temperatures, multiple temperature measurements are required. Two methods of accomplishment are possible. One is to install a parallel network of thermocouples at preselected locations so that the singular output represents a pseudo average temperature. The second method is to utilize certain other temperature transducers installed at various locations in the vehicle to monitor cabin thermal control systems and operating equipment. The computer can interrogate the transducers and process this information into an equivalent temperature. The remaining parameter which must be measured is pressure. There is an absolute pressure transducer as an integral component of the four-gas mass spectrometer which functions to bias the individual sensor amplifiers so that the sum of the signals represent total pressure. In addition to this pressure representation, a differential pressure transducer, one leg of which is referenced to a reservoir pressurized to the desired cabin level, is recommended. This should allow measurement of cabin pressure changes with an error limit of ±0.1 mm Hg.

To complete this leak detection system, these sensors are integrated by use of the computer. The computer interrogates the sensors, computes the gas quantities, and compares these quantities with previous values and tests for excessive depletion. The computer issues warnings if depletion exceeds budgeted rates and displays the equivalent hole size causing the excessive rate. Because the computer monitors the storage amount and the amount of gas issued to the cabin, any shortage between storage depletion rate and cabin feed rate would be symptomatic of a gas leak in the storage vessel or the plumbing to the gas feeding device. The above discussion is applicable to both oxygen and nitrogen control and management. In addition, the product of O_2 use rate and CO_2 concentration is an interesting parameter because of the possibility of its use in detecting a vehicle fire. The upper limit of this parameter may be characterized during normal manned activities; any value above this could result from inadvertent combustion.

The control function of the computer monitors any discrepancy in cabin oxygen and nitrogen levels and when a discrepancy reaches a preselected amount, commands a solenoid valve in the respective gas supply to open for a fixed length of time. The quantity of gas flows through a sonic orifice at a regulated upstream pressure. In this way, known fixed quantities of gas are withdrawn from storage and added to the cabin. This allows cross-auditing of the gas quantities between storage and the cabin. The quantity added per "pulse" is selected depending on vehicle volume and fixed leakage. In practice, it has been customary to adjust the pulse size so that 10 pulses per hour will accommodate normal usage including leaks. A block diagram showing the relationship of the various components of the two-gas controller is presented in Figure 3-2.

Cabin atmosphere content changes with crew activity. For example, changes in the levels of CO_2, O_2, and N_2 partial pressure, dewpoint, and temperature will occur in a spacecraft cabin occupied by eight personnel, two of whom are exercising, one is taking a sponge bath, and the others are engaged in less strenuous activities. The system described above would react under these conditions in the initial and final gas inventories shown below:

	Initial		Final		Net Change		
	kg	(lb)	kg	(lb)	kg	(lb)	
O_2	86.2	(190.0)	85.4	(188.2)	-0.8	(-1.8)	(apparent)
N_2	173.6	(382.2)	171.2	(376.9)	-2.4	(-5.3)	
CO_2	4.4	(9.7)	5.1	(11.2)	+0.7	(+1.5)	
H_2O	3.04	(6.7)	4.4	(9.7)	+1.36	(+3.0)	
Total	267.24	(588.6)	266.1	(586.0)	-1.2	(-2.6)	

The most significant change in inventory is the 2.4 kg (5.3 lb) loss of nitrogen which would signal that nitrogen leakage has occurred. The low apparent loss of oxygen is somewhat misleading as it does not consider the oxygen feed rate. Using the above information, the oxygen feed may be estimated. The oxygen lost with the nitrogen amounts to 49 percent of the nitrogen on a weight basis or 1.2 kg (2.6 lb). In addition, 0.59 kg (1.3 lb) of oxygen has been used by metabolic functioning of the crew to form the 0.68 kg (1.5 lb) of CO_2 in the cabin. Actually, more oxygen than this has been used by the crew, as during this period the EC/LS system would have been removing carbon dioxide from the cabin at an unknown rate. Disregarding this amount, the oxygen addition would be the total of the amounts or 2.6 kg (5.7 lb). This again illustrates that nitrogen inventory is the most convenient method of leak detection. Assuming the ± 1 percent accuracy for the nitrogen channel of the mass spectrometer, a leak signal would be generated after a 3.5 mm Hg loss in nitrogen partial pressure, which in this case would be 1.5 kg (3.3 lb) of nitrogen or a 2.22 kg (4.9 lb) loss of cabin gas.

The conclusion from this analysis is that the two-gas controller utilizing a four-gas mass spectrometer sensor would be capable of generating a leak warning at a point in time after approximately 2.3 kg (5 lb) of gas had been lost from the cabin. Parametrically, the minimum detectable gas quantity can be developed as follows:

The quantity of gas in the cabin can be expressed as:

$$n \text{ (moles)} = \frac{P_T V}{RT} \qquad (3\text{-}8)$$

where:

P_T = Cabin pressure (mm Hg)

V = Cabin volume, m^3 (ft^3)

T = Average cabin temperature, ^oK (^oR)

R = Gas constant, 62.3 (mm) m^3/kg mole ^oK (554.5 (mm) ft^3/lb mole ^oR)

The partial pressure of nitrogen in the cabin is P_{N_2}/P_T but for cabin atmospheres operating between 1/2 and 1 atmospheres pressure, the expression is

$$P_{N_2} \cong \frac{P_T - P_{O_2}}{P_T}$$

or (3-9)

$$P_{N_2} = \frac{P_T - 155}{P_T}$$

Combining these gives the moles of nitrogen in the cabin:

$$n = \frac{(P_T - 155)\ V}{RT}$$

or (3-10)

$$N_2 = \frac{(P_T - 155)\ V\ (28)}{RT}$$

Factoring in the accuracy of the nitrogen sensor will now define the "minimum" change in nitrogen quantity detectable as:

$$D_{N_2} = \frac{0.01\ (P_T - 155)\ V\ (28)}{RT} \qquad (3\text{-}11)$$

With the above equation, the minimum detectable change in quantity of nitrogen can be calculated for any size vehicle. Assuming a vehicle with a volume of 125 m^3 (4, 420 ft^3), the calculated quantities are 0.96 kg (2.12 lb) at 1.01×10^5 N/m^2 (14.7 psia), 0.69 kg (1.52 lb) at 6.89×10^4 N/m^2 (10 psia), and 0.432 kg (0.95 lb) at 5.17×10^4 N/m^2 (7.5 psia).

This equation shows that the main parameters which influence the minimum detectable quantity are sensor accuracy, cabin pressure, and cabin volume. The more accurate the sensor and the smaller the cabin volume, the greater is the potential for detecting small leaks.

Figure 3-21 presents a logic schematic of the computer processing of gas sensor signals to issue warnings and alarms, as well as to control the injection of stored gases into the cabin. The flow diagram is preliminary, and can be refined to include such features as comparing previous and present stored quantities to detect overboard leaks of the gas storage bottles. The type of data processing illustrated is applicable for both nitrogen and oxygen. The processing method utilizes a subroutine to set the inherent cabin leakage and compare it with the depletion rate.

The explanation of the computer flow diagram (Figure 3-21) utilizing the four-gas mass spectrometer for leak detection of space vehicles is presented below. The terms used in the figure are:

R	=	Gas constant
V_C	=	Volume of vehicle
V_S	=	Volume of gas storage containers
θ	=	Time, minutes
$K\Delta\eta$	=	Number of gas addition pulses
Lad	=	Amount of admissible leak, moles
Lab	=	Amount of absolute admissible leak, moles, assumed to be larger value than Lad
$\eta a-1$	=	Moles of N_2 previously in vehicle
ηa	=	Moles of N_2 presently in vehicle
P_{N_2S}	=	Pressure of N_2 in storage, mm Hg
T_{N_2S}	=	Temperature of N_2 in storage
Z	=	Compressibility factor, a function of storage pressure and temperature
ηS	=	Moles of gas presently in storage
P_{N_2C}	=	Pressure of N_2 in vehicle, mm Hg

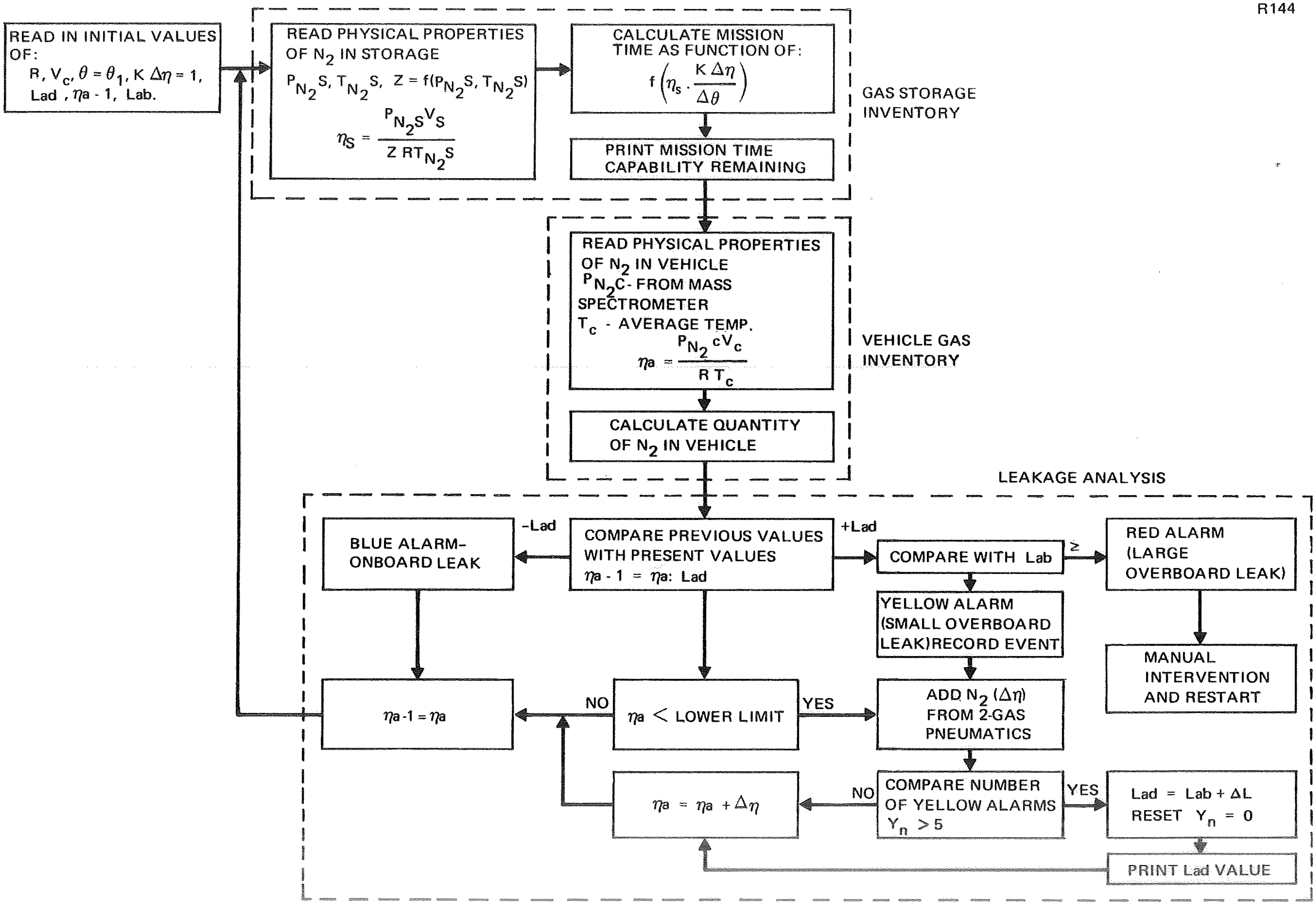


Figure 3-21. Vehicle Leak Detection Logic Diagram

T_c = Average temperature of gas in vehicle

Y_n = Number of "yellow" alarms

The startup block (upper left) in Figure 3-21 supplies the initial values and constants required for the first execution cycle. The second and third blocks read in storage pressure and temperature, respectively. In the next operation, the computer enters a stored table of compressibility factors using the pressure and temperature to select the proper factor. The number of moles of storage gas are then computed. Next, mission time is computed using the stored amounts and the addition rates. This value is then printed out. The computer is instructed to read in the value of the nitrogen partial pressure from the four-gas mass spectrometer and cabin temperature in the next two blocks. The number of moles of N_2 in the cabin (ηa) is then calculated, and compared with the value calculated in the previous cycle. If the present value is larger than the previous value, an onboard leak alarm is actuated and the present value replaces the previous value for the next cycle. If the present and previous values are equal, no leakage has occurred and the cycle continues; the present inventory is compared with a lower limit to assure minimum cabin pressure. If inventory is low, the two-gas controller is actuated and a known quantity of nitrogen is added to the cabin, and the computer adds the gas addition ($\Delta\eta$) to the cabin inventory and recycles.

If the present gas inventory is less than the previous inventory by the admissible amount (Lad), the difference is compared with the maximum leak (Lab). If the difference exceeds or equals Lab, a "red alarm" (overboard leak) is actuated. A leak of this nature would call for immediate use of pressure suits prior to leak location and repair. Gas has not been added to the cabin during this period by the computer to avoid gross depletion of stored gas inventory. The manual intervention and restart block allows override to manually add gas and to restart computer control after the leak has been repaired.

If the difference is less than Lab, a "yellow alarm" (overboard leak) is actuated and the event recorded; the two-gas controller is actuated and a known quantity of N_2 is added to the cabin. The number of "yellow alarms" is counted and if it exceeds five (arbitrary), the computer increases Lad by a fixed increment and resets the number of "yellow alarms" to zero. This operation allows the computer to "learn" and allows the computer control to be used on various vehicles having different unknown leak rates. Each time the two-gas controller is actuated, the present gas inventory is increased by the amount added and becomes the yardstick value for the next computer cycle.

3.3.2 Passive Ultrasonics

One of the first approaches to the detection of overboard leakage of atmosphere through discontinuities in the space cabin wall was the application of the ultrasonic translator leak detector technique. This technique is based on the detection of the ultrasonic noise generated by a gas as it passes through an orifice.

The standard commercial ultrasonic leak detectors are generally designed to detect leakage of gas from a higher than atmospheric pressure region into a region of atmospheric pressure, with a leak detector located on the low pressure or downstream side of the leak. The ultrasonic noise generated by such leaks generally has a broad maximum of intensity around 40 kHz. The leak detector can employ a contact probe or an airborne probe as the noise-detecting transducer.

Recently, experimental studies have been carried out to determine the feasibility of detecting a leak of cabin atmosphere into outer space vacuum from the upstream side of the leak using an ultrasonic translator detector (Reference 19). A systematic investigation has been carried out at NASA-LaRC. The NASA-LaRC study employed a vacuum system capable of sustaining a pressure below 0.5 torr on the low pressure side of small leaks 0.89×10^{-3} m (0.035 in.) dia or smaller. While these holes represent large leaks from an atmospheric loss point of view, such leaks were not detectable with an ultrasonic detector when the pressure on the vacuum side was below about 1.0 torr. Some examples of the NASA-LaRC results are shown in Figure 3-22. In these measurements, both single- and double-wall space cabin structures were simulated.

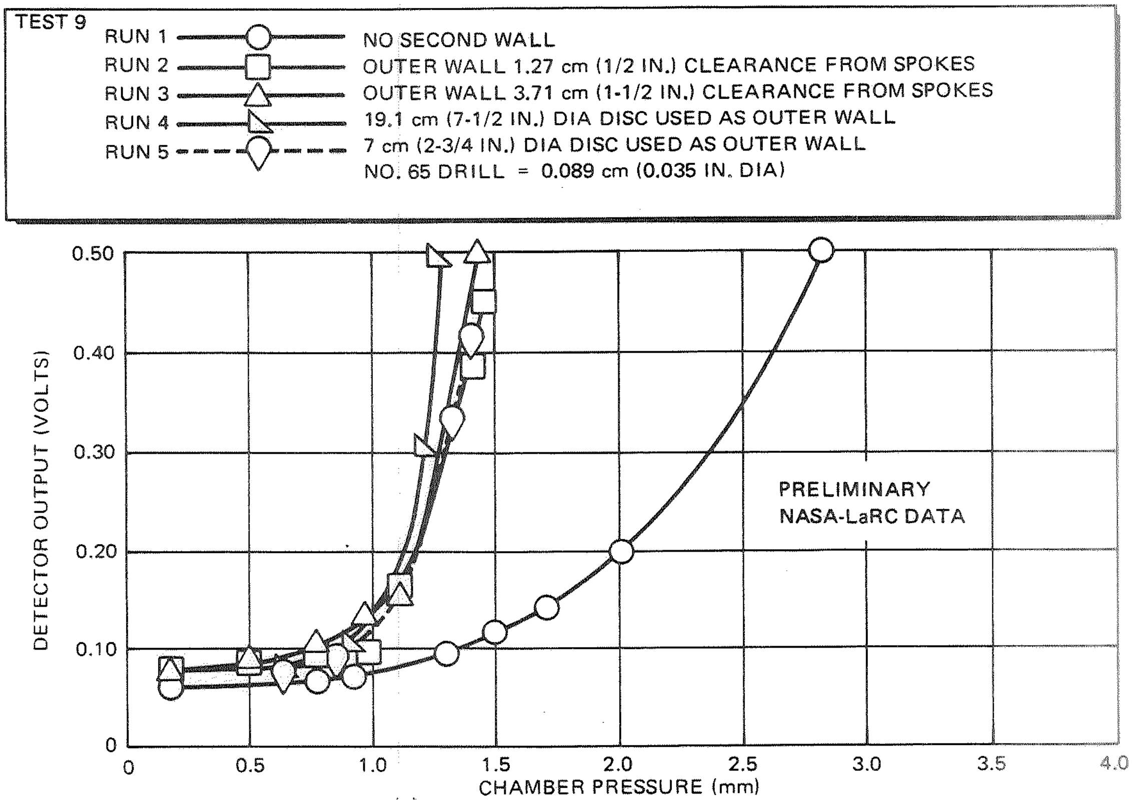


Figure 3-22. Effect of Double-Wall Configuration—Ultrasonic Leak Translator Measurements

The following observations can be made on the basis of the double- and single-wall measurements at NASA-LaRC. In the experiments, noise well above the background level appeared only after the pressure on the low pressure side rose to about 1.0 mm Hg. It appears that this amount of down-stream pressure is required to cause sufficient generation and coupling of sound into the structure for the ultrasonic leak translator to detect the leak.

In all the experiments, the high-level detectable noise did not appear instantaneously upon opening the leak. This effect indicated that the noise generated in the orifice itself is either extremely weak or far out of the range of the instrument's frequency response, or both. Also, the noise level detected in the double-wall measurements did not appear instantaneously upon opening the leak, so the possibility of the noise being generated by the jet of air striking the second wall can be considered to be unlikely. Finally, the similarity of all of the measurements (i. e., the amount of noise) and the necessity of a vacuum side pressure of at least 1.0 mm or greater suggests that the noise signal being detected is in the fringe of some broad frequency distribution centered away from the 40-kHz center frequency of the ultrasonic translator.

Results to date for ultrasonic overboard leak detection using commercial instruments have not been promising. A conventional translator may be the correct type of sensor (ultrasonic detector), but simply does not operate in the correct frequency range.

The details of the noise generated by a leak where air at or near atmospheric pressure passes through a small orifice into a rarefied gas are not yet fully understood. The processes of noise generation merit further investigation.

A preliminary analysis of possible noise-generation mechanisms (Appendix A) suggests that small holes and cracks will generate some noise at high ultrasonic frequencies. For such orifices, the flow through the leak is expected to be unstable, giving rise to turbulence and consequent noise generation.

Preliminary results indicate that an expression such as $f = \frac{SU}{d}$ may govern the dominant noise frequency generated, where f = frequency, S = coefficient which may be dependent on the Reynolds number, U = velocity of flow after the free shear layer of gas becomes turbulent after separation, and d = diameter of hole. For example, for a 1-mm hole, the dominant frequency is of the order of 300 kHz. This analysis suggests that, except for gross holes, an ultrasonic translator is simply not sensitive in the high frequency range characteristic of typical holes on the order of 60 mils or less. To understand the process of the noise generation, some experimental work will be required to determine the frequencies and parameters involved. A more detailed discussion of possible noise generation mechanisms involved in producing noise from a leaking orifice or crack is found in Appendix A.

3.3.3 Active Ultrasonics

The concept of an active ultrasonic inspection system using permanently mounted transducers appears promising for inclusion in a damage control system for Space Station applications. The basic operation of an active ultrasonic inspection system involves sending pulses of ultrasonic energy through a structure, and then detecting the ultrasonic signals reflected from flaws (holes or cracks) in the structure by employing several transducers. Triangulation techniques can be applied to locate the flaws.

Such a system has several attractive features. Ultrasonic techniques can detect small flaws and cracks. An active pulsed ultrasonic damage control system would detect leaks by remotely detecting and locating the cracks or holes through which gas is escaping. As part of an independent research and development program at MDAC, a series of surface wave pulse echo measurements was performed to determine the remote flaw detection capabilities of surface waves in aluminum. Surface waves of 2.25 MHz were used to study small simulated flaws of approximately 0.762 mm (0.030-in.) width. A flaw of dimensions $7.6 \times 10^{-4} \times 7.6 \times 10^{-5} \times 3.8 \times 10^{-5}$ m (0.030 x 0.003 x 0.015 in.) could be detected up to 2.53 m (100 in.) from the ultrasonic transducer. Results of some of these measurements are shown in Figure 3-23. Some examples of the ultrasonic echo signals received at various points between the transducer and flaw are shown in Figure 3-24.

Since a space cabin can be thought of as a pressure vessel, such an inspection system could also be designed to look for weldment flaws or cracks in parent material that could develop and become leaky after extended service in space.

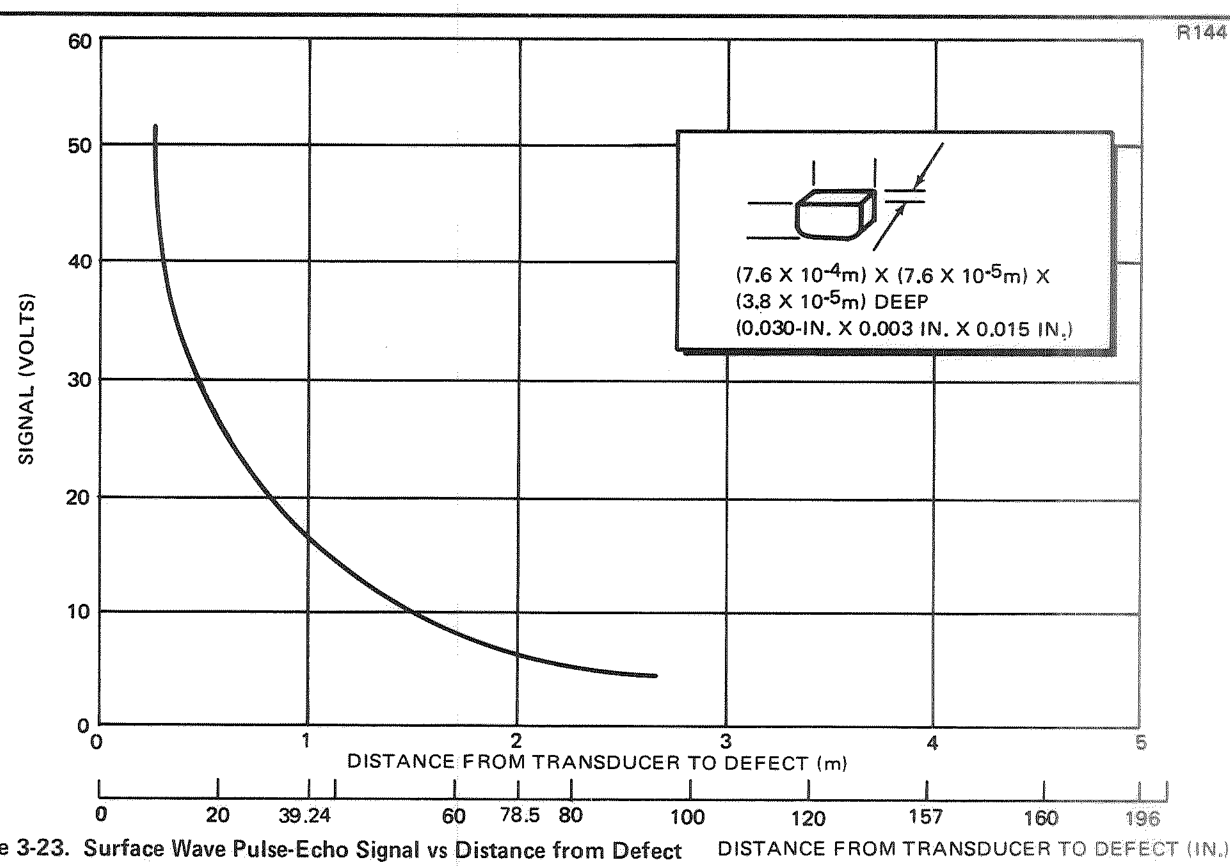
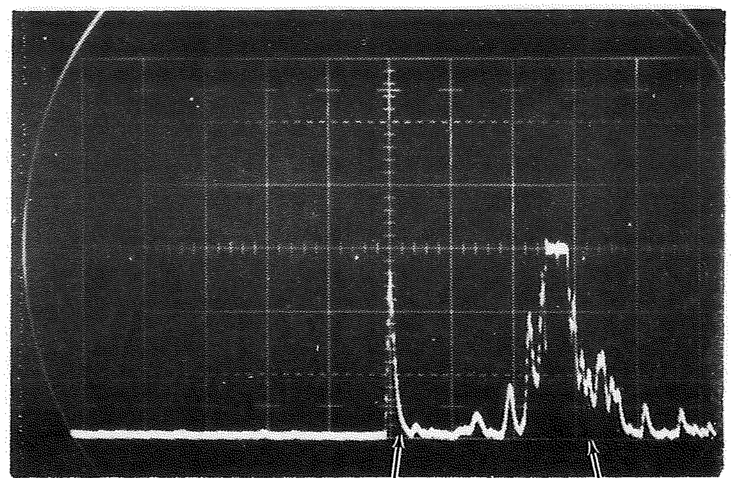
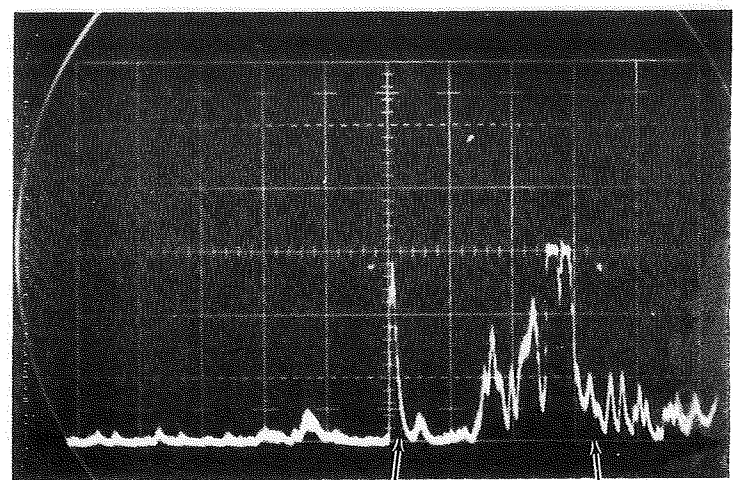


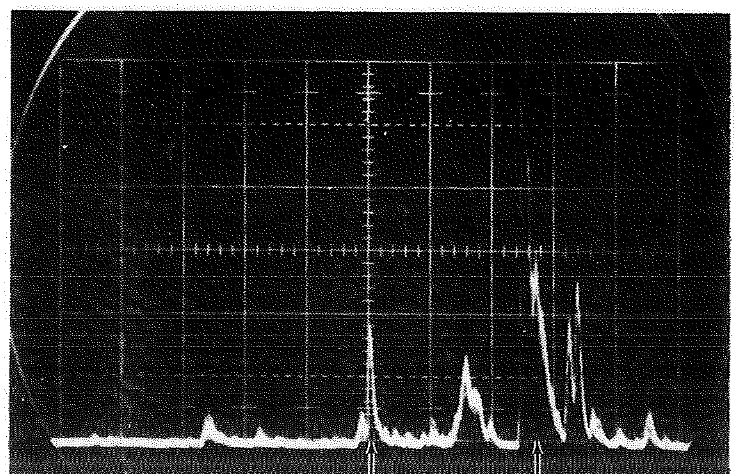
Figure 3-23. Surface Wave Pulse-Echo Signal vs Distance from Defect



25.4 cm (10 IN.) FROM FLAW — REFLECTED SIGNAL FROM FLAW — EDGE OF TEST DISTANCE SPECIMEN



101.6 cm (40 IN.) FROM FLAW — REFLECTED SIGNAL FROM FLAW — EDGE OF TEST SPECIMEN



254 cm (100 IN.) FROM FLAW — REFLECTED SIGNAL FROM FLAW — EDGE OF TEST SPECIMEN

FIXED DISTANCE FROM FLAW TO EDGE OF TEST SPECIMEN = 7.62 cm (3 IN.)

Figure 3-24. Oscilloscope Traces of Flaw Signals

Ultrasonic transducers could be permanently mounted and then scanned automatically and their output analyzed by remote control. Figure 3-25 shows a possible configuration of a permanently mounted ultrasonic inspection system. Each transducer in the array can be used as a transmitter and a receiver for the ultrasonic pulses, and is expected to be omnidirectional in its response so as to monitor a wide area of the panel. In the figure, transducer No. 1 sends an ultrasonic pulse which is reflected by a flaw. The flaw reflects a signal into transducers No. 2 and No. 3.

Knowing the sound velocity and the time delay between sending the pulse and the reception of a reflection from a flaw, the total distance traversed by the reflected energy can be determined. From the definition of an ellipse, the locus of a point for which the sum of the undirected distances to two fixed points called the foci (here, a pair of transducers) is a constant greater than the distance between the foci (transducers), the total distance traversed determines an ellipse about any pair of transducers. This ellipse is the locus of all possible locations for the flaw. Taking a second pair of transducers, a second ellipse is determined. The intersection of the two

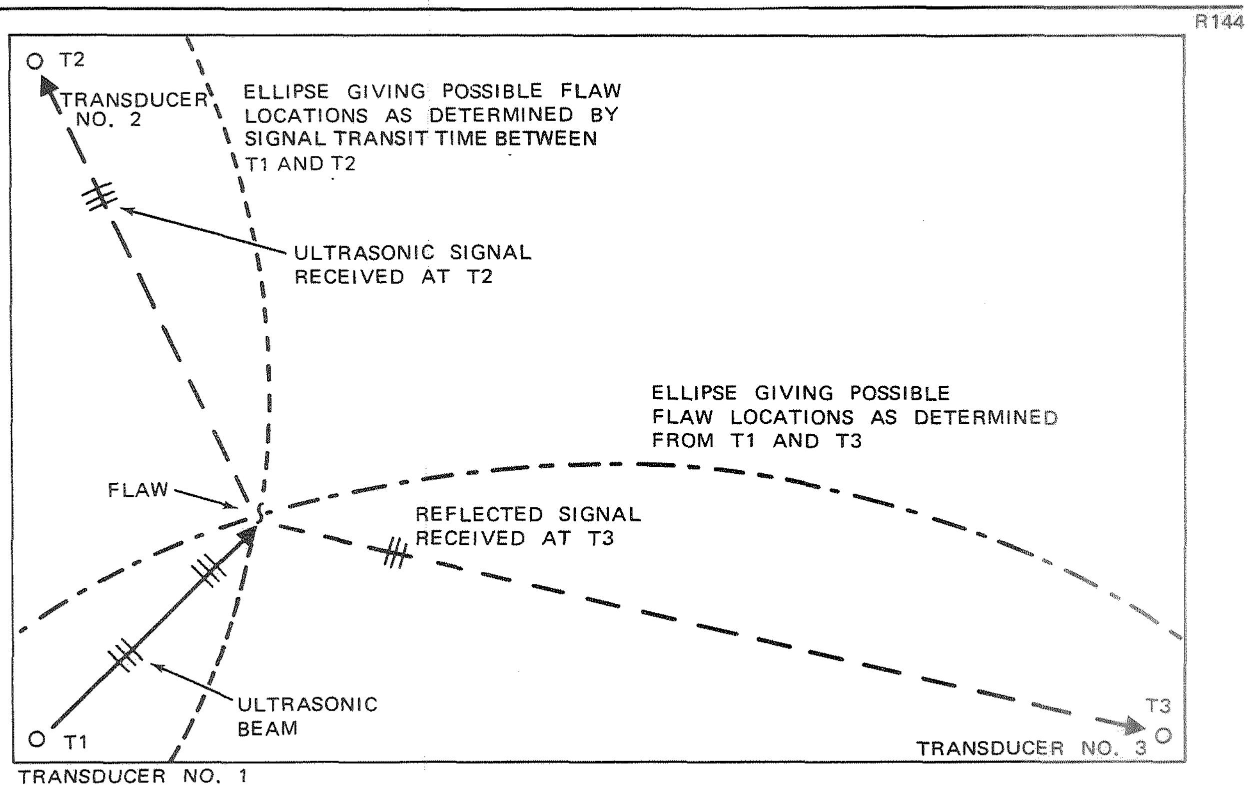


Figure 3-25. Permanently Mounted Active Ultrasonic Inspection System

ellipses gives the location of the flaw. For such an ultrasonic system to be constructed, research and development efforts must be expended to develop omnidirectional transducers and to optimize techniques for sending ultrasonic energy through structures past structural ribbing attachment points.

A pulsed ultrasonic inspection system could be used to classify flaws as to their size, and thus the magnitude of a leak could be determined indirectly. Broad bandwidth ultrasonic transducers are available for use in nondestructive flaw detection applications. These transducers are capable of transmitting short-duration pulses (less than two cycles) of ultrasonic energy which enable good flaw resolution. These transducers also give a high degree of uniformity of the sound beam intensity in the near field of the transducer. This beam uniformity enhances the transducers' ability to detect flaws that may develop in the near field of the transducer.

3.3.4 Acoustic Emission

Acoustic emission can be defined as the stress waves generated in a solid material by energy released as the material is deformed or fractured. These waves can be detected at the surface of a pressure vessel wall by piezoelectric transducers. The detection technique is limited to dynamic strain or flaw modes. Static flaws do not generate acoustic waves. For detection of static flaws, the active ultrasonic method discussed in the previous section is indicated.

The basic phenomenon in acoustic emission is the generation of a signal with a very short time period over a frequency spectrum from less than 1 MHz to 50 MHz. As usually measured, the signal is only an analog of the true signal in the sense that it represents the transducer response characteristic (Reference 20).

For continuous structural integrity monitoring of Space Station pressure walls, the frequency band to detect acoustic emission should be chosen to lie above the noise background of the Space Station. A typical frequency range would extend from a few hundred kHz to 1.5 MHz.

By applying a transducer array to the Space Station pressure wall and utilizing triangulation techniques, a growing crack could be detected and located. The acoustic emission monitoring technique would extend the capability of the overboard damage control systems to ensure safe life of the structure by detecting real-time dynamic flaws before they culminate in a leak or rupture.

Continuous acoustic emission monitoring systems are in an early stage of development. Considerable effort has been directed toward developing such systems for nuclear reactor pressure vessels and for pressure vessels in the petroleum industry.

As part of an independent research and development program at MDAC, acoustic emission studies have been carried out on cryogenic pressure vessels. Figure 3-26 shows the result of a cryogenic burst test. During the test, the vessel was monitored by two acoustic emission sensors.

Analysis of the difference in time arrival of the acoustic emission signal at each transducer yielded a prediction of the line on which the fracture was initiated. A third transducer would be necessary to locate the actual point of fracture initiation. Figure 3-27 illustrates cumulative acoustic emission signal count for a transducer as a function of applied load. The onset of a significant increase in cumulative count was obtained well before the failure load was applied.

An acoustic emission monitoring system and a meteoroid impact gage (see next section) have a number of elements in common. Both use similar transducers in arrays and both detect and locate a dynamic damage mode by triangulation techniques. Meteoroid impacts on the pressure wall are likely to generate cracks in the impacted area. For this event, there would be a time relationship between the meteoroid impact signal and the acoustic emissions. The major difference in the two systems lies in the signal conditioning requirements. A meteoroid impact is likely to produce a large signal, whereas acoustic emissions pulse are small in magnitude. A dual

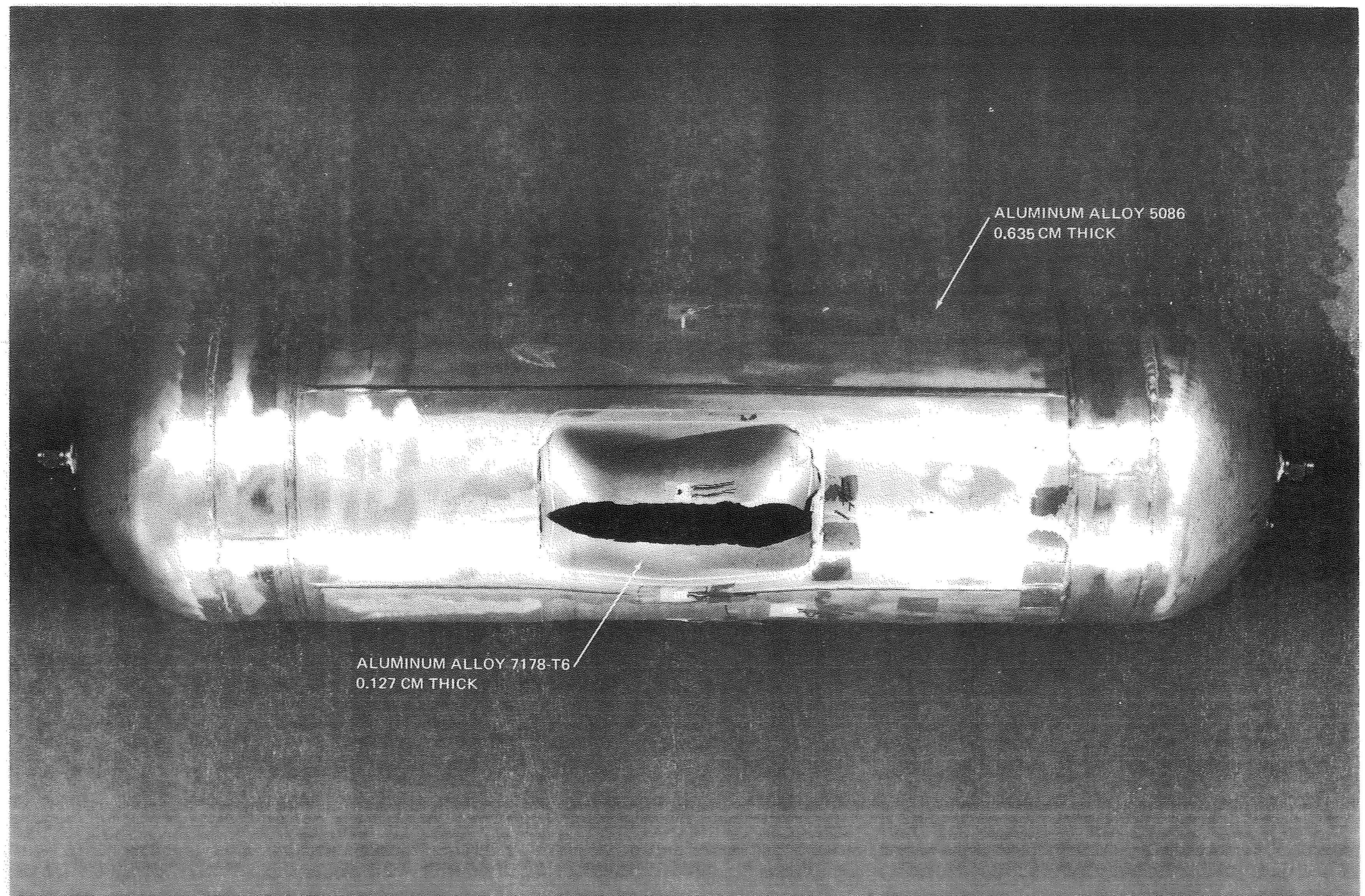


Figure 3-26. Aluminum Pressure Vessel After Burst Test (Cryogenic)

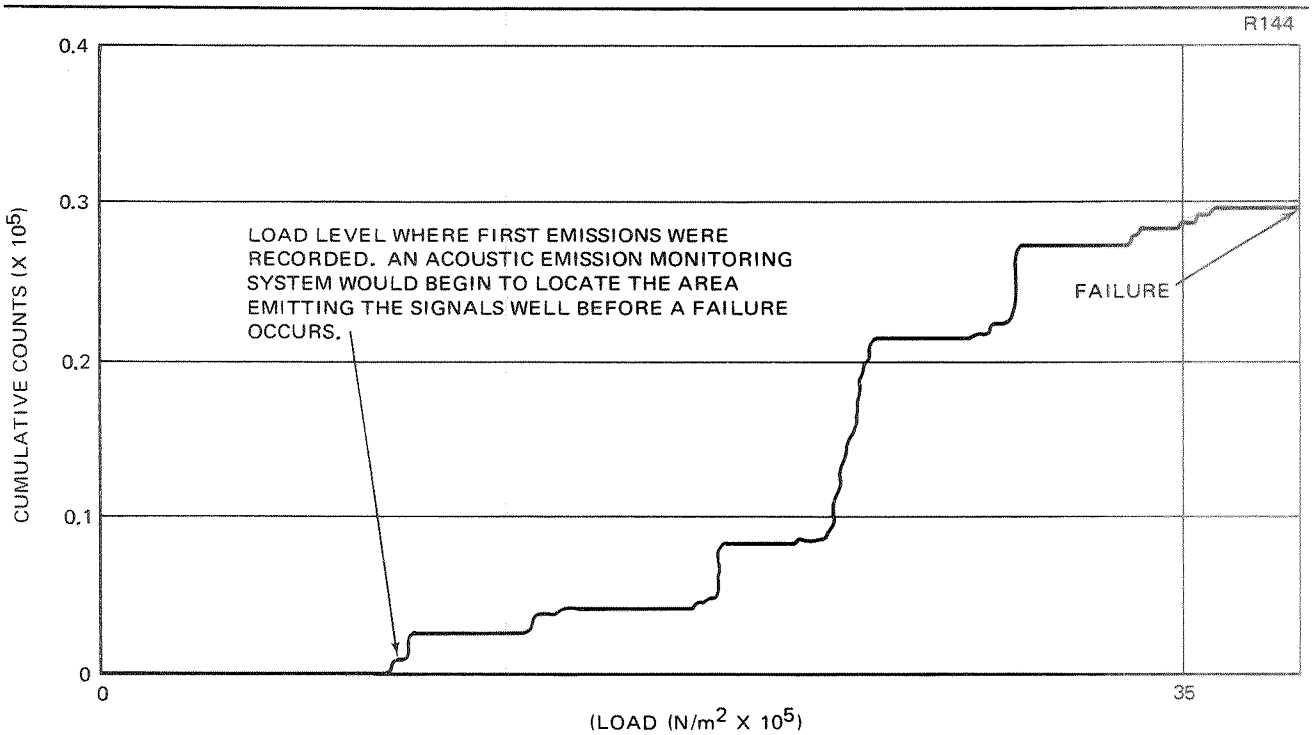


Figure 3-27. Cumulative Count of Acoustic Emissions as a Function of Applied Load for Pressure Vessel Burst Test

function system is considered feasible and would offer considerable promise for extending the potential of a passive ultrasonic damage control system.

3.3.5 Meteoroid Impact Gage

Meteoroid impacts may occur anywhere on the Space Station structure. Meteoroid or bumper debris impacting the main pressure wall can cause damage modes ranging from dimples and spall to massive penetrations. A transducer array mounted on the pressure wall will serve to locate the area of impact. Signal analysis may yield a quantitative measure of the damage mode.

3.3.5.1 Impact Gage Concepts

Two impact gage concepts were identified. One is based on sensing the impact-generated wave arrival times at three widely spaced locations. The second is based on sensing the wave direction vector at two locations.

A. The first is a detection system employing three omnidirectional nonlinear sensors that are widely spaced over the surface of the structure being monitored. A schematic of such a system is shown in Figure 3-28. Since this is a passive system and must be excited by an impact, the system measures the differences in the time of arrival at the transducers of the stress waves excited by the impact. The difference in the arrival time can be related to the differences in distance of the impact point with respect to the various transducers if the velocity of the stress wave is known. From the definition of a hyperbola: the locus of a point for which the absolute value of the difference of the undirected distances to two fixed points called the foci (here, the distance between a pair of transducers) is a constant which is less than the distance between the foci (transducers), the difference in time of arrival between two transducers can be used to determine a hyperbola upon which the impact point lies. The first transducer excited distinguishes between the two branches of the hyperbola to select the branch on which the impact point lies. By considering another pair of transducers, another hyperbola and the branch on which the impact point lies are determined. The point of intersection of the two hyperbola branches gives the point of impact. For this impact

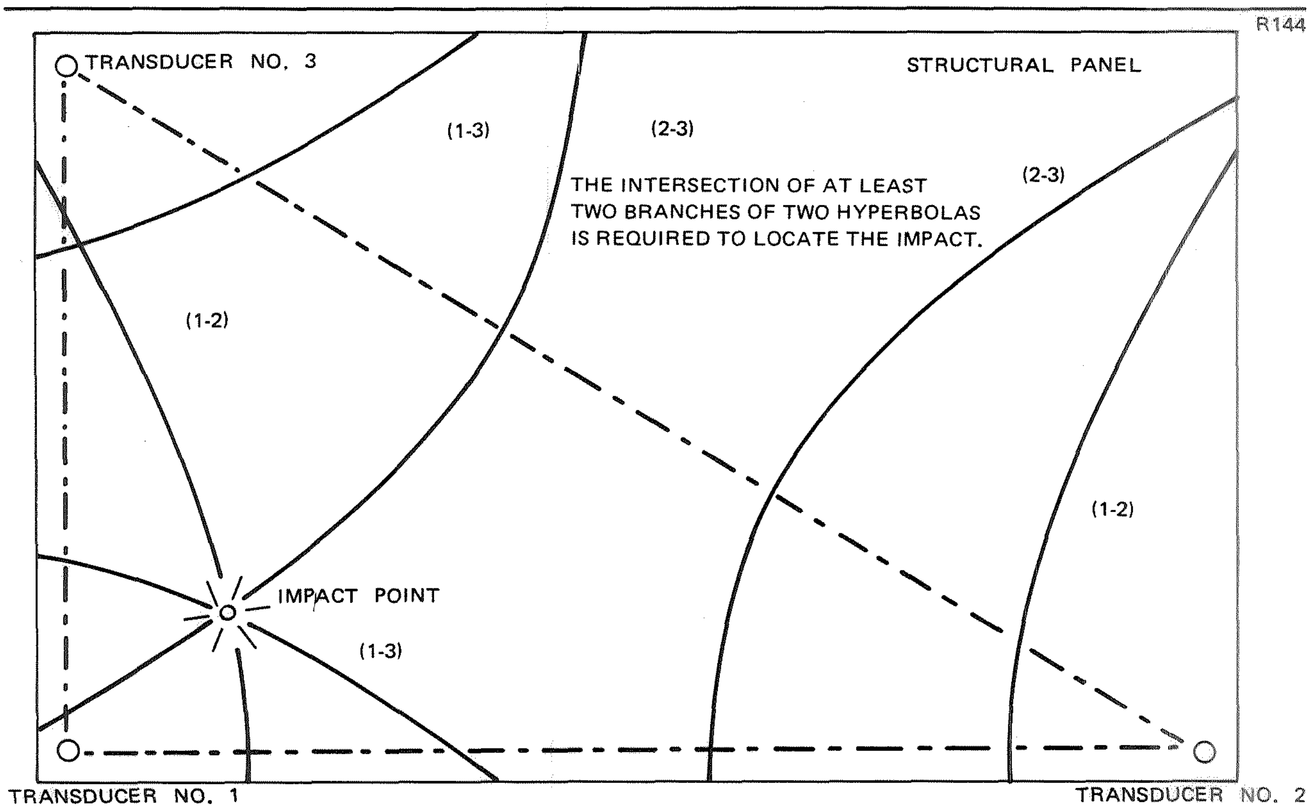


Figure 3-28. Impact Gage for Damage Control System

system to be functional, the velocity of propagation of the stress wave must be a known constant.

B. A second detection system can locate the region of impact without requiring knowledge of the velocity of propagation of the stress wave resulting from the impact. This would provide an advantage over the first system if the velocity of propagation of the stress wave depends upon the nature of the impact, i. e., upon the type of stress wave generated. In this second detection and location system, two sets of three closely spaced, non-colinear sensors are used. The simplest configuration for this set is a sensor on each vertex of an equilateral triangle. Figure 3-29 shows one of the sets of three sensors. The separation of the transducers can be on the order of one or two inches. In this array, a positive X-axis is defined as a line originating at the last transducer struck by a stress wave, and passing through the first transducer excited. The time delay between the arrival of the stress wave at the first two transducers excited is taken as t_1, and the time delay between

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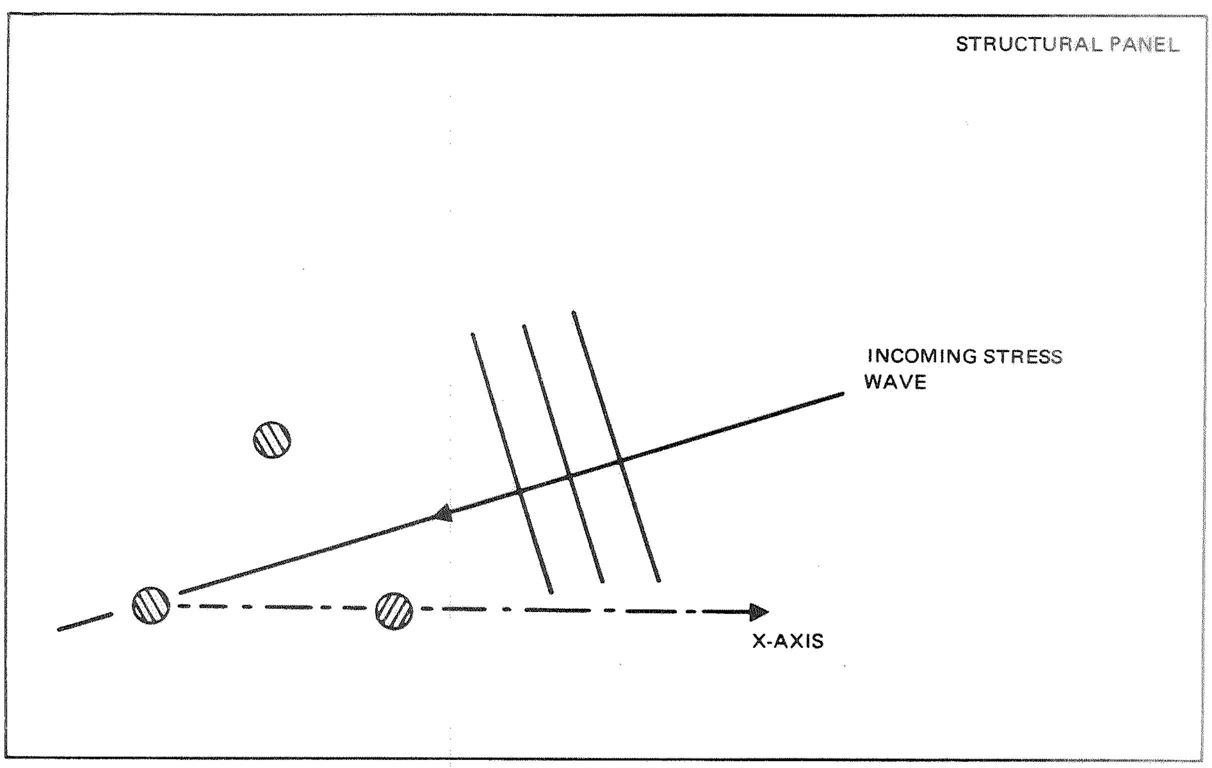


Figure 3-29. Closely Spaced Three-Transducer Array

the second and third transducers excited by t_2. The slope of the line in the direction of the incoming wave is given by:

$$m = \frac{1}{\sqrt{3}} \frac{t_2 - t_1}{t_1 + t_2} \qquad (3\text{-}12)$$

By measuring these time delays, the position of the X-axis with respect to the three transducers on the plate and the slope of the direction of the incoming wave can be determined. This information determines a line on the panel along which the stress wave struck the sensor array. By employing a second set of three closely spaced transducers that is widely separated from the first set, as shown in Figure 3-30, a second line is determined. The intersection of the lines gives the point of impact. The operation of this system depends on the incident wave front being well defined and approximately planar, and upon the sensors in the array having a fast response time to give good definition of the time delays.

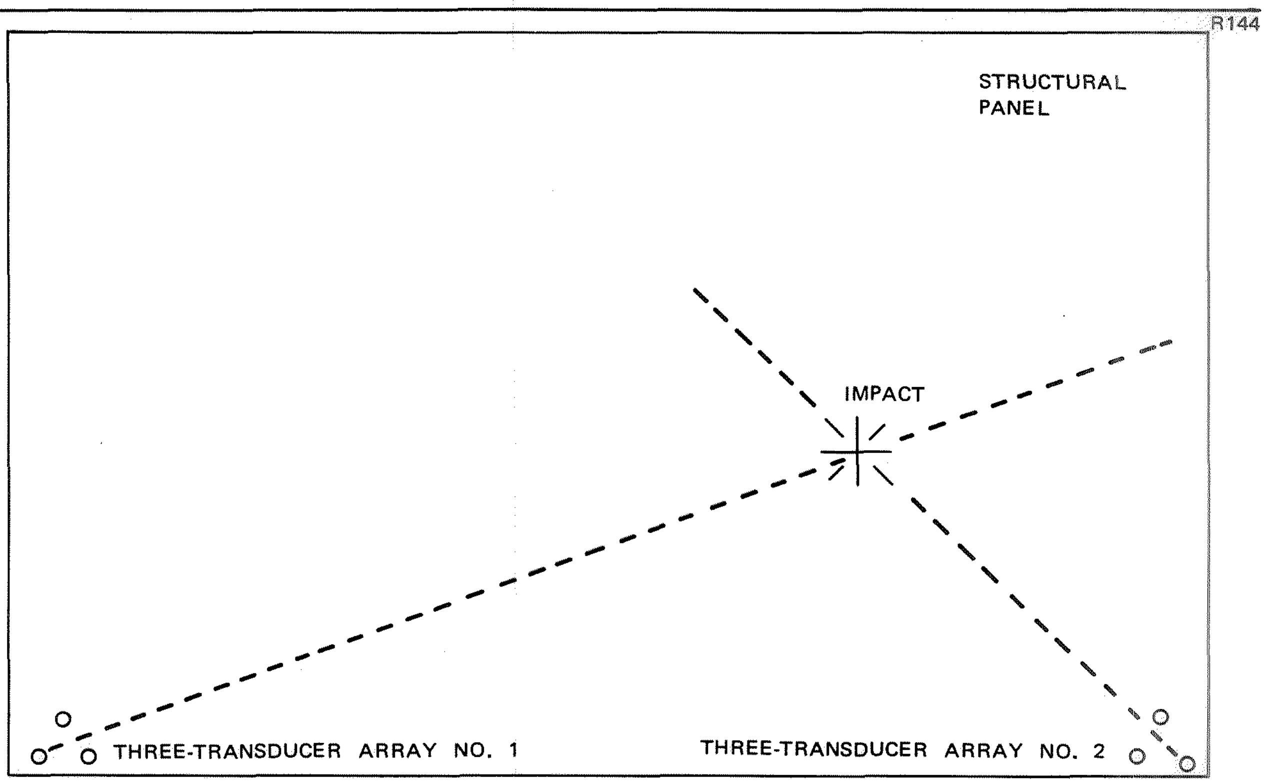


Figure 3-30. Damage Control System Using Two Three-Transducer Arrays

This system could employ strain gages for the sensing elements. Rosette or mutually perpendicular strain gages would be used (Figure 3-31). A Rosette strain gage contains three unidirectional gages oriented at 120 degrees with respect to each other. The relative amplitude of the strains in each arm of the gage determines a line of possible impact points. In the system discussed above in A, strain gages could be employed.

Strain gages offer the advantages of having very low mass and very short transient response times. The low mass will lower the weight penalty due to a permanently mounted damage control system used for detection of meteoroid impacts. If, however, a permanently mounted active ultrasonic damage detection system is also envisioned for the structure, the transducers used in the ultrasonic system may also be suitable for use as meteoroid impact detection devices. The intensity and particle displacements of the stress waves must be considered in the selection of transducers. More experimental data on the stress waves resulting from an impact must be available before the usefulness of the above approaches can be determined.

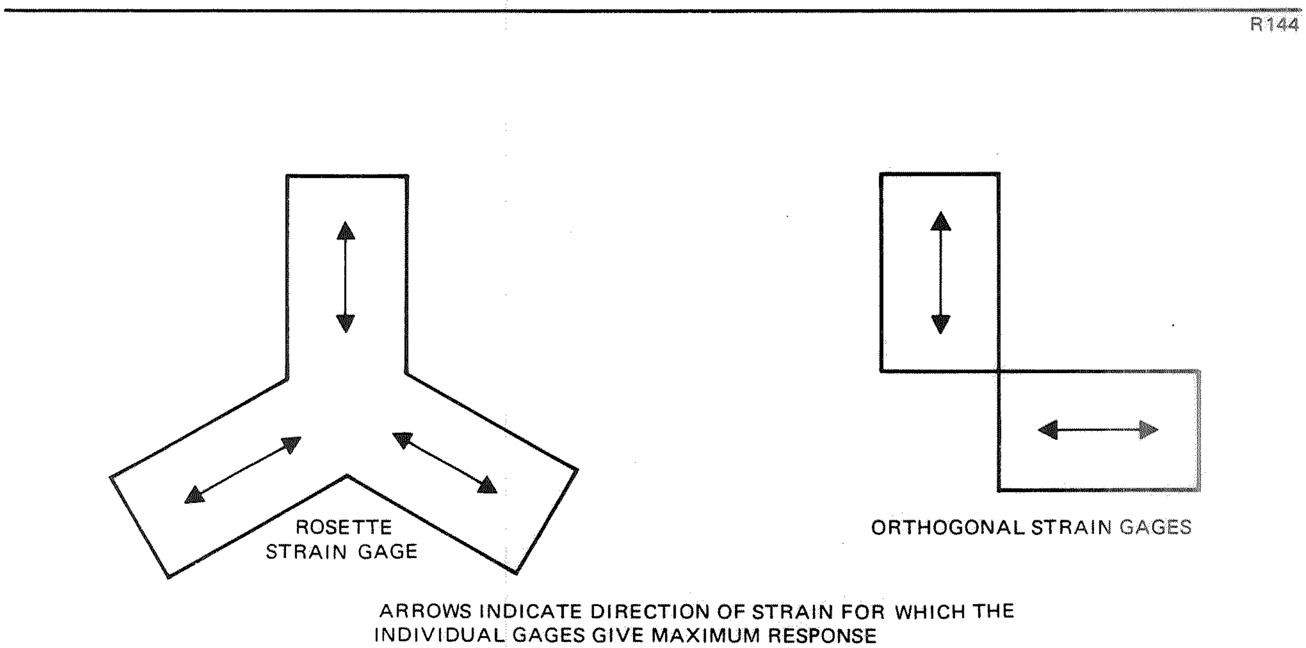


Figure 3-31. Rosette Strain Gage Array

3.3.5.2 Experiment Results

To evaluate the feasibility of any impact gage system, it is necessary to determine the acoustic signature of the meteoroid impacts and establish the transmission characteristics of the resulting pressure waves within the structure. Results obtained from an MDAC independent research and development program on impact physics in 1970 are relevant to gage requirements. A series of hypervelocity simulated meteoroid impacts on single- and multi-wall structures were carried out. These tests (see Appendix B) resulted in the following conclusions:

- The signature of a meteoroid impact contains high-frequency components not generated by other likely impacts. The presence of these components can serve as the foundation for a meteroid impact detection system.
- Impact location by a wave arrival time technique using a transducer array has been proven on a limited scale test.
- The influence of structural irregularities on impact location was less than originally predicted.

3.3.6 Sensors for Seal Leak Detection

The objective is to develop simple, rugged, long-lived sensors for the detection of overboard leaks past static and dynamic seals of manned spacecraft with a detection sensitivity of 10^{-4} atm-cc/sec or better for cabin atmospheres from 4.8×10^4 to 1.01×10^5 N/m^2 (7 to 14.7 psia). The sensors must furnish an electrical signal that can be easily integrated into a central damage control system.

The main constituents of space cabin stmosphere, in decreasing concentration, are N_2, O_2, H_2O, and CO_2. These gases can be considered as individual tracer gases. The measurement of any (or all) of these gases by a sensor can be related to the total leakage rate when the relative concentrations of each in the cabin atmosphere are known. However, a basic differentiation must be made between permeation and leaks past seals. While each of the cabin atmosphere gases will have a specific permeation through an elastomeric (O-ring) seal, there is no significant difference in leakage rate among the gases when the leak is in the 10^{-2} to 10^{-5} atm-cc/sec range. The sensor may detect permeation rates if it is sufficiently sensitive, but the primary concern is to detect and measure the larger flows associated with a seal failure. To accurately measure the leakage rate and to increase the sensitivity of detection, all of the escaping gases must be temporarily confined by a secondary seal and passed through the sensor.

Several criteria were invoked to choose sensor concepts for evaluation:

A. The sensor must be inherently sensitive, simple, lightweight, rugged, and long-lived.

B. The sensor must be attached to the monitored seal with only electrical leads which can easily be passed through the cabin wall and potted in place. (Pneumatic tubing to a central analytical instrument introduces additional complexities of valving, tubing, and weight.)

C The electrical signal output must be capable of integration into a damage control system.

Based upon the foregoing, three sensor concepts were chosen for further evaluation.

A. Electrolytic hygrometry to measure moisture.

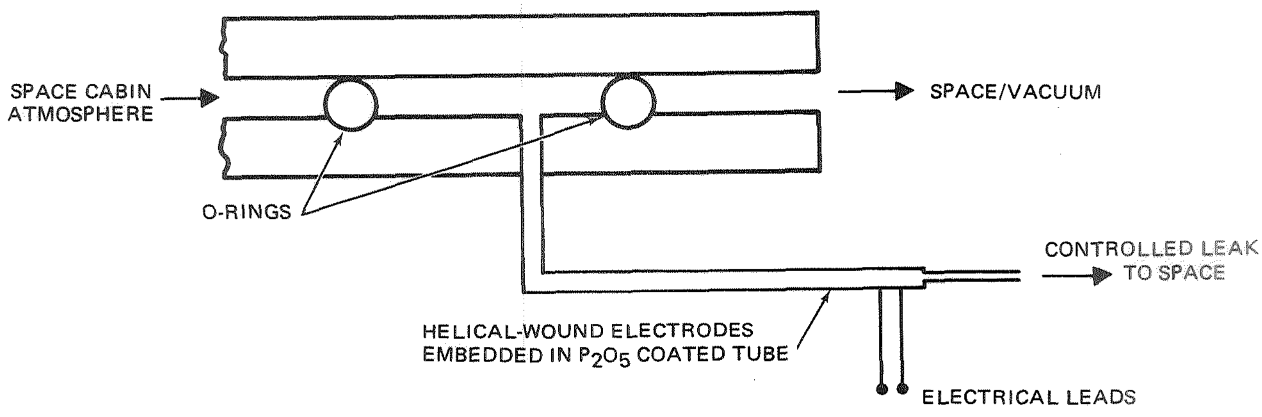
B. Capacitance to measure moisture.

C. Thermal conductivity to measure all gases.

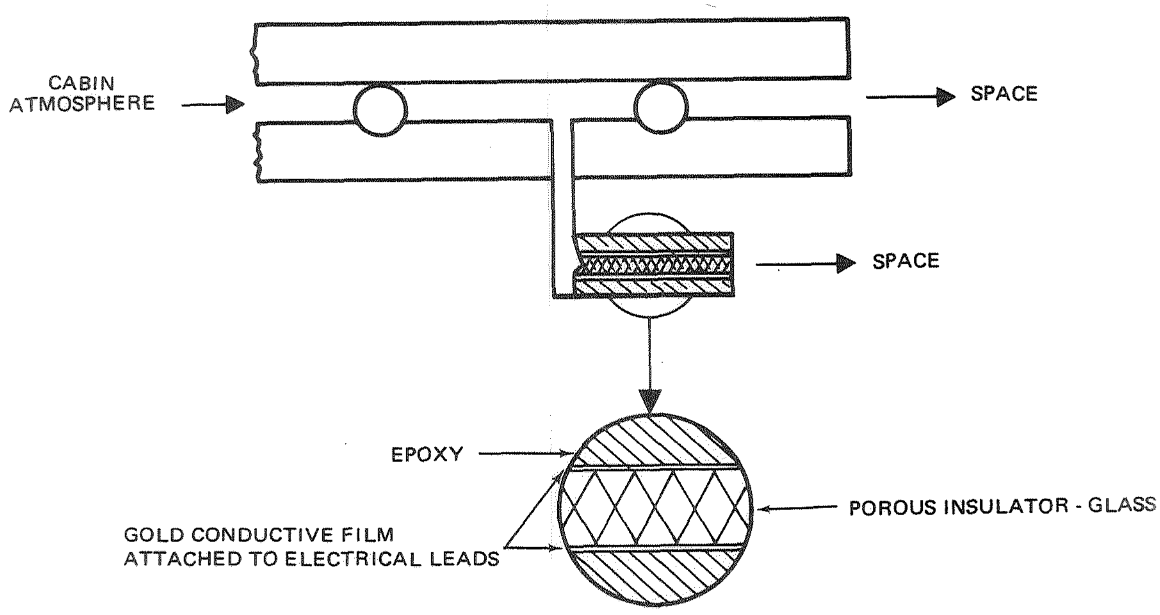
3.3.6.1 Electrolytic Hygrometry

Cabin atmosphere moisture is estimated for the Skylab at approximately 2,000 to 4,000 ppm. Future manned missions may be up to 16,000 ppm – i.e., 50 percent RH at 1.01×10^5 N/m^2 (14.7 psia) and 25°C. Two sensor variations are considered:

A. Moisture passes through a tube whose inner surface is coated with a thin layer of phosphorous pentoxide (P_2O_5) which absorbs moisture. Embedded within the P_2O_5 are two helically wound wire electrodes with an applied potential. The presence of moisture permits a current to flow which is proportional to the amount of moisture electrolyzed. The phenomenon of recombination (H_2 and O_2) may enhance the signal by controlling the rate of passage through the sensor to vacuum or space, Figure 3-32 (A).



(a)



(b)

Figure 3-32. Moisture Measurement—Electrolytic Hygrometer

B. A variation of the elctrolytic hygrometer is the use of a porous insulator coated on two sides with a conductive (gold) film. Moisture penetrating through the porous insulator is electrolyzed to H_2 and O_2, resulting in a current flow between the conductive films. While simpler than the previous concept, it might not be as sensitive, Figure 3-32 (B).

3.3.6.2 Capacitance

Silicone rubber is very permeable to moisture as well as other gases such as O_2, N_2, and CO_2. The dielectric constant of water is approximately 25 times that of silicone rubber. The difference in capacitance is registered on a capacitor with silicone rubber as the dielectric permeated by moisture. An improvement in signal would result if the capacitance between the plates could be reduced. For example, using a porous cellulose dielectric between the plates would reduce the initial capacitance by approximately a factor of 4, thus increasing the signal differential when moisture permeates (Figure 3-33).

3.3.6.3 Thermal Conductivity

Gas leaking past a seal is vented to space via a small-diameter tube which contains a thermistor. Another thermistor exposed to space is used as reference (Figure 3-34). The differences in signal are balanced with a modified Wheatstone bridge. The leak rate is equivalent to the summation of all the differences in thermal conductivity of the leaking gases versus

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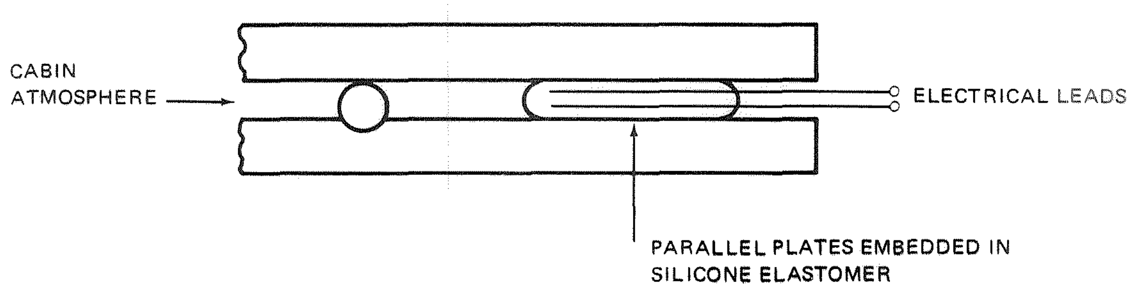


Figure 3-33. Moisture Measurement—Silicone Elastomer Capacitor

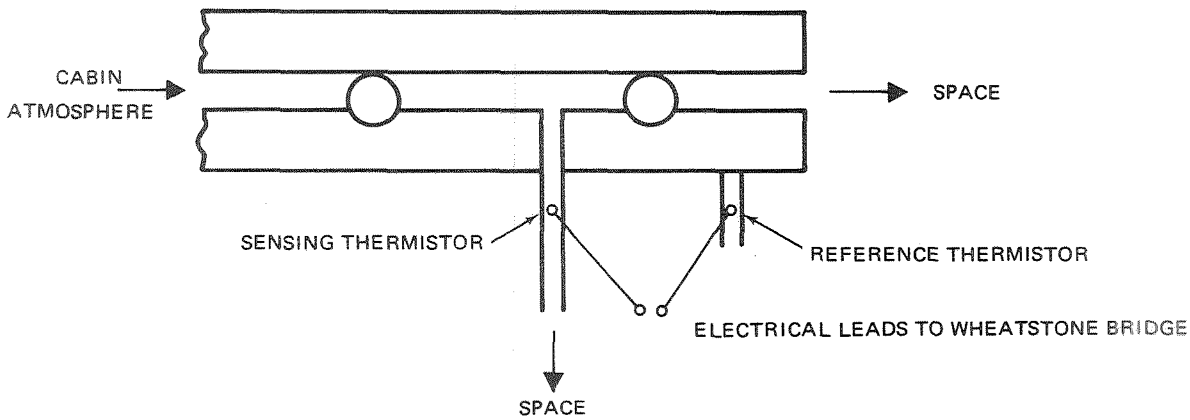


Figure 3-34. Gases/Vapors Measurement—Thermal Conductivity Detector

that of a vacuum reference. Response is directly proportional to the leak rate in the true cabin atmosphere. This concept in initial laboratory testing has demonstrated capabilities of detecting and measuring space cabin atmosphere leak rates from 10^{-8} to 10^{-2} atm-cc/sec.

A seal leak detector design concept based on the thermistor principle for a Space Station hatch closure is shown in Figure 3-35.

3.3.7 Portable Overboard Leak Detector

A portable hand-held leak detector is needed for detecting overboard leaks from within a gas pressurized compartment. The handheld trigger gage leak detector developed by the Marshall Space Flight Center (Reference 21) is designed to detect overboard leaks from outside the space vehicle.

Three methods for detecting leaks into a vacuum based on the principle of air flow measurement have been identified. These are (1) ion deflection air flow sensor, (2) fluidic velocity sensor, and (3) thermal conductivity thermistor sensor.

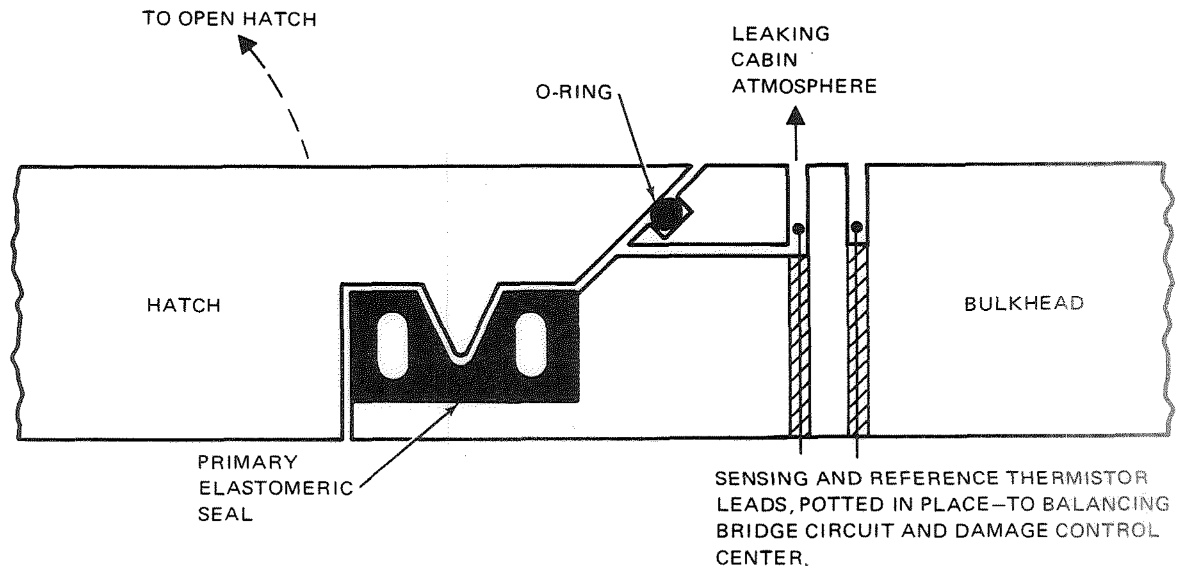


Figure 3-35. Location of Sensors Used to Detect Hatch Seal Leaks

An instrument based on an ion-drift principle has been found capable of measuring air velocities down to values as small as 30 cm/min (Reference 22).

Air velocity is sensed by an electronic control circuit which transduces the axial drift of a positive ion cloud generated by a corona discharge. Signal output is linearly proportional to the total mass flux through the transducer.

A fluidic velocity sensor has been described for measuring low air flow velocities such as might exist at holes exhausting to space (Reference 23). The principle involes the deflection of a jet by a transverse flow of gas or liquid.

A jet of fluid from a nozzle impinges upon two receiver tubes which are connected to a differential pressure gage. The two receiver tubes are so placed that the ΔP is zero when the fluid jet is not deflected by a cross-flowing fluid. However, when the jet encounters a cross-flowing fluid, the jet is slightly displaced, causing an unequal distribution of the jet velocity profile between the two receiver tubes and resulting in a total pressure change which is proportional to the cross-flowing velocity stream and registered as a change in differential pressure between the two receiving tubes. The system is simple and quite sensitive to small air flow cross velocities. This concept has utilized a differential pressure sensing mechanism. The potential exists to greatly increase its sensitivity by using thermistors or hot wires as sensors in the two receiving tubes.

The third concept which is under study at MDAC is based on thermistor sensing of air flow. Figure 3-36 shows a version of a portable digital leak detector based on the thermistor thermal conductivity principle. A slight, reduced pressure exists in the vicinity of an overboard leak and is sufficient to induce an air flow in a sensing tube in which a thermistor is mounted. The thermistor is self-heated and yields a change in resistance with flow. The sensing thermistor is balanced via a Wheatstone bridge circuit with a matched reference thermistor in a non-flow (diffusion) configuration. The signal is proportional to the induced flow rate in the sensing tube which in turn corresponds to the leak rate. The detector configuration shown in Figure 3-36 allows rapid scanning of a space station wall with one-hand operation. Channels built into the scan surface of the detector are connected via a multiport switching valve to the central sensing tube probe and facilitate checking a large area in a single sweep across the wall.

Laboratory setup test results have been encouraging, even in the simulated presence of typical ventilation air flow rates.

3.4 HIDDEN OVERBOARD LEAKS

Hidden leaks can be defined as:

A. A leak located in an inaccessible part of the space vehicle; as for example, behind equipment or ventilation ducts.

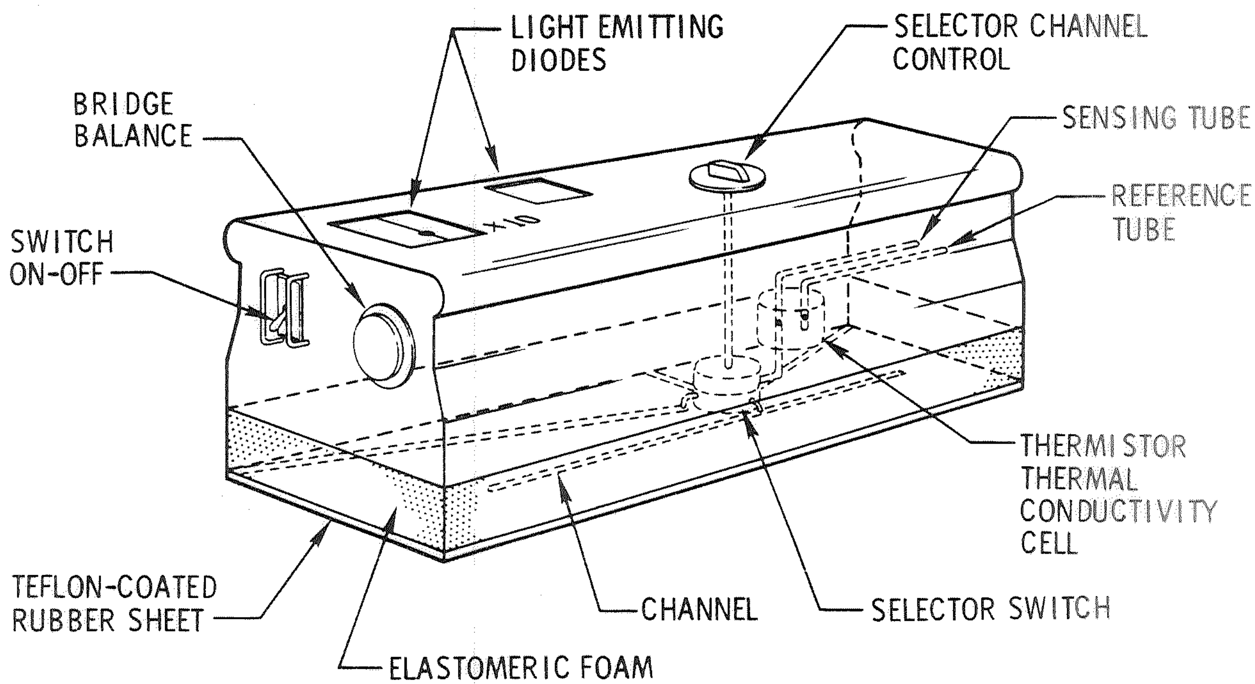


Figure 3-36. Portable Digital Leak Detector

B. A leak that has been detected but not readily located by a damage control system. This type of leak could be a large number of very small leaks which add up to a detectable level, yet each individual leak is below the resolution limit of the location capability of the damage control system.

C. A leak too small to be detected by a standard damage control system, but amenable to detection by a special high-resolution detector.

A leak that is readily detected and located but is inaccessible (Type A) can best be handled by designing accessibility into the vehicle, as detailed in Section 6. Without built-in accessibility, the strategy of coping with the leak will depend on the size of the leak. For a small leak, the time required to move the equipment is justified as no hazard is presented. For a larger class of holes, this would depend on some measure of hole size and rate of change of pressure. For this purpose, the two-gas controller would prove invaluable by providing safe-time data as a basis for decision-making.

Type B and Type C leaks, even though generally small, are not to be dismissed as having a negligible overall effect on the operation of the space vehicle. Such leaks may grow with time. Causes of such leaks are diverse, ranging from human error to fatigue cracks, impact cracks, or faulty repair techniques.

Two examples of leaks caused by human error during the recent 90-day manned test by MDAC that are representative of hidden leaks occurred when the vent valve on the commode was not closed tightly and when the dry waste storage container lid was not properly seated. In both cases, cabin atmosphere was lost and the two-gas controller indicated an increased rate of gas consumption. These hidden leaks were located by referring back to the timeline of crew activities to determine the sequence of events at the approximate time the increased gas rate occurred. Hence, it is evident that locating hidden leaks may be facilitated by using accurate information on crew activities together with the data from the damage control system. All leaks hidden or otherwise should be considered potentially dangerous until quantified, located, and repaired.

A tentative procedure for handling hidden leaks is shown in Figure 3-37.

3.5 ANALYSIS OF SMALLEST DETECTABLE OVERBOARD LEAK

3.5.1 Two-Gas Controller

The two-gas controller normally supplies about 10 pulses of gas per hour at nominal atmospheric conditions of 1.01×10^5 N/m^2 (14.7 psia) at 21 percent O_2 and 79 percent N_2. Small hole detection is accomplished through an increased pulse rate, which shifts to resupply the new gas consumption (i.e., leakage) requirements. Details of how this is accomplished is explained in Section 3.3.1 of this report.

Figures 3-8 through 3-10 display the time to detect a leak-equivalent hole size for pressures of 4.82, 6.89, and 10.12×10^4 N/m^2. The time to detect a given size hole decreases with increasing pressure. In the ideal case, without onboard pressure perturbations, holes of 2.5×10^{-5}m (1 mil)

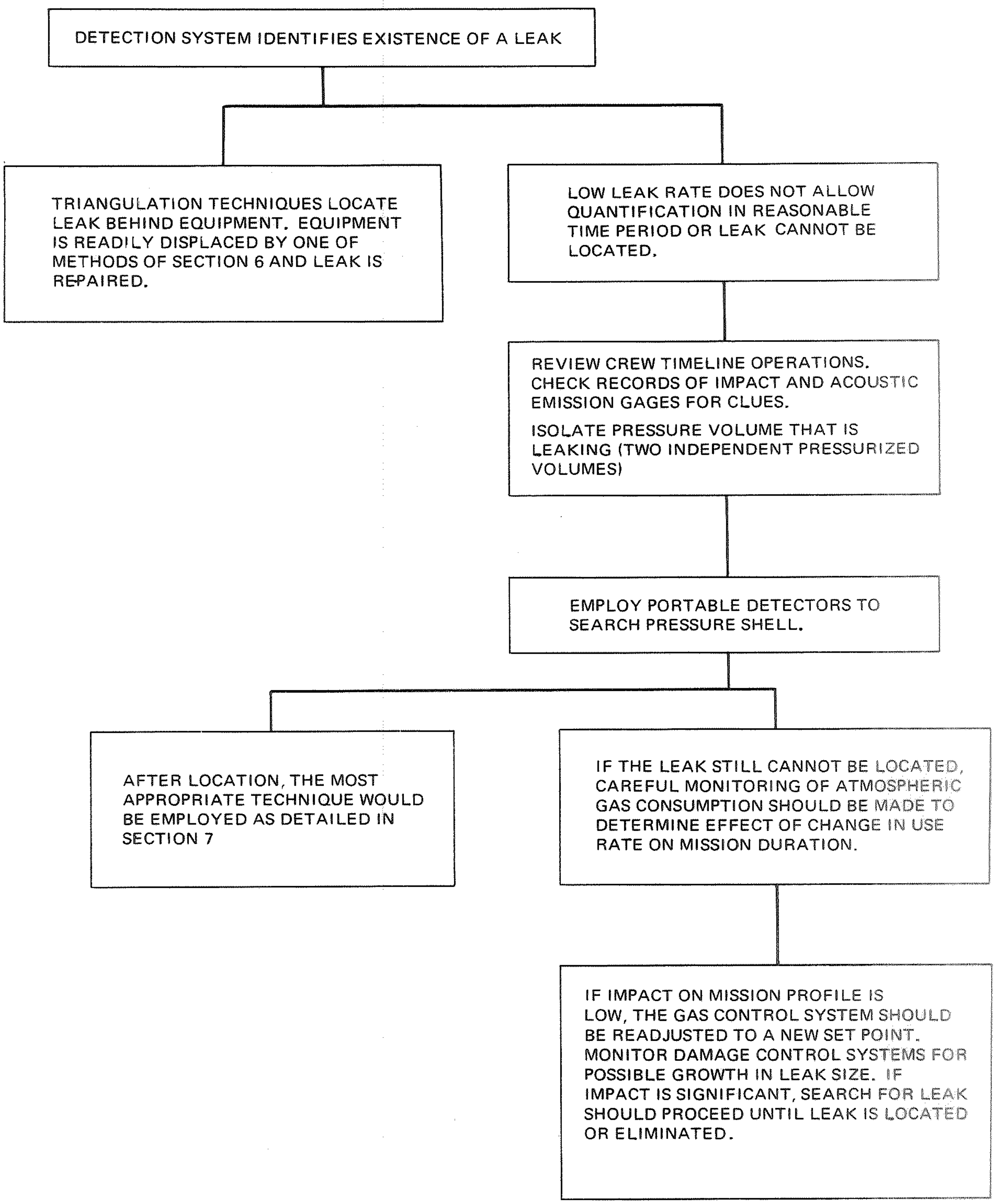


Figure 3-37. Procedures for Handling Hidden Overboard Leaks

or smaller could be detected by accumulating enough pulse data. Functionally, airlock operations, temperature variations, life support system performance, and crew activities in the space vehicle can produce perturbations in the atmosphere that overshadow the small changes associated with hole sizes that are less than the baseline leak rate of 0.45 kg (1 lb) per day for an independent compartment. Long-run monitoring, however, will identify these leaks, as the perturbations are averaged out. Using a pN_2 decay of 2.25 mm Hg, as explained in Section 3.3.1, a 0.45 kg (1 lb) per day atmosphere gas leak rate can be detected in about three days and quantified in approximately one week. For 1.01×10^5 N/m^2 (14.7 psia) cabin atmosphere, this leak rate is indicative of an equivalent hole size of 0.015 cm (0.006 in.) diameter. Although this response time is moderately long, the total gas lost as a result of the leak is 1.36 kg (3 lb) before identification. This analysis is based on a vehicle volume of 283 m^3 (10,000 ft^3). If the volume is decreased to 141 m^3 (5,000 ft^3), the detection time for the 0.45 kg (1 lb) per day leak rate, 0.015 cm (0.006 in.) diameter equivalent hole size is only one day and quantification would take place in less than two days. Thus, only 0.45 kg (1 lb) of atmospheric gases would be lost before leak identification.

Table 3-2 illustrates the time to locate and quantify a leak rate equivalent to an 0.015-cm-dia hole as a function of cabin pressure for a 283-m^3 volume compartment.

Table 3-2

TIME TO DETECT LEAKS

Compartment Volume
283 m^3 (10,000 cu ft)

Compartment Pressure (N/m^2)	Leak Rate for 0.015 cm dia Hole (kg/day)	Time to detect (days)	Quantity of Gas Lost before Detection (kg)	Time to Quantify (days)
10.12×10^4	0.454	3.0	1.36	7.0
6.85×10^4	0.309	4.4	1.36	10.25
4.8×10^4	0.216	6.3	1.36	13.20

3.5.2 Active Ultrasonics

This system is designed to detect cracks or flaws whether or not they leak. Sensitivity which is independent of cabin pressure is tentative at present. An estimate based on MDAC experimental data indicates a flaw 0.76 x 0.0076 x 0.038 mm deep can be detected at distance as great as 2.5 m. Experimental data are required to provide a more precise measurement of sensitivity as a function of distance and flaw size.

3.5.3 Acoustic Emission

Passive monitoring is designed to detect a growing flaw before it culminates in a leak or rupture. Sensitivity of detection is independent of cabin pressure. Acoustic emission techniques are capable of detecting crack growth increments as small as 6.5×10^{-6} cm^2 at distances ranging up to about 6 m.

3.5.4 Impact Gage

Impact gage response is generated by the impulse imparted to the pressure wall whether or not a leak is produced. Therefore, the most meaningful measurement of the smallest event detected can be expressed in terms of the impulse imparted to the wall. An estimate of sensitivity based on MDAC work is that impulses greater than 1×10^{-2} dyne-sec can be detected at a distance of up to 6 m. The larger the momentum transfer to the pressure wall, the greater the range of detection. The response of this system is independent of cabin pressure.

3.5.5 Seal Leak Detector

The thermistor leak detector has experimentally demonstrated the capability to detect leak rates in the 4.54×10^{-7} to 4.54×10^{-5} kg (10^{-6} to 10^{-4} lb) per day range. This sensitivity would extend over the pressure range from 4.82 to 10.1×10^4 N/m^2. Such leak rates are within the normal diffusion rates of a seal. Therefore, the thermistor detector would provide a signal even under normal seal operation. Leak rate sensitivity data for electronic hygrometry and capacitor techniques have not been determined, but both methods are expected to yield lower sensitivity than the thermistor type.

3.5.6 Portable Leak Detector—Thermistor Type

The data in Table 3-3 were derived from experiments conducted during the course of this program (constant-flow-rate conditions).

These results are based on ideal laboratory conditions with the sensor right over the leak. The actual operation of a portable instrument is not likely to yield such optimum results.

Table 3-3

SENSITIVITY OF PORTABLE LEAK DETECTOR

Pressure		Leak Rate		Equivalent Hole Size (dia)	
N/m^2	psia	kg/day	lb/day	cm	in.
3.43×10^4	5	4.54×10^{-3}	10^{-2}	2.54×10^{-3}	1×10^{-3}
4.82×10^4	7	4.54×10^{-3}	10^{-2}	2.03×10^{-2}	8×10^{-4}
6.3×10^4	10	4.54×10^{-3}	10^{-2}	1.9×10^{-3}	7.5×10^{-4}
10.12×10^4	14.7	4.54×10^{-3}	10^{-2}	1.42×10^{-3}	5.6×10^{-4}

Section 4
DAMAGE CONTROL SYSTEMS FOR ONBOARD LEAKS

Before an analysis of onboard leaks can be conducted, it is necessary to define the limits of fluids to be investigated. In any closed environment containing people and operating equipment, numerous contaminants will accumulate in the atmosphere. Some of these will be outgassing from materials of construction and habitability, others would be byproducts of chemical reactions and metabolic processes. Still others will be losses of logistic fluids by leakage. Selecting all categories for investigation would entail the selection of different equipment for more than 100 different chemical compounds and elements, and not all contaminants could be included in the analysis. This analysis concentrated on selecting leak detection equipment for fluids commonly found in EC/LS systems. Typical processes of these systems are the Sabatier reaction for carbon dioxide reduction, which produces water and methane and water electrolysis, which produces oxygen and hydrogen and uses potassium hydroxide as an electrolyte. The analysis also includes consideration of equipment for detecting leaks from logistics stores such as water, oxygen, hydrogen, freon, or other coolant.

It has been assumed that the materials of construction and habitability used in the spacecraft have been selected with care. Thus, outgassing of materials will produce minute quantities of trace contaminants whereas a leak from operating equipment or logistic stores will produce quantities far in excess of the levels described for outgassing. This does not mean that the equipment studied cannot detect minute quantities (parts per million levels) nor does it eliminate equipment suitable for outgas detection from being used for logistic fluid leak detection. In many cases, the best piece of detection equipment available will perform both functions.

4.1 SOURCES OF ONBOARD LEAKS

The materials to be monitored by the onboard leakage subsystem were selected utilizing the following criteria:

A. Vehicle and logistical supplies similar to those identified in the 10.1-m-dia Space Station Phase B definition study.

B. General consideration to the failure modes and effects analyses and safety analysis.

C. Detailed analysis of the possible failure or serious degrading of subsystems contained in the EC/LS system based on 90-day manned test experience.

Preliminary review of the available data indicated that the most critical function of the onboard leakage system is to avoid contamination of the crew compartment and to detect incipient degradation of EC/LS system. Another area requiring attention is the stabilization and attitude control (S/AC) propellant storage tanks, lines, and valves. The propellant for the larger thrusters is considered to be N_2H_4 used as a monopropellant (catalytically decomposed). The propellants for the small thrusters are CO_2 and CH_4 from the Sabatier reactor. While failure of propellant components will not likely contaminate the crew compartment, leakage would degrade the attitude control capability.

Consideration of the EC/LS system is dependent upon the specific processes utilized to recover metabolic waste. The EC/LS system for the Space Station provides cabin atmosphere control and purification, water and waste management, pressure suit support, and thermal control. Primary characteristics of the EC/LS system include the following:

A. The atmosphere is nearly sea level. However, in accordance with the guidelines and constraints, the system is designed to operate in a variable atmosphere of 4.8×10^4 N/m^2 (7.0 psia) to 1.01×10^5 N/m^2 (14.7 psi), with a partial pressure of oxygen constant at 2.16×10^4 N/m^2 (3.1 psi).

B. Two 12-man subsystems are provided, one for the compartment (defined as a volume of space enclosed by pressure-resistant structure) which includes Decks 1 and 2, and one for the compartment which includes Decks 3 and 4. The tunnel can be referenced to either subsystem.

C. The subsystem provided has full water recovery; that is, more water is recovered in the Space Station than is required for drinking and washing. The subsystem also has partial O_2 recovery; the shortage is made up by water contained in the food.

D. The EC/LS system provides methane and unreacted CO_2 to the propulsion system which uses these gases as propellants for orbit-keeping and CMG desaturation.

E. The total heat generated in the Space Station is rejected to space through a segmented radiator integrated with the micrometeoroid shield independent of the heat distribution between compartments.

A total mass balance for the EC/LS system is shown in Figure 4-1. Inputs are food, water contained in the food, and gaseous nitrogen makeup. Outputs are leakage gases, fecal water, miscellaneous solids associated with the metabolic process, nonrecoverable water from urine purification, methane and unreacted carbon dioxide utilized by the propulsion subsystem, and a water surplus part of which is used for EVA cooling.

The wash water and condensate recovery assembly purifies 80 percent of the condensate and wash water; the 20 percent residue is cycled to the urine water recovery assembly. There, the residue, the urine, and the urine flush water are purified at a 99 percent efficiency; the only water lost is that contained in the replaceable wicks. The carbon dioxide is converted into water by the Sabatier reactor. The purified water from the water recovery units and the Sabatier water provide water for electrolysis and the water consumed by the crew in excess of that provided in the food. The electrolysis assembly provides the oxygen required for breathing and the amount lost because of leakage. The CH_4 and unreacted carbon dioxide are transferred to the propulsion system where they are used as propellants for

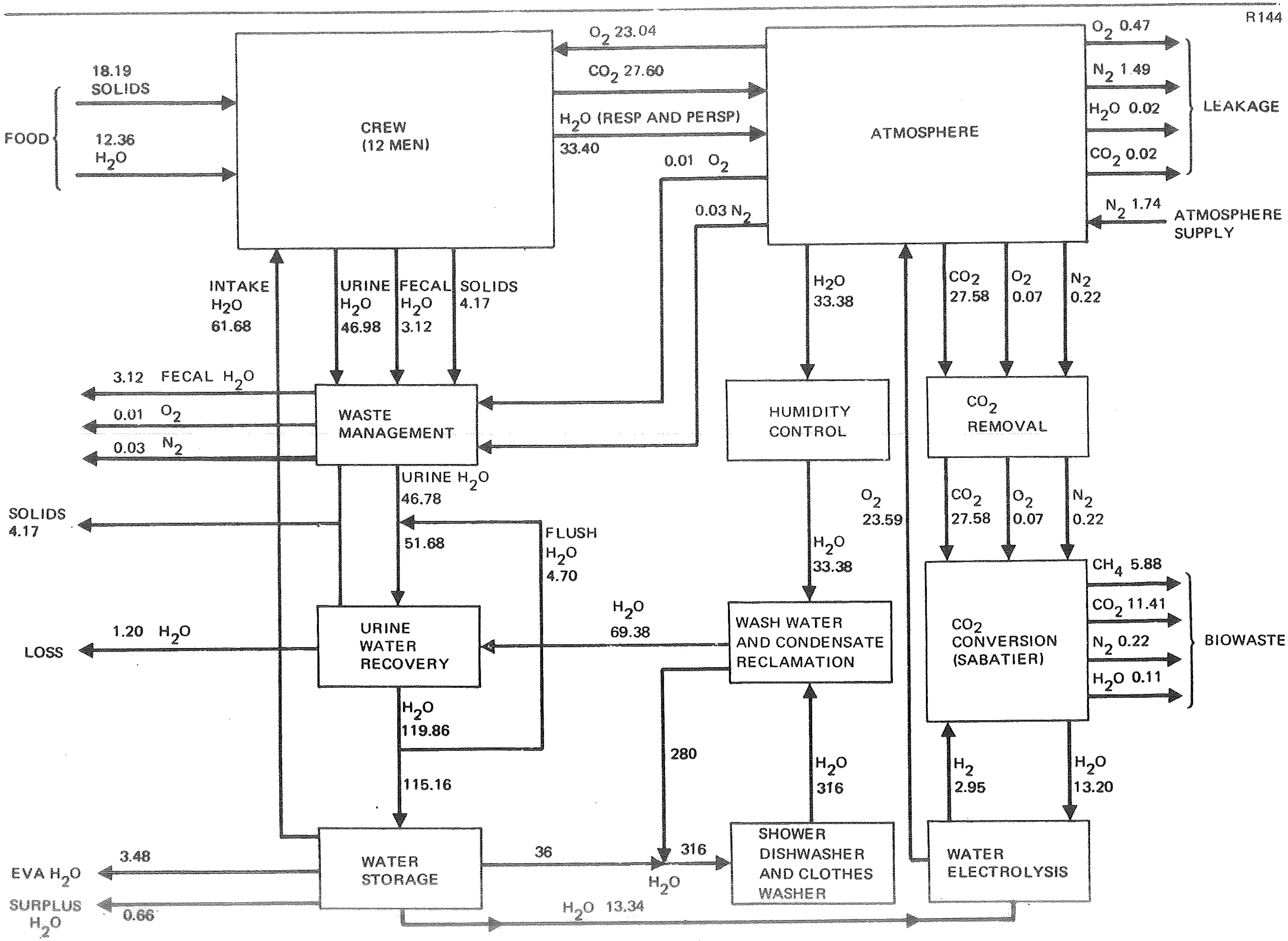


Figure 4-1. Environmental Control and Life Support System Functional Block Diagram

orbit-keeping and CMG desaturation. The total system provides excess water, most of which is used for cooling during EVA events. A smaller surplus provides a contingency that can be used for experiments and an allowance for uneaten food or water lost in trash disposal.

The gaseous nitrogen is provided to make up for nitrogen lost due to leakage and to other miscellaneous losses (e.g., CO_2 conversion and fecal waste collection).

The water lost due to trash disposals is not shown on this mass balance because the amount actually lost by the Space Station is not known. If it develops that this amount is beyond the surplus shown, then additional water for producing gaseous oxygen would have to be provided or water recovery from trash could be considered.

The assemblies provided on Decks 1 and 2 and Decks 3 and 4 each have the capability to support 12 men. The tunnel atmosphere can be interchanged with either system through the valving and interconnecting ducting; however, the atmosphere for Decks 1 and 2 and for Decks 3 and 4 are not intermixed normally through the ventilation system. Cross-linking between assemblies is provided, however, to allow one assembly to serve as an installed spare for the other.

With this concept, if a major emergency occurs such as a fire, decompression, or massive contamination, it will affect only the atmosphere in half of the Space Station. The crew will always be able to live in the other compartment within the time limit established by the amount of consumables onboard at the time of the emergency. This concept also easily accommodates the 24-man crew during the overlap period. The thermal control circuits are also designed to be completely independent so that if fire disables the heat-transport loops in either compartment, it does not affect the entire Space Station.

4.2 DESCRIPTION OF SELECTED ONBOARD LEAK DETECTION SYSTEMS

The onboard leak detection systems monitor leakage of the following EC/LS materials from the sources indicated.

A. Hydrogen (from electrolyzer).

B. Ammonia (from urine and waste collection and recovery subsystems).

C. Carbon monoxide (from overheated equipment or spontaneous combustion).

D. Total hydrocarbons (CH_4 from Sabatier reactor).

E. Water (thermal control loop, potable water, electrolyzer, Sabatier product water, urine collection subsystem).

F. Potassium hydroxide (electrolyzer).

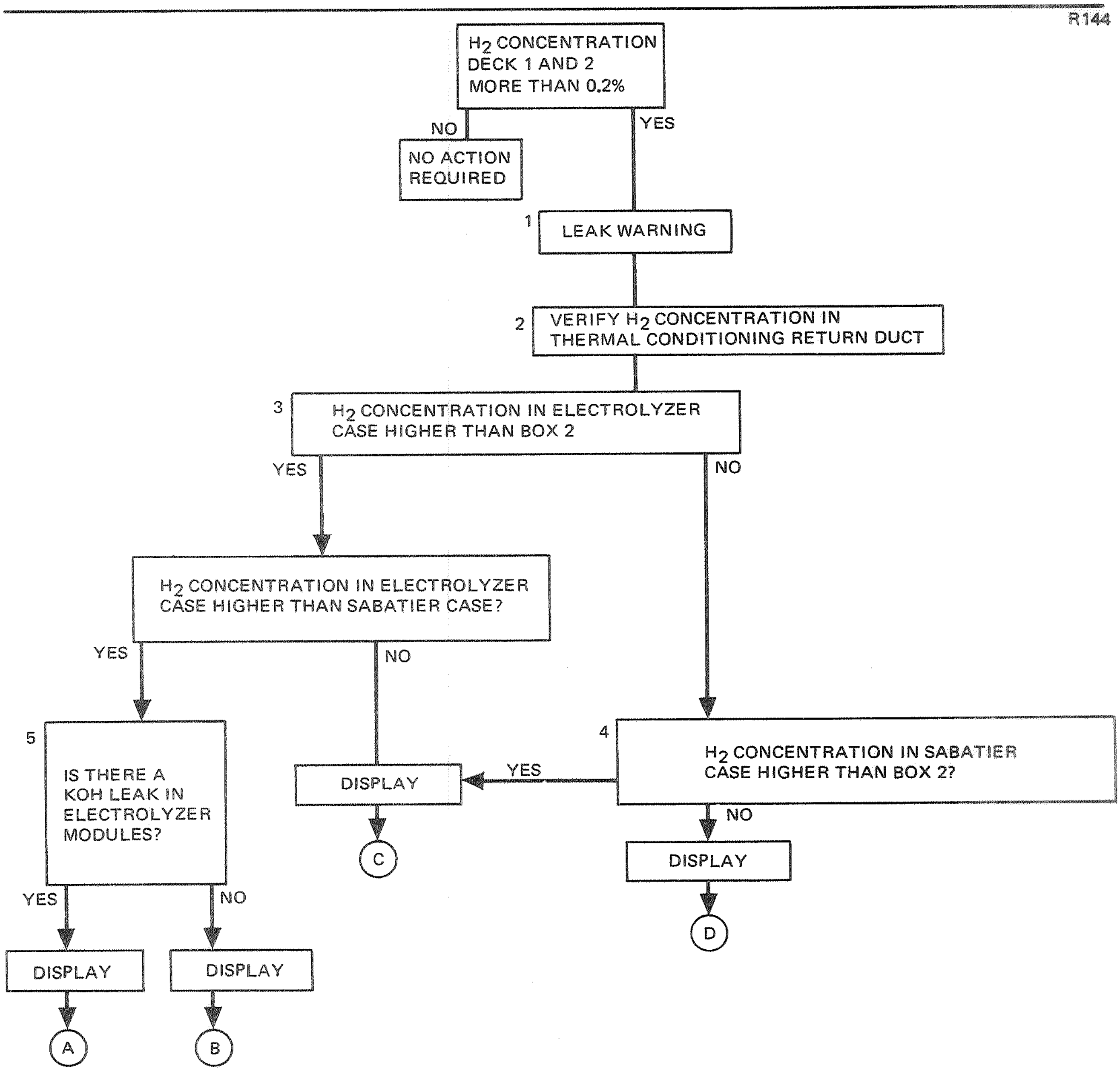
G. Freons (from GO_2-cleaned components).

H. Oxygen (from upstream of two-gas).

I. Nitrogen (from upstream of two-gas).

Items A, D, and H represent explosion or combustion hazards. Item C represents a poisoning hazard. Item F represents a caustic burn hazard. Items B, E, and G represent potential operational degradation of specific subsystems. Item I represents potential leakage of atmosphere.

The logic flow diagrams for each of the above materials are presented in Figures 4-2 through 4-10. The diagrams define information and decisions required to detect and troubleshoot leaks. The logic diagrams assume a vehicle configuration similar to the Space Station wherein there are two compartments, each with a separate EC/LS. The ventilation circulation of the compartments is not normally intermixed. However, cross-linking between them is provided to allow one assembly to act as an installed spare for the other. This allows flexibility in case leakage situations arise in which the time to find and repair the leak would allow excessive contamination of the compartment atmosphere. In such a situation, it would be prudent to secure the leaking subsystem and transfer operations to the standby unit. The leak



(A) LEAK IN AN ELECTROLYZER MODULE. RECOMMEND MODULE BE SECURED WITHIN NEXT 30 MINUTES TO AVOID EXPLOSIVE MIXTURES OF HYDROGEN. MEAN TIME TO REPLACE MODULE IS 0.5 HR (REFERENCE APPLICABLE MAINTENANCE PROCEDURE).

(B) LEAK IN ELECTROLYZER PLUMBING. RECOMMEND IMMEDIATE SECURING OF ELECTROLYZER TO AVOID EXPLOSIVE MIXTURE. RECOMMEND STARTING STANDBY UNIT. MEAN TIME TO FIND AND REPAIR LEAK IS 2.7 HR (REFERENCE APPLICABLE MAINTENANCE PROCEDURE).

(C) LEAK IN SABATIER PLUMBING. RECOMMEND IMMEDIATE SECURING OF UNIT TO AVOID EXPLOSIVE MIXTURES OF H_2. RECOMMEND STARTING STANDBY UNIT. MEAN TIME TO FIND AND REPAIR LEAK IS 1.8 HR PER APPLICABLE MAINTENANCE PROCEDURE.

(D) LEAK IN H_2 LINE BETWEEN ELECTROLYZER AND SABATIER ON DECKS 1 AND 2. CABIN H_2 WILL APPROACH EXPLOSION HAZARD IN 12 HR. MEAN TIME TO FIND AND REPAIR LEAK IS 6.3 HR PER APPLICABLE MAINTENANCE PROCEDURE. EXPECT DEGRADED OPERATION OF SABATIER REACTOR.

Figure 4-2. Hydrogen Leak Logic

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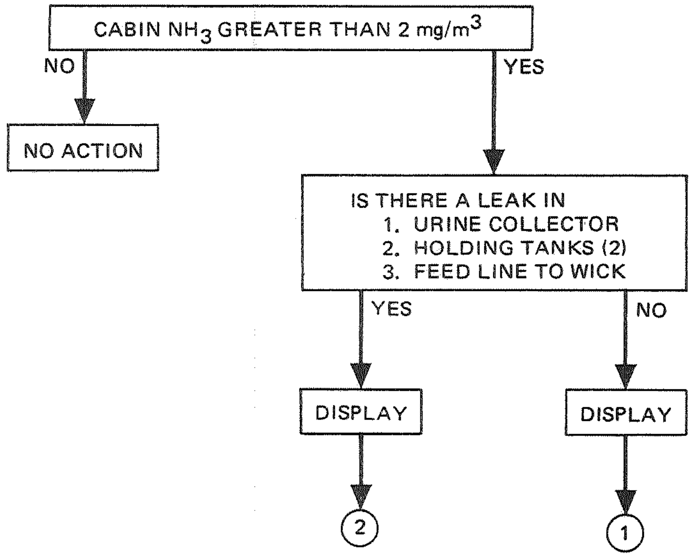

(1) THERE IS A LEAK IN THE CLOSED-CYCLE EVAPORATOR. RECOMMEND REPAIR WITHIN 100 HR TO AVOID BUILDUP OF NH_3 AND N_xO_y. MEAN TIME TO LOCATE AND REPAIR IS 2.7 HR PER APPLICABLE MAINTENANCE PROCEDURE.

(2) THERE IS A LEAK. RECOMMEND REPAIR WITHIN 4 HR TO MAINTAIN SANITARY CONDITIONS. LEAK IS X METERS DOWNSTREAM FROM DRAIN. MEAN TIME TO FIND AND REPAIR LEAK IS 0.8 HR PER APPLICABLE MAINTENANCE PROCEDURE.

Figure 4-3. Ammonia Leak Logic

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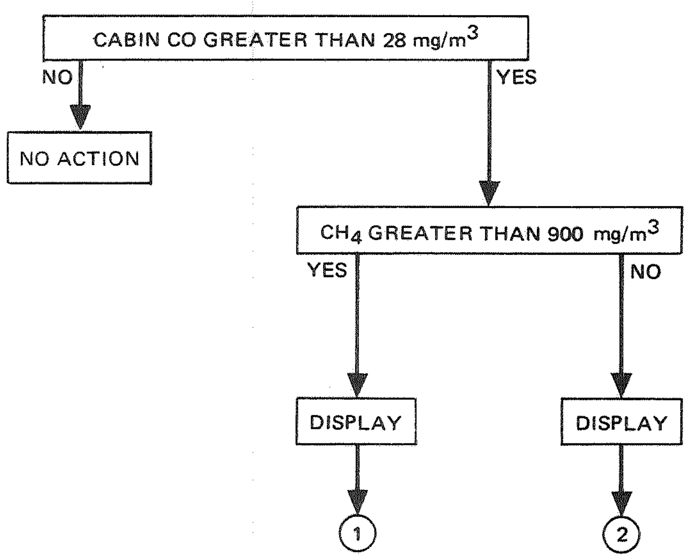

(1) WARNING – CO AND CH_4 CONCENTRATIONS INDICATE UNPLANNED COMBUSTION ON DECK 1 OR 2. RECOMMEND IMMEDIATE SEARCH OF AREA TO AVOID TOXIC LEVEL OF CO.

(2) WARNING – CO CONCENTRATION ON DECKS 1 AND 2 IS CONTAMINATING ATMOSPHERE. ORIGIN UNKNOWN, CHECK FOR HOT EQUIPMENT, AND CHECK FOR PROPER OPERATION OF CATALYTIC OXIDIZER.

Figure 4-4. Carbon Monoxide Leak Logic

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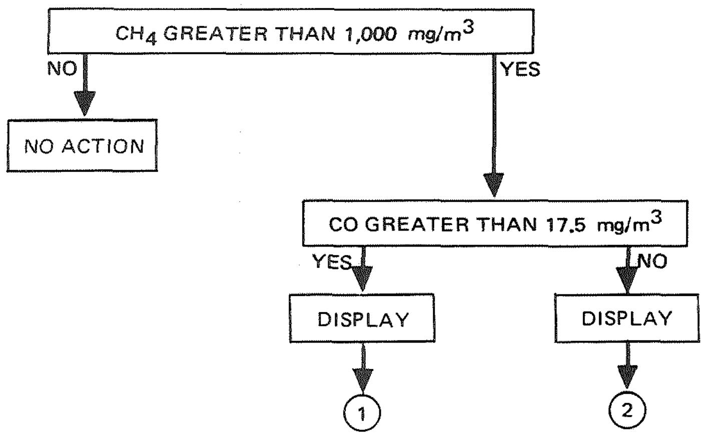
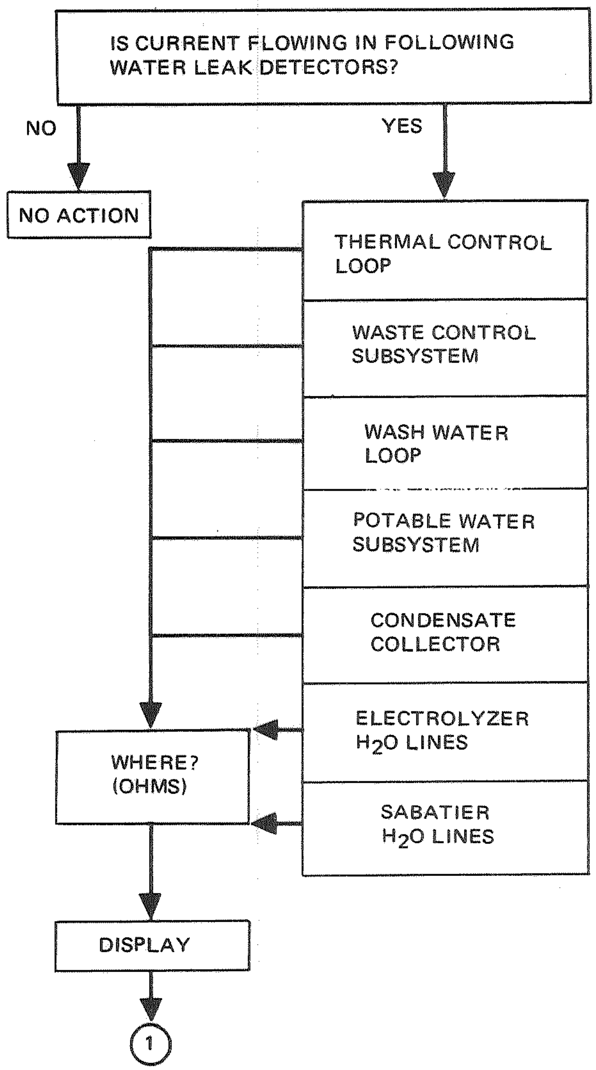


(1) WARNING – CH_4 AND CO CONCENTRATIONS INDICATE UNPLANNED COMBUSTION ON DECKS 1 AND 2. RECOMMEND IMMEDIATE SEARCH OF AREA TO AVOID ATMOSPHERE CONTAMINATION; ALSO CHECK CATALYTIC OXIDIZER FOR PROPER TEMPERATURE LEVEL OF 650°F.

(2) WARNING – LEAK IN SABATIER EXHAUST LINE. RECOMMEND SECURING UNIT WITHIN NEXT 0.7 HR TO AVOID TOXIC LEVEL OF HYDROCARBONS. RECOMMEND STARTING STANDBY UNIT. MEAN TIME TO LOCATE AND REPAIR LEAK IS 4.2 HR PER APPLICABLE MAINTENANCE PROCEDURE.

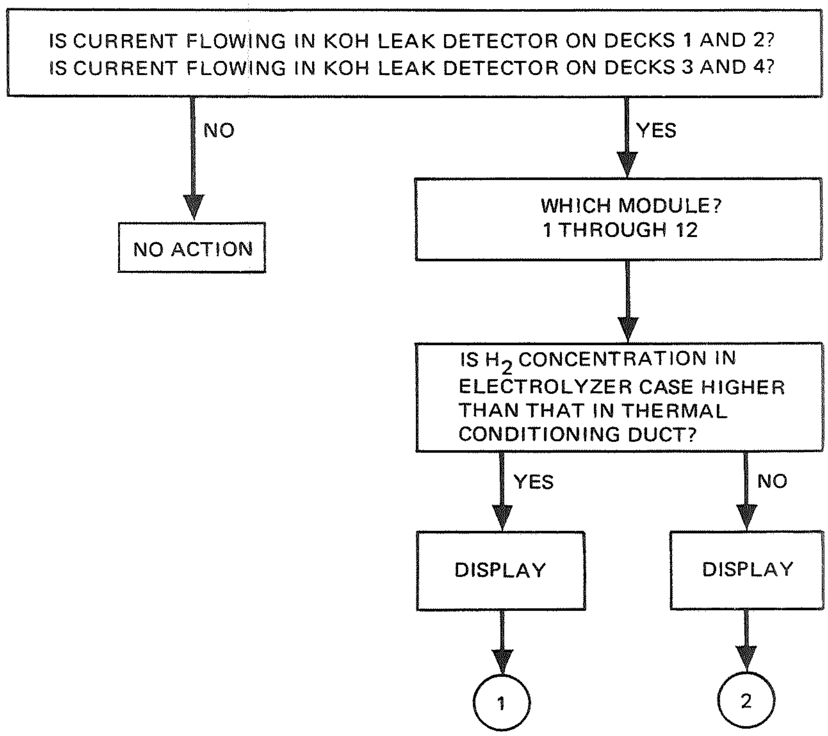
Figure 4-5. Methane (Combustion) Leak Logic

points can then be pursued without time constraints. Since the range of potential leaks and the repair requirements are so diverse, the leak detection subsystem can provide only a fixed level of information regarding leak location and what action should be taken to repair the leak. Operation and action to determine the exact location and repair procedure must be done by a crewman. For onboard leaks, the leak detection subsystem through the multiprocessor should provide information defining the leaking fluid, a graphic display of what lines carry this fluid, including line routing location and which portions of the line are accessible, and an estimate of time required to locate and repair the leak. In addition, the multiprocessor should provide information as to expected consequences of operation without repair. With this information, the crewmen could make decisions as to use of standby assemblies, priority of repair activities, etc. The determination of leak location would entail several procedures.



(1) WATER LEAK IN SUBSYSTEM. LOCATION IS X METER DOWNSTREAM OF REFERENCE POINT. FAILURE TO REPAIR LEAK COULD CAUSE SERIOUS DEGRADATION OF SUBSYSTEM. MEAN TIME TO LOCATE AND REPAIR LEAK IS 2.7 HR PER APPLICABLE MAINTENANCE PROCEDURE.

Figure 4-6. Water Leak Logic



(1) LEAK IN ELECTROLYZER MODULE. RECOMMEND MODULE BE SECURED WITHIN NEXT 30 MINUTES TO AVOID EXPLOSIVE MIXTURES OF HYDROGEN. MEAN TIME TO REPLACE MODULE IS 0.5 HR PER APPLICABLE MAINTENANCE PROCEDURE.

(2) LEAK IN ELECTROLYZER MODULE. RECOMMEND INSPECTION OF MODULE TO DETERMINE EXTENT OF KOH LEAK. KOH WILL CAUSE SEVERE SKIN BURNS. MEAN TIME TO REPLACE MODULE IS 0.5 HR PER APPLICABLE MAINTENANCE PROCEDURE.

Figure 4-7. Potassium Hydroxide Leak Logic

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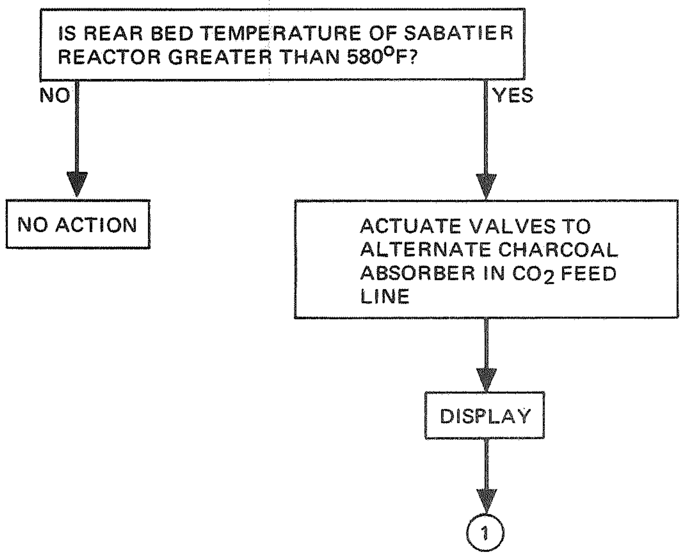

(1) FREON IS INDICATED IN CO_2 FEED TO SABATIER REACTOR. THE ALTERNATE CHARCOAL FILTER HAS BEEN PLACED IN SERVICE. RECOMMEND THAT EXPENDED FILTER BE REPLACED WITHIN 3 DAYS TO AVOID DEGRADING REACTOR OPERATION. MEAN TIME TO REPLACE FILTER IS 0.4 HR PER APPLICABLE MAINTENANCE PROCEDURE.

Figure 4-8. Freon Leak Logic

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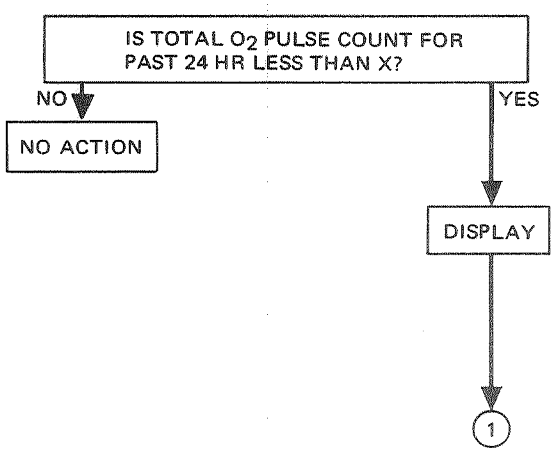
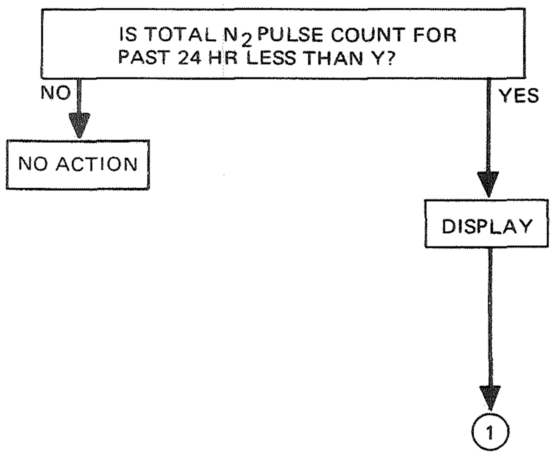


(1) LEAK IN O_2 LINE TO ATMOSPHERE CONTROL SYSTEM. RECOMMEND REPAIR WITHIN 24 HR TO AVOID SERIOUS ERRORS IN GAS STORAGE INVENTORY. MEAN TIME TO LOCATE AND REPAIR LEAK IS 4.5 HR PER APPLICABLE MAINTENANCE PROCEDURE.

Figure 4-9. Oxygen Leak Logic



(1) LEAK IN N_2 LINE TO ATMOSPHERE CONTROL SYSTEM. OVERBOARD LEAK DETECTION CAPABILITY IS DEGRADED. MEAN TIME TO LOCATE AND REPAIR LEAK IS 4.5 HR PER APPLICABLE MAINTENANCE PROCEDURE.

Figure 4-10. Nitrogen Leak Logic

The main methods are:

A. Scanning the suspected assemblies, lines, and fittings with a directional ultrasonic translator operating at about 40 kHz packaged as a portable leak detector. This is a rapid and convenient method of leak location, but it is susceptible to noise generation by rotary devices in nearby areas.

B. Pressurizing the suspected assembly with a working fluid and scanning with a portable device specifically sensitive to the pressurizing medium. One practical medium is carbon dioxide. Since the gas is generated by man, it is continuously available without a weight penalty. It possesses unique chemical and physical properties suited to portable gas phase detection, does not contribute to atmospheric contamination, and is continuously removed from the atmosphere by the EC/LS system.

In addition, the gas is considered to be relatively inert and the only fluid indentified in the Space Station with which it would react is potassium hydroxide contained in the electrolyzer. Since KOH leakage is monitored by a separate scheme which provides leakage location information, all situations are considered.

The liquid leak monitoring transducers utilize two layers of resistive tape separated by a thin layer of porous insulative paper. One external surface of the tape is coated with pressure-sensitive adhesive. The tape is applied along the plumbing containing water, urine, or KOH solution. A small electrical potential is applied across the resistive tapes. As long as the tape remains dry, current will not flow. If a leak occurs, however, the insulation is wetted and current will flow. The multiprocessor is notified by the current flow and measures the apparent resistance which will vary with the distance along the tape to the wetted segment. The multiprocessor displays data as to which segment of the tape network is shorted and the distance from some reference point to the leak.

It is of interest to note that with the exception of the liquid leak transducers, all gas transducers are presently defined as part of the trace contaminants subsystem. This is a logical case of using a transducer to warn the crewman that his atmosphere is being contaminated and utilizing the capability of the multiprocessor to provide additional information concerning leak location and corrective action required.

The onboard leakage subsystem described above meets the following requirements:

A. The subsystem monitors leakage of all common and critical gases and fluids associated with Space Station EC/LS systems.
B. The subsystem utilizes a multiprocessor only when an out-of-tolerance event (leak) occurs.
C. The subsystem produces a maximum of essential information in a minimum of time.

D. The subsystem utilizes existing gas analysis transducers, thereby minimizing weight penalty and maximizing simplicity.

Leak detection of the propulsion tankage is made difficult because it is influenced by the location of the tanks in the unpressurized compartment. This tank bay contains N_2H_4 pressurized by helium (He) and separate accumulators containing methane (CH_4), CO_2, and water. The compartment vent can be closed and the compartment pressurized for maintenance purposes in the event of extended crew attention. In the case of an N_2H_4 or CH_4 leak requiring crew maintenance, EVA suits would be advisable to avoid toxic effects. In addition, it is questionable that any of the pressurizing atmosphere could be salvaged (pumped into the crew compartment) if it is contaminated to any extent with N_2H_4. Leaks in the tankage compartment will be difficult to detect if the vent area is large. This is because the leaking medium will vaporize and vent to space before it is detected. For maximum sensitivity, the leak sensor should be configured as an integral part within the approach section of the vented opening. A mass spectrometer is a suitable detector for this application. There is a commonality of mass peaks associated with N_2H_4, CH_4, and CO_2. However, resolution of the mass 12, 14, and 16 peaks should allow determination of the leaking compound. After pressurization, leaks could be located with flow visualization techniques. For example, a jet of moist CO_2 could be impinged along the hyrazine lines and the reaction at the leak point would form a white fog of $(NH_3)_2\ CO_3$. NH_4OH could likewise be used to find CO_2 leaks.

4.3 ONBOARD LEAK DETECTION AND LOCATION CONCEPTS

4.3.1 Mass Spectrometer/Gas Chromatograph/Gas Fractometers

The fluids discussed in the previous section are commonly found in space vehicles and are difficult to detect by use of partial pressure sensors. The organic heat transfer fluids generally have very low vapor pressures, and special sample concentration (absorption) columns are required to detect them in closed atmospheres. Present practice has been to pump atmospheric gas samples through the column for a period of 30 to 45 minutes and then to thermal-vacuum desorb the column into a vapor fractometer and mass spectrometer in series. This portion of the determination requires about 30 minutes. The whole procedure requires a sizable amount of equipment and an hour delay for data acquisition. This method does not appear useful for space vehicles at its present state of development.

Mass spectrometers for monitoring vehicle atmospheres have been under development for over 10 years. The principle of operation involves the electronic ionization of a continuous gas sample stream expanded to a low pressure; electrostatic acceleration of the ions which then undergo magnetic field deflection to separate masses. The ion-current measurement at strategically located electrodes is used to establish species concentration.

A newer method called "time-of-flight" utilizes pulse techniques to accelerate ion bunches into a drift chamber and mass separation is determined by the relative arrival time at the single ion collector.

Instrument vacuum may be obtained by two means. One is to vent the chamber to space vacuum. The second is by use of an ion pump placed as an integral part of the detector chamber. Sample gas loss typically amounts to less than 0.1 g/hr. For space application, instrument design problems relate to sensitivity and resolution of higher mass numbers as well as weight and power. For example, to increase resolution for the higher masses (250) requires a large increase in the magnetic field (weight) and a larger detection chamber, resulting in significant increases in instrument weight and size. The time-of-flight type of mass spectrometer can handle high mass compounds, but tends to fragment them into simpler compounds and computer techniques are required to determine the original compound by matrix methods of the fragment signals. All of this adds complexity to the system. Until more knowledge is produced defining specific high-mass compounds associated with impending fire, toxic, or other malfunction events, there seems little justification in designing and using mass spectrometers for anything but primary gases (O_2, N_2, CO_2, and H_2O).

Continued development of flight-type mass spectrometers will allow measurements of higher mass (molecular weights of 150 to 250) compounds. During the 90-day manned test, about 100 compounds were identified in the atmosphere; fortunately, most of the materials were there only in trace concentrations. The presence of many of these compounds has been attributed to the vast use of cleaning fluids, solvents, and plasticizers in the fabrication of components, wire insulation, and potting compounds. This complicates the problem of obtaining damage control information from analysis of compounds in the closed atmosphere, since the "signatures" of interest will vary with the components used to fabricate the vehicle.

Work remains to be done in this area and valuable information can be gained utilizing a Space Station damage control simulator. This will require the capability to perform various types of gas analysis. Methods should include vapor fractometers, mass spectrometers, and wet chemistry. Such equipment can be located within the simulator or in a laboratory near the simulator so that atmosphere samples can be conveniently taken and analyzed. The instruments may be the commercial configuration, since their purpose is to define the analytic requirements of future - generation flight instruments.

Any discussion of onboard leaks and their detection by use of vapor analysis must in certain aspects utilize or overlap the discipline of trace contamination detection and control. To provide a more reasonable scope for this investigation, trace contamination detection will be defined as monitoring the vehicle for vapor species which are known to be physiologically harmful to crewmen. The damage control aspect of vapor analysis is concerned with inventory depletion and system failure prevention efforts. As an example, a leak in a cooling water line to the thermal control system might not be of interest in a trace contamination study, but would be of great interest in a damage control study as loss of cooling water could cause the thermal control system to fail.

Freons, such as TF or 12, are another family of compounds often found in closed atmospheres. Their presence in vehicle atmospheres stems from their use in cleaning fluids used on many mechnical components of the vehicle. These compounds can be detected down to less than 5 ppm by use of ordinary vapor fractometer techniques. The interest in Freon traces in cabin atmospheres is based on experience gained during the recent 90-day manned test. The Sabatier reactor catalyst was poisoned during the initial period of the test. The source of poisoning was suspected to be Freon TF, an agent commonly used in cleaning many space cabin components. The Freon was removed along with the carbon dioxide by the atmospheric control system and was discharged along with carbon dioxide to the Sabatier unit, causing the reactor to become disabled. The prcblem was resolved by placing a charcoal absorption unit in the carbon dioxide feedline to the Sabatier unit to remove the Freon. It is further suspected that the Hopcalite catalyst used in the toxin burner was adversely affected by Freon.

A sample of white powder found by the crew on the toxin burner discharge was collected and passed out for chemical analysis. Results indicate the material was mainly metallic chlorides. It would appear that the material resulted from the thermal decomposition of Freon in the toxin burner to form chlorides and probably fluorides with the Hopcalite catalyst and the stainless steel and aluminum components of the unit. It can be concluded that Freon coming in contact with hot components decomposes, allowing the halogen fragments to react with catalytic materials to the extent that subsystem failures can result.

A flame-ionization hydrocarbon detector is recommended to monitor vehicles which utilize Sabatier oxygen recovery units as the reactor exhaust contains significant quantities of methane. An exhaust leak into the vehicle represents both an explosive and a toxic hazard. During the 90-day test, stress corrosion of the exhaust line occurred—it is suspected the corrosion resulted from Freon decomposition—allowing exhaust to escape into the simulator. The event was detected by a rapid increase in the atmospheric hydrocarbon concentration. The crewmen were instructed to find the leak by painting the exhaust fittings with a bubble fluid. This effort was unsuccessful, and the reactor had to be secured. The reactor and plumbing were then pressurized with carbon dioxide. A flexible line was connected to the sampling port of a CO_2 analyzer and used by the crew to sniff along the exhaust line with the result that the leak was quickly and easily found, even though the leak was covered with thermal insulation. The CO_2 analyzer was a Luft-type infrared unit used to backup the four-gas mass spectrometer.

Techniques using CO_2 are feasible as a leak location medium for space vehicle plumbing. Logistically, CO_2 is continuously generated by man. It can be continuously removed from the vehicle atmosphere by the atmospheric control subsystem. Any line (liquid or gas) suspected of a leak could be pressurized from the CO_2 storage tank and sniffed using a portable detector. This method has some limitations. While CO_2 is used as a fire-extinguishing agent for many materials, it will chemically react with a number of reducing agents and should not be used in lines containing the following materials: diborane, pentaborane, decaborane, UDMH, N_2H_4, and NH_3.

A space vehicle using an oxygen regeneration system or a fuel cell power supply implies the use of hydrogen and associated plumbing within the vehicle. Leakage of hydrogen because of its unusual characteristics represents a significant explosion hazard. This gas has a wide flammability limit (4 to 94 percent) and a low ignition temperature (580°C). Ignition can be initiated by very low energy sources. For example, a spark which is invisible to the naked eye of only 20 microjoules of energy will cause ignition. Detonations are likely in atmospheric mixtures containing 18 to 59 percent hydrogen in confined spaces. In detonations, reaction propogation is aided by a shock wave moving ahead of the reaction zone. The shock wave compresses and heats the reactant gases to the ignition temperature. This effect is greatly reinforced by reflection of the shock wave from walls and other structures. The resulting pressures, though of short duration, can produce destructive effects on the confining walls. Hydrogen will diffuse through minute holes and cracks at an impressive rate due to its low molecular weight. To prevent combustible mixtures occurring within the vehicle, combustible gas detectors can be used to give an alarm and secure the electrolysis unit before a hazardous level occurs.

The gas fractometers should be flexible enough to permit utilization of several column materials and types of detectors. The advice of experienced laboratory workers and the instrument manufacturer can be utilized before the final selection of instruments to obtain the best fit of equipment. Wet chemistry has been utilized on the 60-and 90-day manned tests for the determination of NH_3, N_xO_y, SO_2, HCN, H_2S, Cl_2, and HCl.

A proper approach to obtaining meaningful data is to build up the compound "signatures" in a step-wise manner. This can be accomplished by closing the simulator prior to the installation of any equipment and taking gas samples; the initial sample would likely contain solvents and other volatile components of the interior paint. Sampling would be accomplished as each subsystem or component is added to the simulator. Each compound found may be cataloged as to its subsystem and location by document or computer. In addition, materials such as insulated wire may be placed in a bell jar and an overload condition applied.

4.3.2 Resistive Tape Leak Detector and Locator

The four-gas mass spectrometer can be used for O_2, N_2, H_2O, and CO_2 leaks. Due to the diverse sources of H_2O in a space vehicle, cabin humdidity is not a useful parameter for monitoring water line leaks. The low signal-to-noise ratio of cabin humidity defeats this approach. In addition, the humidity control unit will remove significant rates of water from the vehicle atmosphere, further complicating water leak detection. The detection and location of other liquids leaking from plumbing and hardware presently relies upon the detection of a loss in liquid inventory, visual appearance of the liquid, or detection of the vapors by odor or instrumentation. The presence of insulation makes the above methods more difficult and delays the appearance of the symptoms.

A number of tape methods have been considered for the detection and location of leaks. One type is the visual indicator tape which operates by a color change induced by a reaction with the leaking gas or fluid. Commercial color-changing tapes are available for such fluids as hydrocarbons, hydrazine, and ammonia.

For hydrogen, heat from a palladium-hydrogen reaction changes the color of a thermo-chromic paint impregnated in the tape (Reference 24). A second method involving an electrical readout based on a capacitor principle has been described for detecting microleaks in tankage (Reference 25). MDAC is presently considering a concept utilizing two layers of resistive tape separated by a layer of porous insulating paper. This tape can be used to provide an electrical signal when a leak occurs and an indication of the general location.

A. Conducting Fluids

1. Individual Detectors

In cases where a few potential leak sites may be predicted, such as near valves, fittings, or pumps, a small detector is installed near the site. The detector is a small foil electrode, faced with a wicking material which is applied to the hardware near the potential leak site. The plumbing is used as a ground, and a very small electrical potential is applied to the electrode. When a leak occurs, the wicking material becomes conductive, thus allowing a small current to flow which is then amplified and activates an alarm or indicator. There is no current drain until a leak occurs. For safety considerations, voltage and current-limiting resistors can be used to prevent fires.

2. System Detectors

A total system detector involves high-resistance wire or film with an untreated fabric insulation that acts as wicking material. This wire or film is applied along the surface of plumbing and hardware. A galvanometer circuit continuously or occasionally monitors the resistance of the circuit (no current flow). A leak will cause conduction between the wire and ground, thus changing the apparent resistance of the circuit. By measuring the new resistance, the location along the wire and thus the system may be approximated. Complex systems would require several wires; however, the change in resistance of two or more detectors could be used to compute exact leak locations.

A variation of the above would involve coating the wire or film with an insulation material that is soluble in the fluid and tightly applying it to the plumbing surfaces. A leak would dissolve the insulation, thus providing contact. These systems could be modified for plastic plumbing by using double wire or films.

B. Nonconducting Fluids

Essentially the same electrode configuration as described for the conductor individual detectors is applicable, except a high-frequency alternating potential is applied. The electrode acts as a capacitor and the dielectric constant difference between air and the leaking fluid will produce a detectable change in capacitance when the wick becomes saturated.

A system detector involving a soluble wire insulation as described for conducting fluids is also applicable to non-conducting fluids with proper choice of materials.

Some of the advantages and unique features of the resistive tape are:

A. Provides an immediate electrical signal when contacted by leaking fluid.

B. Uses no power until actuated by leak.

C. By proper installation, leaks are detected and the characteristic of the electric signal can be utilized to denote the location or area of the leak.

D. Provides electrical signals upon being wetted by a nonconductive fluid.

Figures 4-11A and 4-11B show some of the various configurations the device may assume. Figure 4-11A shows a cross section of either the spot detector or an end view of the tape. Figure 4-11B shows the segments of longitudinal views of the two versions of the tape. The devices are attached to the fitting, pipe, or vessel surface (1) by the adhesive layer (2). The conductive film (3) is then separated from the perforated cover conductive film (4) by either an absorbent wicking material (5) (used with conducting fluids and a resistance measuring device, or a capacitance detector with nonconducting fluids) , or a material (6) which is soluble in the leaking fluid.

Figure 4-12 shows the manner in which the tape version can be used to detect leaks in pipes (1), fittings (2), pumps (3), or valves (4), by placing the tape in close proximity to the suspected leak site, or placing the tape along the pipe and relying on capillary action to get the fluid between the conductive layers and cause a signal in the detector (5). Individual spot detectors could be placed at locations (1) through (4).

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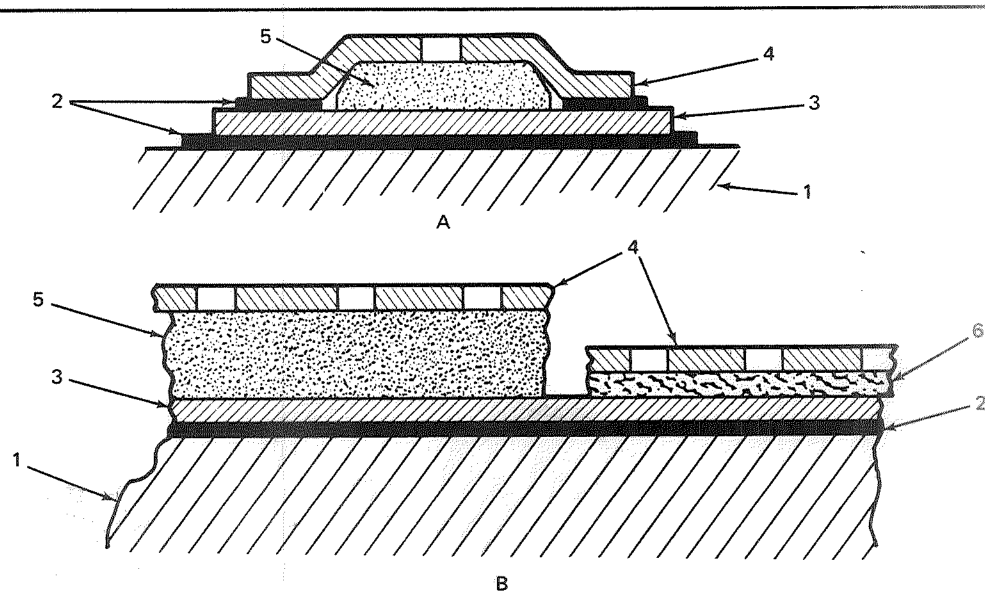

1. PIPE OR FITTING SURFACE
2. ADHESIVE LAYER
3. CONDUCTIVE FILM
4. PERFORATED COVER CONDUCTIVE FILM
5. WICKING MATERIAL
6. SOLUBLE MATERIAL

Figure 4-11. Liquid Leak Detector Cross Sections

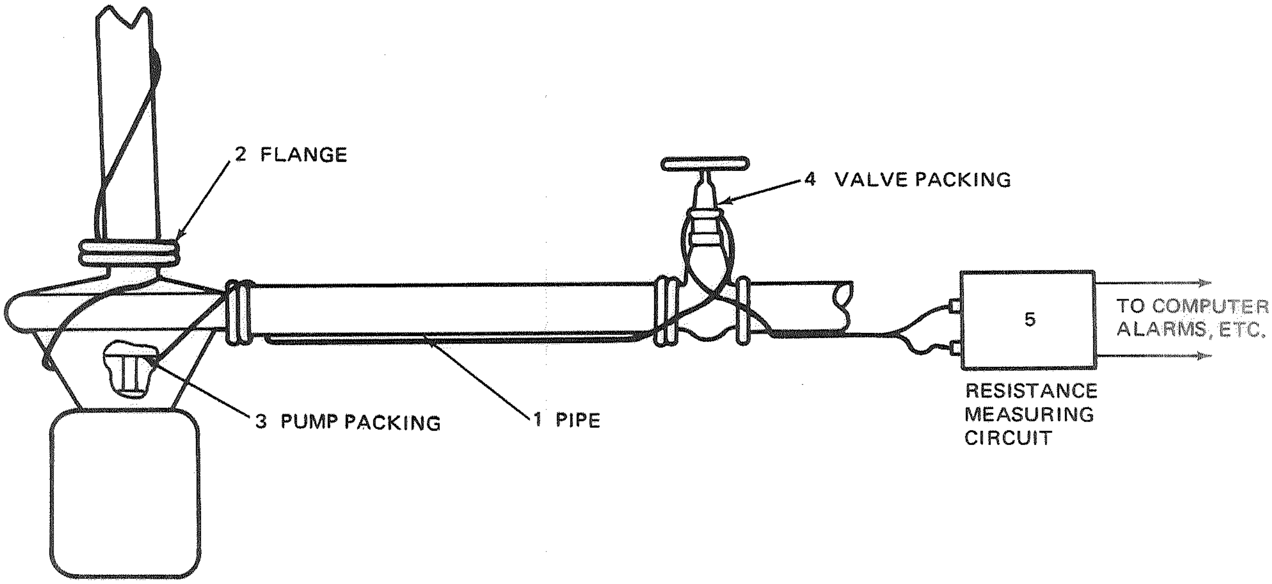

Figure 4-12. Typical Liquid Leak Detector Installations

4.3.3 Solid-State Polymeric Gas Detector

An unconventional detection technique is based on the application of polymeric organic semiconductors. Such a solid-state sensor has low weight, no moving parts, and requires very little power for its operation. Substituted polyacetylenes have been used as materials for the solid-state sensor. Polymer films can be chemically modified so that the effects of substituents on their conduction and complexing capability can be observed. Resistivity measurements are generally made as they yield the greatest numerical change with input of contaminant. Sensor geometry involves a lock-and-key metal electrode on a glass substrate with the polymer film across it. MDAC has conducted a number of projects on the synthesis and characteristics of semiconducting materials and their relation to contaminant detectors. A recent contract effort was the work performed for the NASA Electronics Research Center, Cambridge, Mass. (Reference 26).

One output of this program was the fabrication of a prototype portable gas detector. Figure 4-13 is a schematic of the input stage and Figure 4-14 is a block diagram of the entire unit. One sensor is connected to each side of a differential amplifier and a voltage applied to the sensor. The amplifier detects the currents flowing through the sensors and under standard atmosphere conditions, the differential output is adjusted to zero. When a contaminant is present in the atmosphere, each sensor responds according to the extent of its interaction with the contaminant. The response is sensed by amplifying changes in current flowing through the sensors. Since it operates on a differential basis, the difference of the changes appears at the output as either a positive or negative voltage, the polarity depending on which sensor changes the most. A zero center panel meter which serves as an indicator is connected across the output, and the amplitude of the output voltage is dependent on the relative magnitude of the changes. The unit also incorporates a simple adjustable threshold logic circuit that turns on one of a pair of lights when the differential output exceeds a predetermined level. The light that is on indicates which sensor has responded to the gas introduced.

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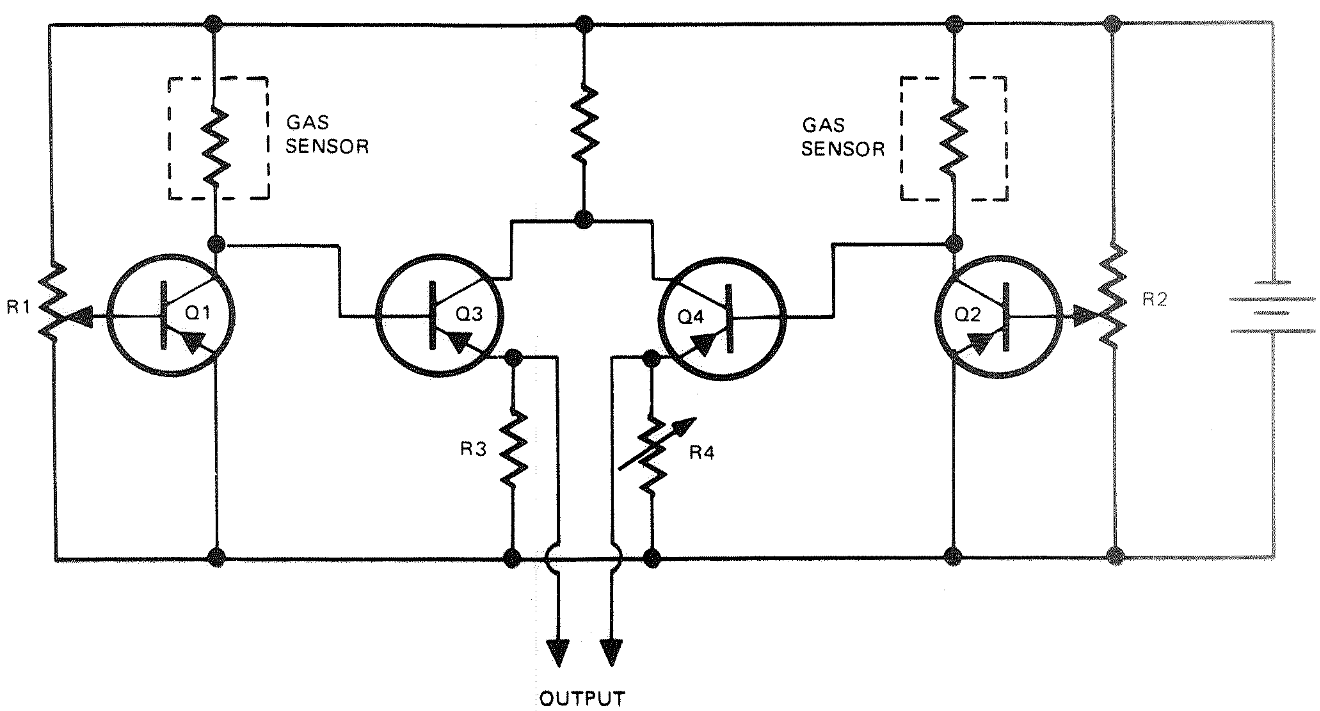

Figure 4-13. Portable Gas Detector Differential Amplifier Circuit Schematic

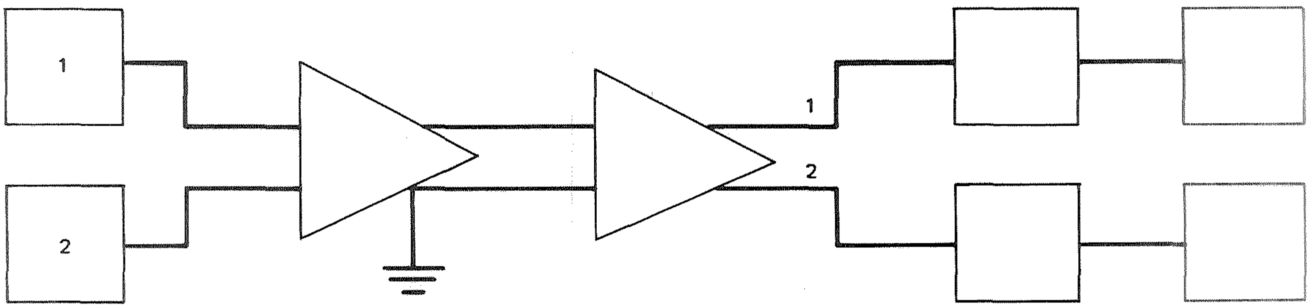

Figure 4-14. Differential Gas Detector (Prototype) Block Diagram

A prototype gas detector has been tested under laboratory atmosphere conditions mostly with ammonia (to which the nitro polymer responds) and sulfur dioxide (to which the amino polymer responds). In a quantitative reliability test, these gases were alternately injected into the sensor chamber with a gas hypodermic syringe. For 20 tests with each gas, the corresponding polymer responded to the gas to which it was sensitive with no responses from the other polymer. Concentrations as low as 190 ppm were used, with no failure to respond. There is reason to believe the sensitivity could be as low as one to 10 ppm. For example, in one instance, when the sensor chamber had been left open, it detected a small leak in a sulfur dioxide bottle 6 feet away which was undetected by a person sitting next to the bottle. Similar behavior was observed with the nitro polymer. By opening a bottle of ammonium hydroxide at varying distances from the inlet duct, it was found that the sensor would respond as anticipated.

Other qualitative tests were also performed with various gases in order to assess the detector's capabilities. Table 4-1 lists some of the gases used and which polymer responded.

It was concluded from this program that a solid-state gas detector based upon the use of polymeric organic semiconductors is feasible. Excellent sensitivities were attained and some specificity was demonstrated. Response and recovery times were on the order of seconds. With further work the solid-state sensor system can be optimized for enhanced sensitivity.

4.3.4 Oscillating Piezoelectric Crystal Detectors

Piezoelectric gas sensors show promise (Reference 27) for monitoring spacecraft atmospheres for contamination and onboard leakage.

This sensor works on the principle that any foreign material attached to an oscillating (excited) piezoelectric crystal tends to dampen (decrease) the frequency at which it resonates. The addition of a hydroscopic film on the crystal makes its frequency change with the humidity to which it is exposed.

The problems associated with these gas sensors stem from the lack of development of selective stable coatings for CO, CO_2, SO_2, and CH_4 which

Table 4-1

RESPONSE BEHAVIOR OF PROTOTYPE GAS DETECTOR

Gas	Polymer Responding
CO_2	Nitro
Diethyl ether	Nitro
BF_3	Amino
Triethylamine	Amino
H_2S	Nitro

are of interest to vehicle damage control leak detectors. Most coatings such as organic polymers will absorb a multitude of organics, and because of many cross-linking reactions, it is possible they may not reversibly desorb.

Uncoated crystals have been used by NASA (Reference 28) to detect backstreaming of diffusion pump oil into vacuum systems, but considerable development will be required to develop a family of selective gas detectors.

One potential use of the crystal is for monitoring an unexpected atmospheric buildup of a component through onboard leakage or outgassing of a vehicle material. There are many materials which fall into this classification. Present state-of-the-art methods utilize the sensitivity and versatility of the vapor fractometers to monitor these trace-type contaminates. These instruments contain several partitioning columns to provide separation of the numerous compounds experienced. Present practice calls for periodic sampling of the vehicle atmosphere through each of the columns, which is somewhat of an arbitrary rationale. A more specific use of the vapor fractometer could be achieved with piezoelectric sensors. Each sensor would be coated with the specific column material. These sensors could be located within the thermal conditioning air return duct.

Any contaminant finding its way into the vehicle atmosphere would absorb on one or more of the sensor surfaces, causing a corresponding change in crystal frequency. This signal could be used as a contaminate "early warning" alarm and could also actuate the vapor fractometer and select the proper partitioning column, since the sensors match the specific fractometer column materials. The vapor fractometer would then identify the compound and its concentration by retention time and signal magnitude, respectively.

4.3.5 Human Nose

Another analytical tool which should not be overlooked is the human nose, which in many cases is more sensitive than chemical analysis. During the 90-day manned test, one of the crewmen awoke during his sleep because he smelled overheated insulation. Investigation revealed that a pump in the water system had stalled and was overheating. His alarm came long before any increased levels of CO or hydrocarbons in cabin gas occurred. In addition, their noses located improperly sealed garbage containers and leaks in the urine recovery subsystem.

Consideration should be given to "coating" critical components with a selection of chemical compounds which generate identifiable odors when a leak, overload, or other malfunction occurs. This concept has the advantage of requiring no equipment or consultation on the crewman's part. Each crewman can conduct his own investigation, allowing a concentrated effort to find the leaking or malfunctioning item. This concept is used by gas companies in injecting an organic mercaptan into all natural gas used by the public. The mercaptan gives the otherwise odorless gas an odor similar to rotten eggs and is detected by the nose at a low ppm level. Various esters could be used, depending on the nature of the malfunction to be detected. High-vapor pressure compounds could be injected into oxygen or the heat transport fluids, for example. Low-vapor-pressure esters could be coated on equipment subject to overtemperature-type failures. In this case, little or no odor could be detected until an above-normal temperature occurs. Typical ester odors are those associated with the smells of fruit (e.g., oranges or pineapples) and flowers (e.g., gardenias or roses).

4.4 HIDDEN LEAKS

Hidden leaks can generally be classified as those which defy detection by conventional methods. Examples are: (1) a leak in the Sabatier catalyst loading flange caused by unequal thermal expansion at the elevated operating temperature; however, the joint shows no leakage when tested at room temperature, (2) a slow but insidious buildup of hydrogen in the vehicle.

Testing with soap suds and hydrogen detectors of all hydrogen lines and components give negative results because the leak is too small for bubble formation and the microjet of hydrogen barely punctures the air boundary layer before it is swept into the dilution of the vehicle ventilation system. There is an infinite mix of situations where the leak "comes and goes" or the leak locater sensor cannot or is not placed in a position to pick up that concentration gradient that allows a leak to be "homed" in on. There are also only limited lines and components which can be bagged with plastic or other coverings so that the gas is prevented from migration until enough concentration is accumulated to detect. Instruction books and procedures cannot be written for finding every leak. The main results will depend upon the ingenuity of the crew and some general provision materials suitable for making improvised repairs.

One of the candidate items suitable to general repairs would be an assortment of flexable lines or hoses terminated with AN connectors. This would allow a whole section of hidden line to be replaced quickly. This replacement technique is sometimes called leak detection by substitution. Other useful items would be tube cutters and a handheld flaring tool which would allow wall-mounted tube runs to be cut and flared at location. For plumbing associated with materials normally found in vehicle cabins and EC/LS systems, emergency replumbing can be performed with copper tubing which is easy to bend, cut, and flare. Many items will suggest themselves as our knowledge and experience in this art increases.

4.5 ANALYSIS OF SMALLEST DETECTABLE LEAK

Detecting onboard leaks is a time-dependent function. Onboard leakage of process fluids produces an increased partial pressure signal. As time passes and more fluid leaks, the partial pressure signal increases until eventually the signal is within the detection capability of the detector. For gas chromatographs, mass spectrometers, and vapor fractometers, the partial pressure signal need only be a few parts per million to be detected.

Therefore, the smaller the enclosed volume, the more rapidly the partial pressure signal will reach the threshold of the detecting instrument for a given size leak. The human nose can also detect odors in the parts per million range.

The tape leak detector may signal a liquid leak with only one drop of liquid being lost, assuming that the tape is attached directly at the point of leakage and that the one drop of liquid is sufficient to wet the wick enough to allow current flow through the foil electrode. In another case, the tape may not be on the exact location of the leak and hence a number of drops may be required before the wicking becomes conductive and sets off the alarm. A very slow leak may never set off the alarm. This would be true if the first drop of liquid did not wet the wick sufficiently to set off the alarm and then evaporated before it was reinforced by a second and subsequent drops of liquid. Leak rates of this low rate, particularly of nontoxic fluids, could continue for days without any detriment to the operating equipment.

Section 5
WEIGHT TRADEOFF ANALYSES

Analyses have been made of the weight tradeoffs between the DCS and atmosphere supply reserves for various leak rates. Assessments also were made of the additional weight penalties that may be incurred due to the inaccessibility of the hole or leak source and the weight of tools and materials required for repairing the leak. The results of these analyses are presented below in a parametric graphical form so that they may be applied to any spacecraft.

The weight tradeoffs are primarily influenced by the size of the hole or the equivalent hole size for any leakage-producing fault. Hole sizes may vary from microholes to major meteoroid penetrations resulting in holes of up to a few inches in diameter. Figure 5-1 gives the amount of gas losses from a sea-level equivalent oxygen-nitrogen spacecraft atmosphere as a function of mission durations for a family of equivalent hole sizes. A range of 0.05 mm to 1 mm diameter holes was considered. Methods of oxygen and nitrogen supplies and the results of the parametric tradeoffs are presented in the following paragraphs.

5.1 METHODS OF OXYGEN AND NITROGEN SUPPLY

Oxygen and nitrogen may be supplied from storage tanks or from the decomposition of chemical compounds such as metallic superoxides and chlorate candles. Oxygen may also be recovered from carbon dioxide exhaled by the crew. Four methods for the storage and supply of oxygen and nitrogen are presented. Included are high-pressure, supercritical and subcritical storage, and electrolysis of water and hydrazine. Both high-pressure and supercritical storage have been flight-tested, while subcritical storage and electrolysis are in the prototype development stage.

5.1.1 High-Pressure Storage of Atmospheric Constituents

High-pressure gaseous storage is usually heavier than cryogenic storage because of the heavy vessels dictated by the high storage pressure

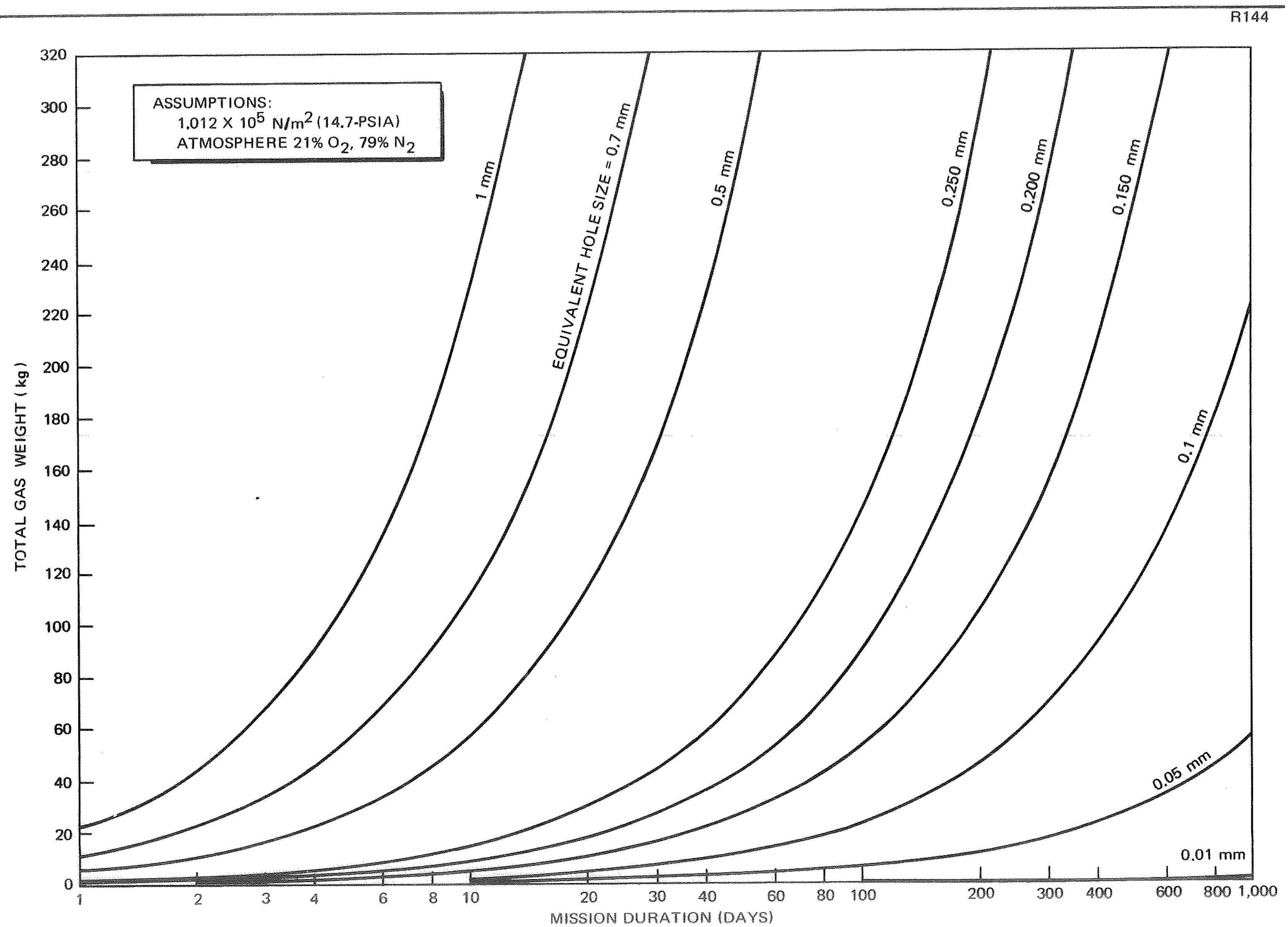

Figure 5-1. Atmosphere Leakage for Equivalent Hole Sizes as Function of Mission Duration

(about 5.17 x 10^7 N/m^2 or 7,500 psia). The primary advantages of high-pressure storage are that the equipment is relatively simple and the gas is readily available for the requirements of rapid repressurization and emergency operation. Oxygen tanks are usually made of 4340 steel while nitrogen tanks are made of titanium alloy (Ti-6Al-4V). The fill pressure may be up to 5.17 x 10^7 N/m^2 (7,500 psia) at cabin ambient for both gases. The storage weights of oxygen and nitrogen supply systems, including gas, tankage, and controls, have been computed parametrically as functions of mission duration for up to 1,000 days.

5.1.2 Supercritical and Subcritical Storage of Oxygen and Nitrogen

Gases may be stored as cryogenic fluids in supercritical and subcritical thermodynamic conditions. The tankage weights for supercritical storage are somewhat higher than those for subcritical storage for short-duration missions because of the greater design operating pressure level. Supercritical fluids are in a homogeneous (i.e., single-phase) thermodynamic state while subcritical fuilds exist as two phases (liquid and vapor) in saturated equilibrium. Subcritical storage has not been demonstrated to be operational for zero-g applications because techniques to draw off vapor selectively have not yet been fully developed.

Supercritical storage tanks are usually filled with subcritical fluid. The vessel is capped and the fluid allowed to heat to a temperature higher than critical. The fluid then exists at a single-phase, homogeneous state at supercritical temperature and pressure. Fluid can be subsequently withdrawn from the tank at constant pressure if heat is added. The supercritical storage pressure range is 4.9 to 5.9 x 10^6 N/m^2 (710 to 850 psia) for oxygen and 2.9 to 3.4 x 10^6 N/m^2 (425 to 570 psia) for nitrogen.

Subcritical tanks are filled in the same fashion as supercritical tanks; however, the operating pressure is then kept as low as practical to minimize vessel weight. As vapor is withdrawn from the tank, heat must be added to vaporize a like amount of remaining liquid. Consequently, the insulation thickness is determined by the heat of vaporization required to maintain the design delivery rate. Higher delivery rates require the addition of electric power through the resistance heater. Lower delivery rates mean that the gas boil-off is lost by venting. The subcritical tanks are usually operated at 8.62×10^5 N/m^2 (125 psia) maximum.

Cryogenic oxygen storage tanks usually utilize Inconel 718 for the inner tank shell and an aluminum alloy such as alloy 2219 for the outer shell. Vapor-cooled shields are often included in the insulation assembly to reduce insulation thickness, for this permits fluid leaving the storage vessel to intercept part of the heat entering the tank through the vessel outer shell. The storage weights for supercritical and subcritical storage systems have been computed parametrically as functions of mission duration for up to one year. Weight of insulation required for longer missions makes these storage methods unattractive.

5.1.3 Oxygen and Nitrogen Supply by Electrolysis

Oxygen and nitrogen may be stored in the form of stable liquids which can be electrolyzed as required. Water and hydrazine are the fluids used for the production of oxygen and nitrogen, respectively. The hydrogen produced when either water or hydrazine is electrolyzed may be used in the CO_2-reduction reactor or dumped overboard. The three most promising candidate water electrolysis systems are the static feed and the continuous flow asbestos matrix KOH electrolyte units and the solid polymer electrolyte water electrolysis. When hydrazine was fed into the electrolyte in a water electrolysis system, it was found to react, forming oxygen at the oxygen electrode in addition to hydrogen at the cathode. Reference 29 indicates hydrazine is oxidized at the anode to produce nitrogen and water. The reactions involved are either chemical or electrochemical. A small amount of nitrogen is also found in the effluent hydrogen at the cathode, where the hydrazine is decomposed to nitrogen and hydrogen.

The major portion of the weight penalties associated with electrolysis systems is due to the power required for electrolyzing the water.

5.2 RESULTS OF PARAMETRIC TRADEOFFS

Curves showing total system weights (for gas reserves required to replenish leakage) as functions of mission durations for equivalent hole sizes up to 1 mm are presented in Figures 5-2 through 5-5, for a cabin pressure of 1.01×10^5 N/m^2 (14.7 psia). The same information for pressures of 4.8×10^4 N/m^2 (7 psia) and 7×10^4 N/m^2 (10 psia) are shown in Figures 5-6 and 5-7. Gaseous and cryogenic storage methods as well as the supply of oxygen and nitrogen through the electrolysis of water and hydrazine are included. The total system weights shown in Figures 5-2 through 5-5 include the weight of gases, tankage, and controls. Figure 5-1 indicates for the actual weight of gases supplied by each system. Superimposed on Figures 5-2 through 5-5 are preliminary estimates of the weight penalties allocated to the DCS, access methods, and repair tools and materials for the 10.1-m-dia Space Station. A weight of 35.8 kg (78.8 lb) allocated to the DCS is described in detail in Section 8 of this report.

The weight attributable to access provisions was obtained by first examining each of the four decks of the 10.1-m-dia Space Station, identifying the equipment placed next to the pressure shell, and then estimating the number and types of access methods to be employed to accomplish shell access. Details of types of access and associated weight penalties are given in Section 6 of this report. The following assumptions were made:

Average Pivot Weight = 0.91 kg (2.0 lb)

Average Slide Weight = 2.7 kg (6.0 lb)

Average Slide/Pivot Weight = 3.63 kg (8.0 lb)

Average Weight for Unit Removal = 3.63 kg (8.0 lb)

Average Weight for Flexible Lines and Ducting per Unit = 0.91 kg (2.0 lb)

A summary of the access provisions weight allocations for each of the four decks of the Space Station is given in Table 5-1.

It should be noted that access provisions may be provided for purposes other than leak repair, such as maintenance or multiple space utilization. Consequently, a number of curves showing percentages of access provision weights were introduced. The proper percentage of access provision weight to be allocated to leak repair purposes is left to the judgment of the user.

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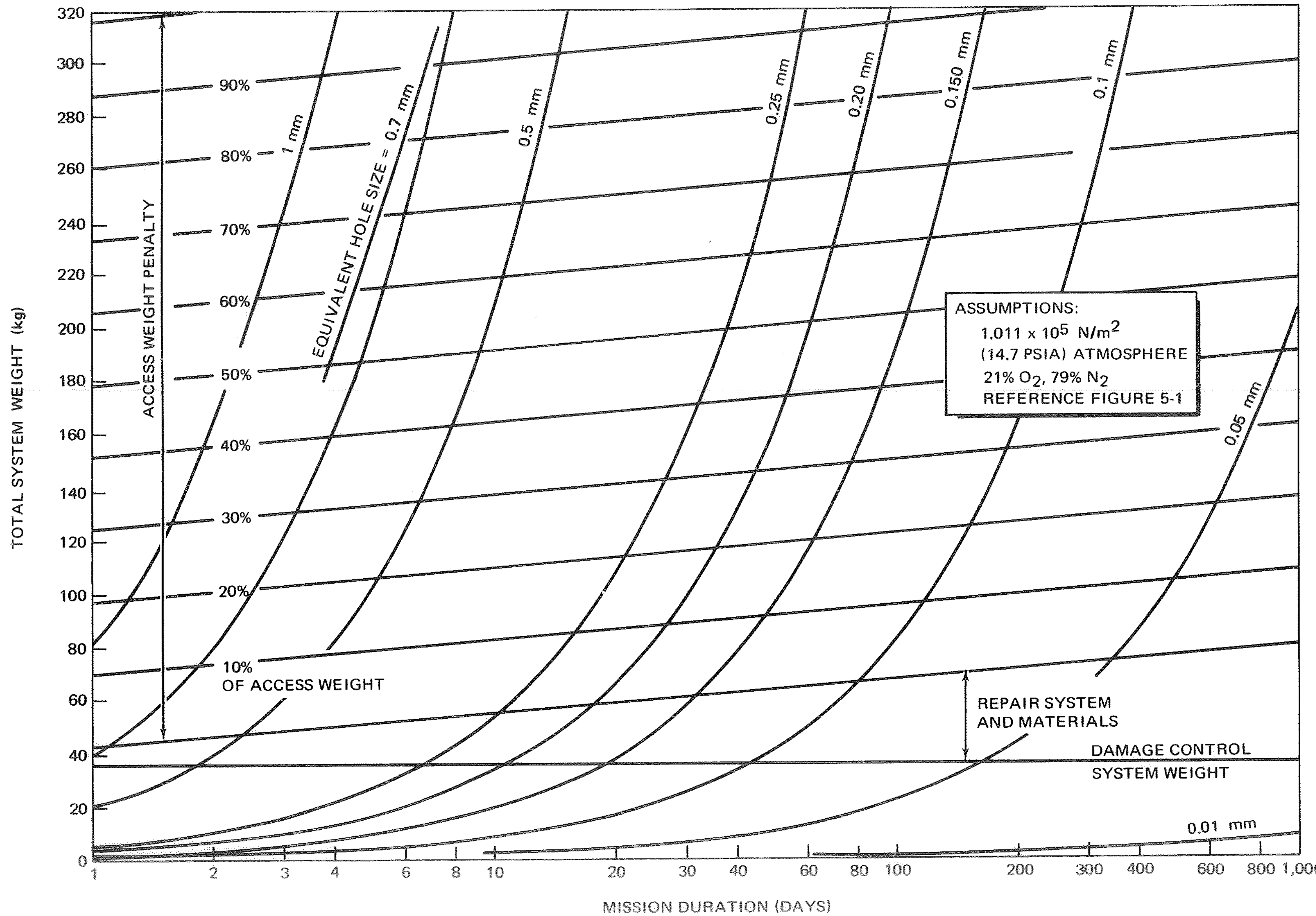

Figure 5-2. Parametric High Pressure Gaseous System Weight as Function of Mission Duration

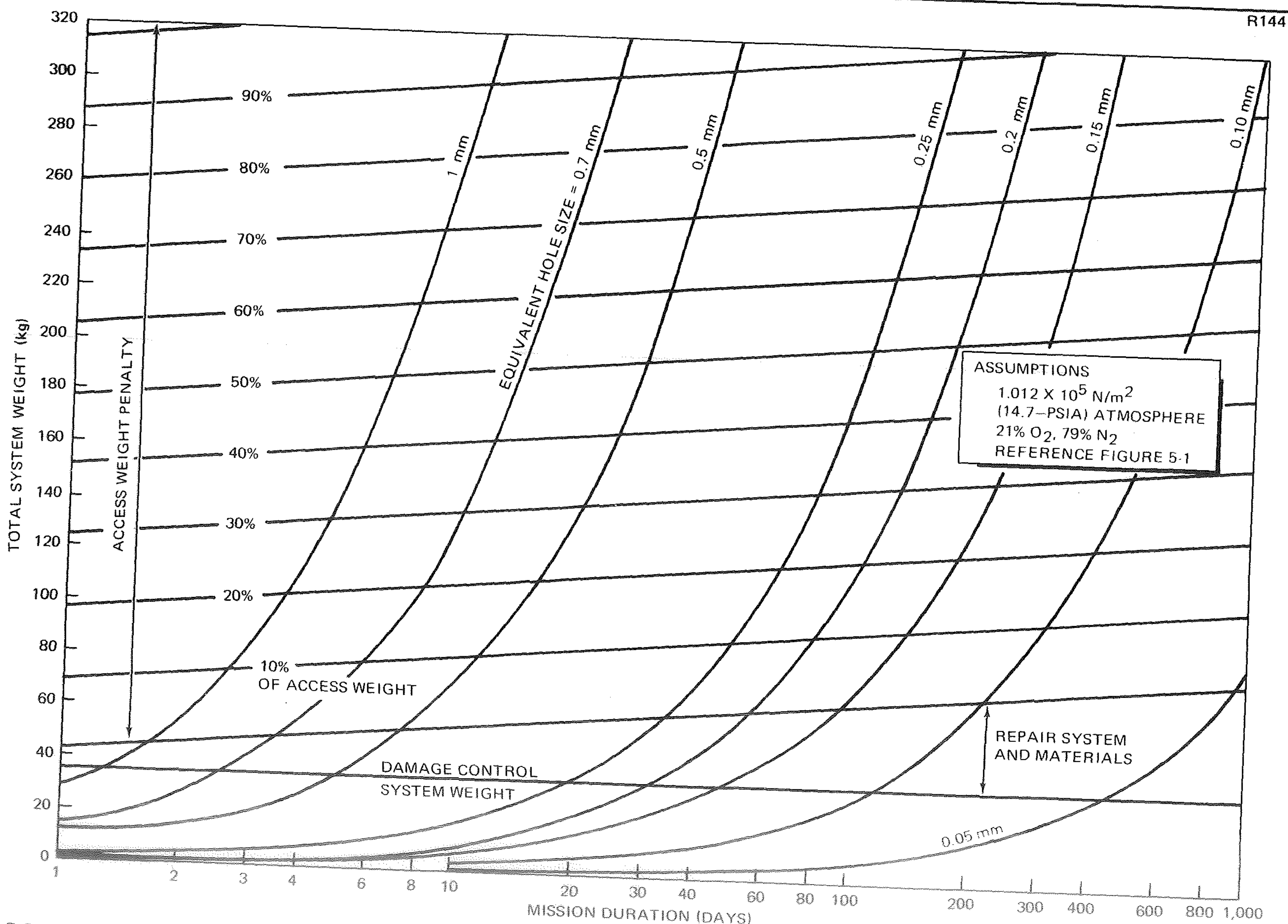

Figure 5-3. Parametric Supercritical Atmospheric Storage System Weight as Function of Mission Duration

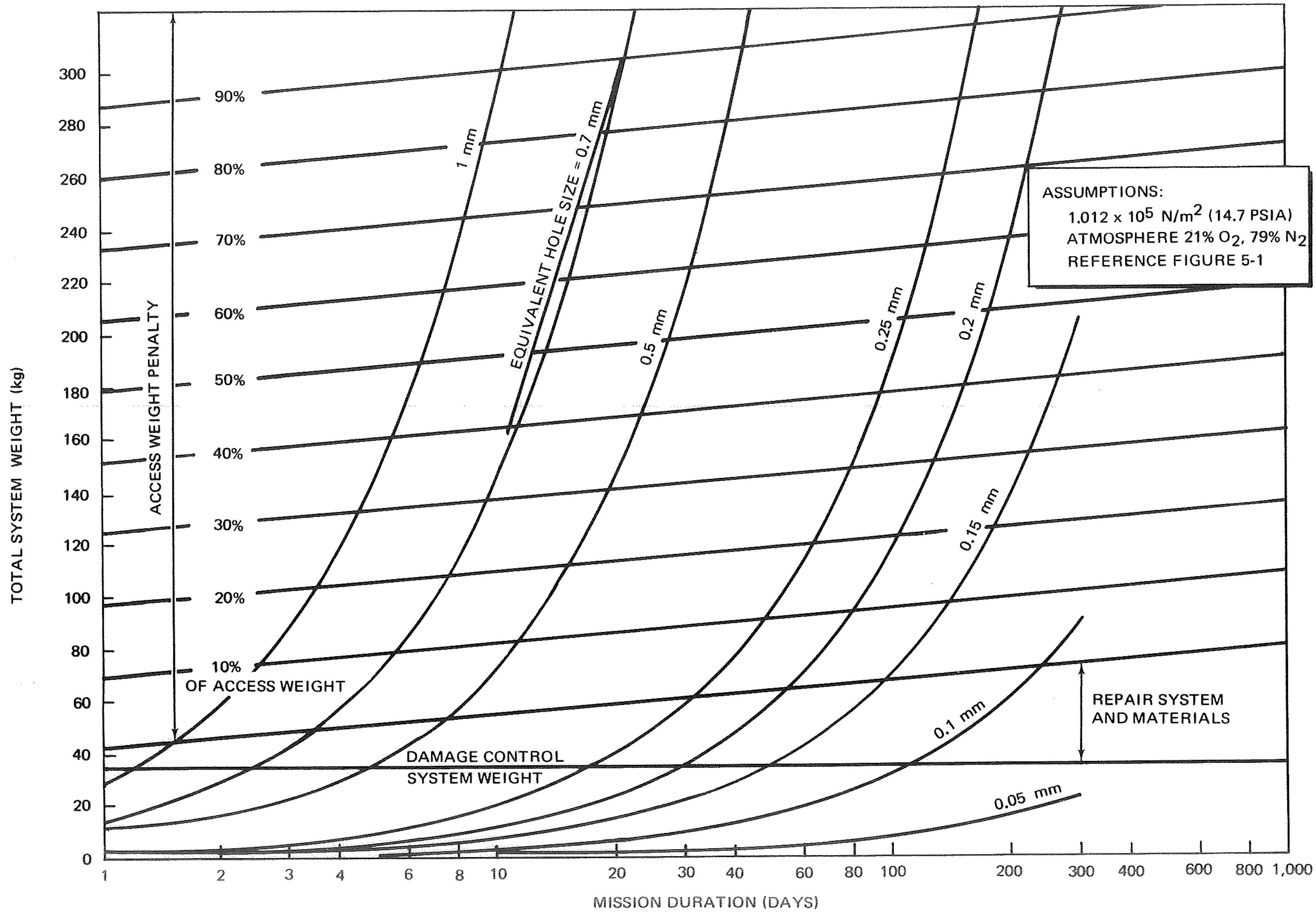

Figure 5-4. Parametric Subcritical Atmospheric Storage System Weight as Function of Mission Duration

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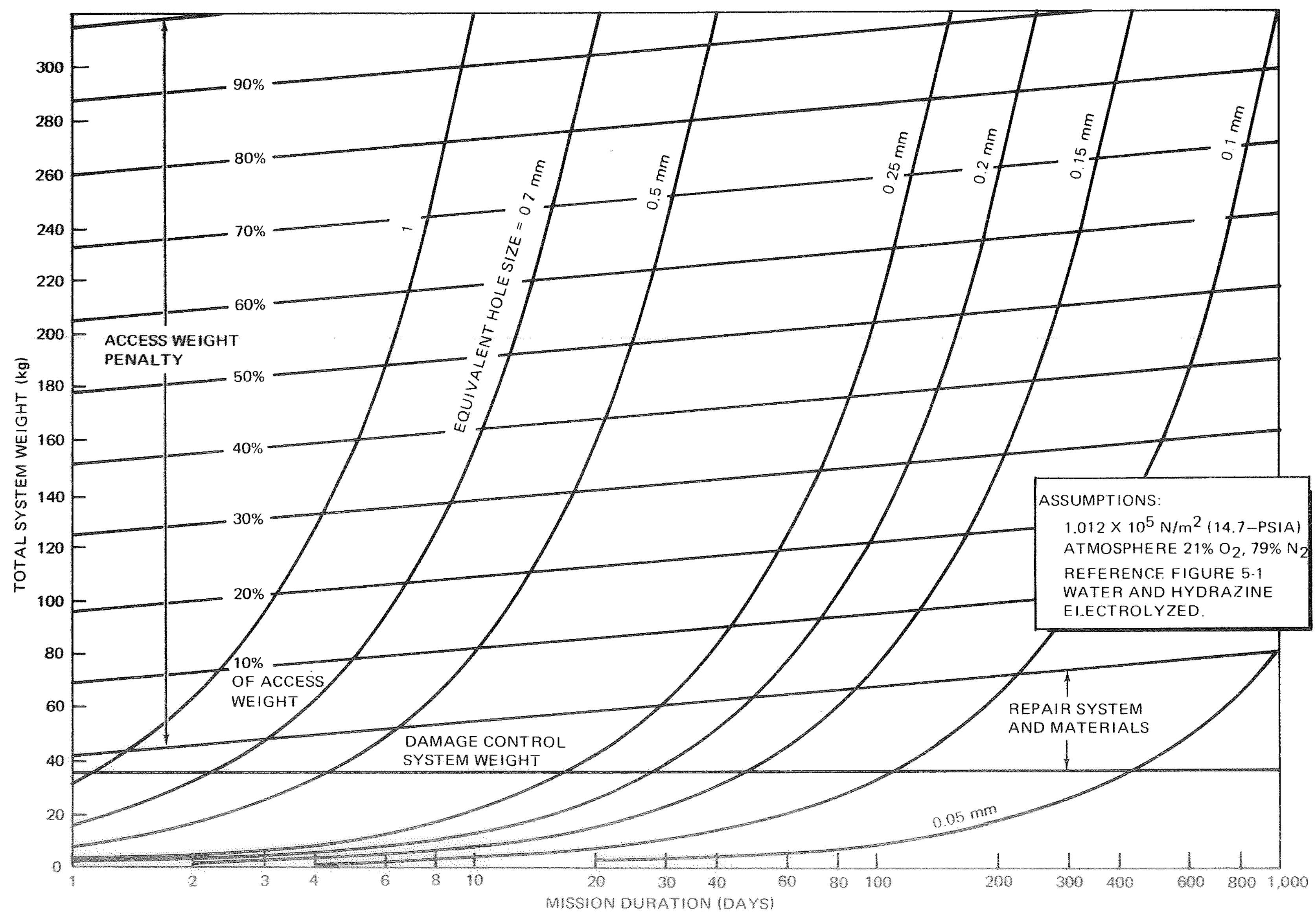

Figure 5-5. Parametric Electrolysis Atmosphere Supply System Weight as Function of Mission Duration

Table 5-1

WEIGHT ESTIMATES FOR 10.1-M DIA SPACE STATION ACCESS PROVISIONS

Deck	Pivots x wt (kg)	Slides x wt (kg)	Slide/ Pivots x wt (kg)	Unit Removal x wt (kg)	Flex Lines/ Ducting x wt (kg)	Total Weight (kg)
1	14 x 0.91	6 x 2.7	3 x 3.63		23 x 0.91	60.76
2	15 x 0.91	4 x 2.7	8 x 3.63		27 x 0.91	78.06
3	14 x 0.91	5 x 2.7	3 x 3.63		23 x 0.91	58.06
4	8 x 0.91	2 x 2.7	5 x 3.63	1 x 3.63	16 x 0.91	49.02
						245.90
			Plus 10 percent for equipment not identified that will require access provisions			24.59
				Total Weight		270.49

In assessing the weight penalties attributed to leak repairs, it was assumed that the two most desirable leak repair systems would be used: elastomer sealant and replacement, which are identified in Section 7. The weight of repair tools and materials, including 5 gallons of elastomer, is assumed to be 34 kg for a mission duration of 180 days, as indicated in Figures 5-2 through 5-5.

In order to assess the effects of varying the total cabin pressure from 4.8×10^4 N/m^2 to 1.01×10^5 N/m^2 (7.0 to 14.7 psia) on the weight tradeoffs between the DCS and the atmosphere supply system, the data in Figure 5-3 have been replotted in Figures 5-6 and 5-7 for 4.8×10^4 N/m^2 (7.0 psia) and 6.89×10^4 N/m^2 (10.0 psia), respectively. A supercritical atmospheric storage method was selected because it was found to be more attractive from a total system weight penalty standpoint than the other supply methods considered. Total atmospheric supply system weights were found to decrease proportionally with reduced cabin pressures. An illustration of the use of Figures 5-6 and 5-7 is given in the following paragraphs.

The weight tradeoffs have been presented parametrically to enable the computed data to be applied to any spacecraft. The access provisioning and repair weights, however, were based on the 10.1-m-dia Space Station and

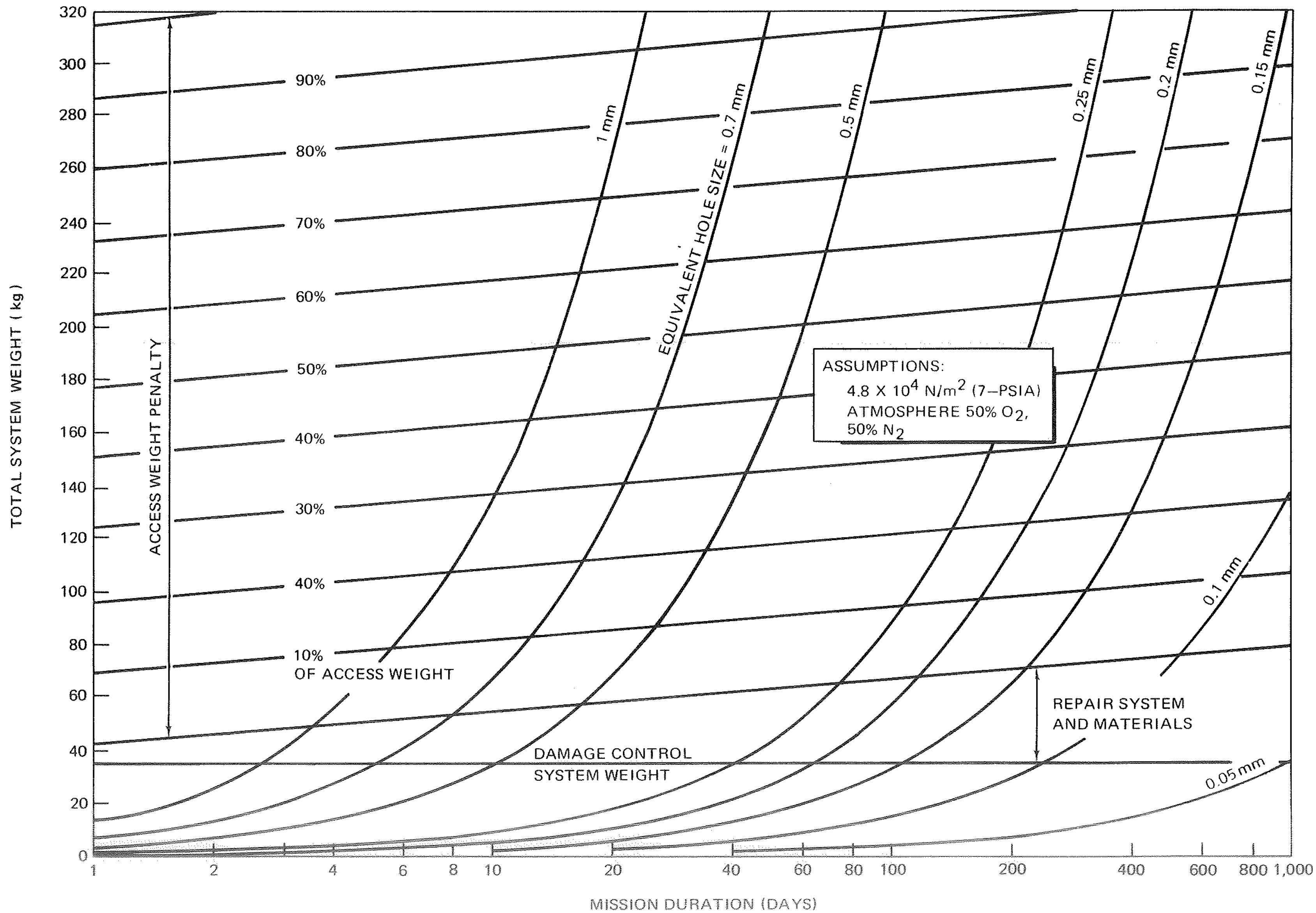

Figure 5-6. Parametric Supercritical Atmospheric Storage System Weight as Function of Mission Duration for 4.82×10^4 N/m^2

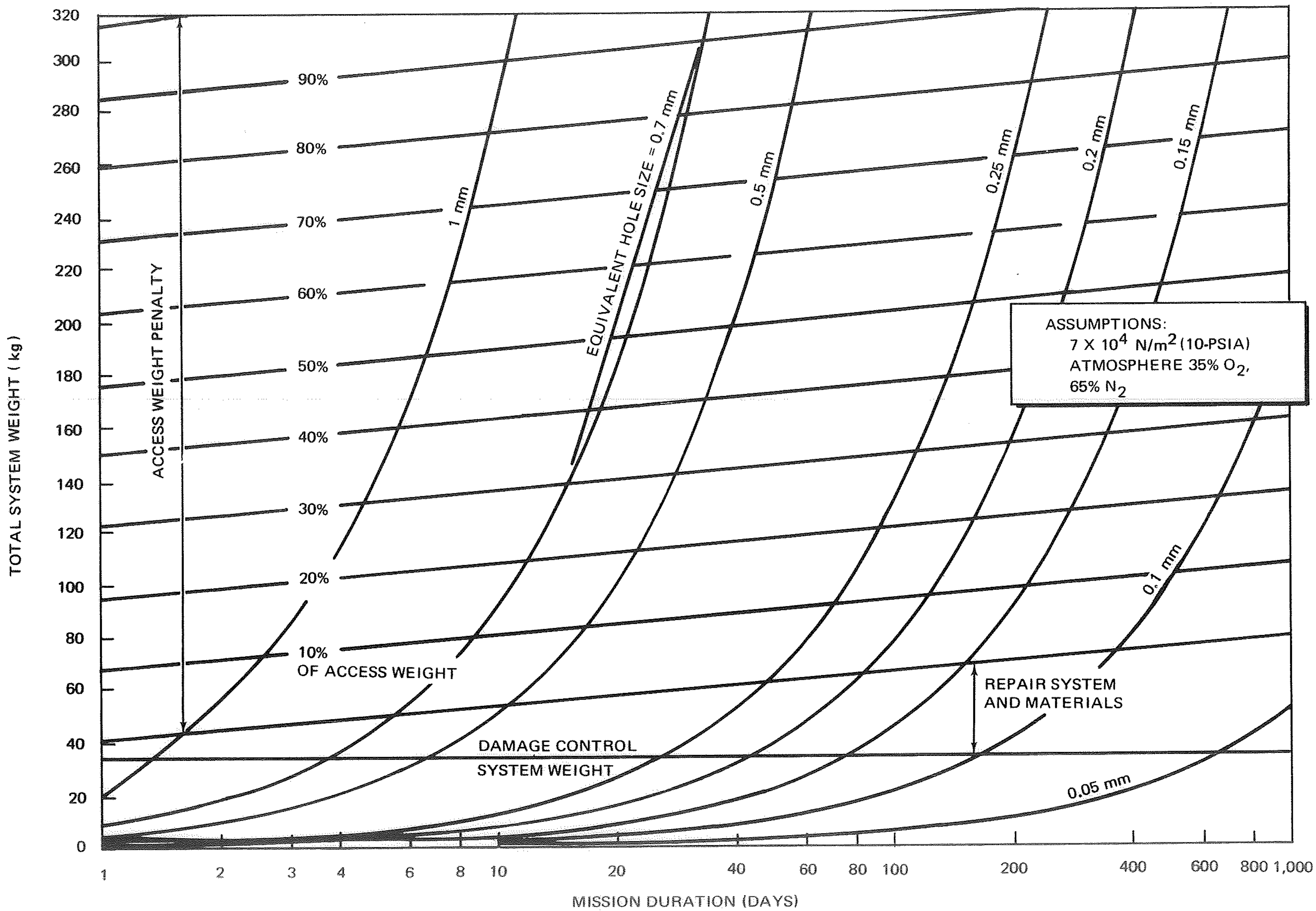

Figure 5.7. Parametric Supercritical Atmospheric Storage System Weight as Function of Mission Duration for 6.89 X 10^4 N/m^2

should be modified or scaled for other applications. The high-pressure gaseous storage incurs the heaviest penalties of all the methods considered, but may be preferred for long mission durations or when fast delivery of gases is required, such as in case of cabin repressurization. The subcritical storage method has the least system weight penalty for missions up to approximately 100-day duration, but requires some additional development effort. Supercritical storage has been flight-tested and is suitable for longer missions than subcritical storage. The supply of oxygen and nitrogen by electrolysis was not found to be competitive with the cryogenic storage methods, mainly due to the weight penalties associated with the required electrical power.

The use of the plotted data may be illustrated by the following example. Consider an equivalent hole size of 0.25 mm (10 mils). Assume use of the supercritical gas storage method and allocate 50 percent of access provisioning weight for leak repair requirements. Then, from Figure 5-3, it can be seen that the crossover point, where the weight of the gas supply system is equivalent to the combined weights of the DCS, access provisions, and repair system, is 105 days. The amount of gases lost in 105 days from the 0.25-mm equivalent hole is approximately 150 kg, as may be seen from Figure 5-1, for a sea-level type of space cabin atmosphere. Thus, the DCS plus access provisions and repair system weights would pay for themselves after 105 days. For a total mission duration of 10 years and a 0.25-mm equivalent hole size, the accrued weight savings resulting from the use of the DCS would exceed 6,800 kg (15,000 lb).

The above example may also be applied to other atmospheric supply methods or spacecraft cabin pressures to show their effects on weight tradeoffs. The results of comparisons, with 0.250-mm equivalent hole size, 50 percent access provision allocation, repair system, and supercritical storage, are as follows.

A. For a 1.01×10^5 N/m^2 (14.7 psia) atmosphere and high-pressure storage method, the crossover point where the weight of DCS, access provision, and repair system is equivalent to total gas supply system weight is seen from Figure 5-2 to be only 38 days.

B. For a 4.82×10^4 N/m^2 (7.0 psia) cabin pressure and supercritical supply method, the crossover point is seen from Figure 5-6 to be 248 days.

C. For a 6.89×10^4 N/m^2 (10.0 psia) cabin pressure and supercritical supply method, the crossover point is seen from Figure 5-7 to be 159 days.

Tradeoffs for various supply methods or spacecraft cabin pressures may be obtained likewise from Figures 5-2 through 5-7.

Section 6

STUDY OF METHODS FOR GAINING ACCESS TO LEAKS

The study approach consisted of: (1) determination of the conditions which restrict access to leaks in any part of the pressure shell;(2) identification of access methods for specific access conditions;(3) evaluation of access methods for specific access conditions, and(4) development of recommendations for use of access methods during configuration design.

The following ground rules are applicable to the study effort:

A. The 10.1 m (33 ft) dia Space Station, as defined by the parallel studies of MDAC and the Space Division of North American Rockwell, will be used as a baseline to identify access restriction conditions.

B. Systems will exist to detect, identify types, and indicate general location of leaks.

C. A leak may occur any place in the pressure shell or onboard the vehicle.

D. Access methods must be compatible with pressurized suit operations.

E. Access methods must be compatible with operations in a zero-g environment.

F. All equipment attachment fasteners will be readily accessible to a crewman in a pressurized pressure suit.

G. Weight penalty for crewman restraints required during access operations will not be included in trade studies.

H. The study will not include EVA access methods.

I. To the extent possible, access methods will be applicable to modular Space Station and Shuttle Orbiter configurations.

J. A perpendicular distance of 0.762 m (30 in.) from the pressure shell to any obstruction will be used to ensure adequate working space for a crewman in a pressurized suit for repair of leaks on the pressure shell or on any vehicle system.

6.1 CONDITIONS RESTRICTING ACCESS TO LEAKS

A detailed review of the 10.1-m (33-ft) dia Space Station configurations identified 10 conditions which prevent access to the pressure shell; (1) partitions located against the pressure shell, (2) storage cabinets or system equipment abutting the pressure shell, (3) storage cabinets or equipment attached to the pressure shell, (4) crew furniture attached to the pressure shell, (5) decor and crew protection padding attached to the pressure shell, (6) liquid transfer lines adjacent to the pressure shell, (7) gas transfer lines and ducting adjacent to the pressure shell, (8) conduit or electrical wiring adjacent to the pressure shell, (9) equipment lying against the pressure shell with flex and disconnect lines, and (10) air-lock equipment protruding into the access area. In addition, though the structural members attached to the pressure shell did not appear to restrict access, the possibility exists that the modular design or orbiter design may impose this type of access restriction. Therefore, this condition preventing access is included in the study.

6.2 IDENTIFICATION OF ACCESS METHODS FOR SPECIFIC ACCESS RESTRICTION CONDITIONS

Each condition which could prevent access to the pressure shell or vehicle system was evaluated in respect to the 10.1-m (33-ft) dia Space Station to identify possible methods of design and procedures which will permit access. This evaluation (Table 6-1) resulted in the identification of eight access methods: (1) inherent in design, (2) pivot, (3) slide, (4) slide/pivot, (5) unit removal, (6) item displacement, (7) disassemble, and (8) partial disassemble.

The titles of access methods are self-explanatory with the exception of inherent in design and item displacement. Inherent in design means the design provides unrestricted access without movement of equipment. Item displacement is applicable to flex gas, liquid, or electrical conduit and means the physical displacement of lines by force of hand (see Appendix C, Figures C-1 and C-21).

6.3 EVALUATION OF ACCESS METHODS FOR SPECIFIC ACCESS RESTRICTION CONDITIONS

A trade study was made of each access method versus the applicable condition restricting access. Evaluation criteria included requirements for tools

Table 6-1 (Page 1 of 2)

DEFINITION OF ACCESS METHODS

Condition Preventing Access	Access Method								
	Condition Identification Numbers	Inherent in Design	Pivot	Slide	Slide/ Pivot	Unit Removal	Item Displacement	Dis-assemble	Partial Dis-assemble
		A	B	C	D	E	F	G	H
Partition Abuts Wall	1		X	X	X	X			
Storage Cabinets Abut Shell	2		X	X	X	X			
Shell Mounted Storage Cabinets	3		X	X	X	X			
Shell-Mounted Crew Furniture	4		X	X	X	X			
Shell-Mounted Decor and Crew Protection Padding	5		X			X			
Liquid Transfer Lines	6						X	X	X

Table 6-1 (Page 2 of 2)

DEFINITION OF ACCESS METHODS

Condition Preventing Access	Condition Identification Numbers	Access Method: Inherent in Design	Pivot	Slide	Slide/ Pivot	Unit Removal	Item Displacement	Dis-assemble	Partial Dis-assemble
		A	B	C	D	E	F	G	H
Gas Transfer Lines and Ducting	7						X	X	X
Conduit and Electrical Cable	8						X	X	X
Equipment Abuts Shell-Flex Lines	9		X	X	X	X			
Equipment Abuts Shell-Disconnect Lines	10		X	X	X	X			
Airlock Equipment Protruding into Access Area	11	X							
Structural Member Attached to Shell	12					X			

and storage fixtures, the number of crewmen required to access, the crew time for access, crew time to reposition equipment for normal operations, task difficulty of access method, weight penalty if access provision is inherent in item design, and weight penalty of portable handling fixture for removal of equipment (Table 6-2).

The following procedure was employed to determine the relative ranking for each applicable access method for a specific condition restricting access. The values for all trade parameters except weight were summed to provide a raw score. This summed value with the raw score weight penalty was entered into the matrix for each access method applicable to specific conditions preventing access. The access method with the minimum weight penalty was used as a baseline for comparison with other applicable access methods. Each pound of weight difference in the method of access from the baseline was increased by a factor of 2.5 and added to the baseline to provide an adjusted weight penalty which reflects the estimated $250 per pound launch cost. The weighting factor for time for access, repositioning of equipment, and task difficulty is included as a part of the rating scale for the matrix entry (Table 6-3). The adjusted values were summed to provide a priority ranking for engineering considerations in configuration layout and design.

6.4 RECOMMENDATIONS FOR CONFIGURATION DESIGN

The detailed review of the 10.1-m (33-ft) dia Space Station configurations reveals a capability for a design which permits unrestricted access to all positions of the pressure shell without a requirement to move equipment. The only condition which presents a problem is the air lock protruding into the living and working areas. When this air lock is pressurized, its shell is in effect the Space Station pressure shell and access to the air-lock shell must be ensured in design. Appendix C (Figure C-1) illustrates one design concept to ensure ready access.

The use of the inherent-in-design method provides the most rapid access with the least weight penalty. It should be used to the maximum extent possible in configuration layout and design to provide access to the pressure shell or vehicle systems for repair of leaks. Increased pressure shell

Table 6-2 (page 1 of 3)

TRADE OF ACCESS METHODS VS ACCESS RESTRICTION CONDITIONS

Access Method	Identification No.	Access Condition	Tools Required For Access	Stowage Fixture Required	Number Of Crewmen Required	Time Required For Access	Time Required To Reposition Equipment	Task Difficulty	Weight Penalty Built Into Equipment	Weight Penalty For Support Equipment	Remarks
Inherent in Design A	11	Airlock Equipment Protruding Into Access Area	None	None	1	0	0	0	None	None	
Pivot B	1	Partition Abuts Shell	None	None	1	1	1	0	0.5	None	1 Pr Small Pivots/Unit (Friction Pivots)
	2	Storage Cabinets Abut Shell	1	None	1	2	2	1	2.0	0.5	2 Pr Large Pivots/Unit
	3	Shell-Mounted Storage Cabinets	1	None	1	2	2	1	2.0	0.5	2 Pr Large Pivots/Unit
	4	Shell-Mounted Crew Furniture	1	None	1	2	2	1	1.0	0.5	2 Pr Small Pivots/Unit
	5	Shell-Mounted Decor and Crew Protection Padding	None	None	1	2	2	1	1.0	None	2 Pr Small Pivots/Unit (Friction Pivots)
	9	Equipment Abuts Shell-Flex Lines	1	None	1	2	2	1	2.0	0.5	2 Pr Large Pivots/Unit—May Require 2 Crewmen to Reposition
	10	Equipment Abuts Shell-Disconnect Lines	3	None	1	3	4	3	2.0	1.5	2 Pr Large Pivots/Unit—May Require 2 Crewmen for Task Completion
Slide C	1	Partition Abuts Shell	None	None	1	0	0	0	3.0	None	1 Pr Light-Duty Small Slides/Unit at 3 lb/pr
	2	Storage Cabinets Abut Shell	None	None	1	1	1	0	10.0	None	1 Pr Large Slides/Unit
	3	Shell-Mounted Storage Cabinets	None	None	1	1	1	0	10.0	None	1 Pr Large Slides/Unit
	4	Shell-Mounted Crew Furniture	None	None	1	1	1	0	6.0	None	1 Pr Small Slides/Unit
	9	Equipment Abuts Shell-Flex Lines	None	None	1	1	2	1	10.0	None	1 Pr Large Slides/Unit—May Require 2 Crewmen to Reposition
	10	Equipment Abuts Shell-Disconnect Lines	2	None	1	4	5	3	10.0	1.0	1 Pr Large Slides/Unit—May Require 2 Crewmen for Task Completion

NOTE:

Time:
- < - 1 Min = 0
- 1 - 2 Min = 1
- 2 - 4 Min = 2
- 4 - 8 Min = 3
- 8 - 16 Min = 4
- > - 16 Min = 5

Task Difficulty:
- Inherent Ability = 0
- Minimal Training = 1
- Training in Pressure Suit = 3

Table 6-2 (page 2 of 3)

TRADE OF ACCESS METHODS VS ACCESS RESTRICTION CONDITIONS

Access Method	Identification No.	Access Condition	Tools Required For Access	Stowage Fixture Required	Number Of Crewmen Required	Time Required For Access	Time Required To Reposition Equipment	Task Difficulty	Weight Penalty Built Into Equipment	Weight Penalty For Support Equipment	Remarks
Slide/Pivot D	1	Partition Abuts Shell	None	None	1	1	1	0	3.5	None	1 Pr Light Duty Slides = 3 lb—1 Pr Small Pivots (Friction Pivot)
	2	Storage Cabinets Abut Shell	1	None	1	2	2	1	12.0	0.5	1 Pr Large Slides, 2 Pr Large Pivots / Unit
	3	Shell-Mounted Storage Cabinets	1	None	1	2	2	1	12.0	0.5	1 Pr Large Slides, 2 Pr Large Pivots / Unit
	4	Shell-Mounted Crew Furniture	1	None	1	2	2	1	7.0	0.5	1 Pr Small Slides, 2 Pr Small Pivots / Unit
	9	Equipment Abuts Shell-Flex Lines	1	None	1	2	3	1	12.0	0.5	1 Pr Large Slides, 2 Pr Large Pivots / Unit (2 CM?)
	10	Equipment Abuts Shell-Disconnect Lines	3	None	1	4	5	3	12.0	1.5	1 Pr Large Slides, 2 Pr Large Pivots / Unit (2 CM?)
Unit Removal E	1	Partition Abuts Shell	1	1	2	3	3	1	None	0.5	
	2	Storage Cabinets Abut Shell	1	1	2	3	3	1	None	6.5	Handling Fixture = 5 lb
	3	Shell-Mounted Storage Cabinets	1	1	2	3	3	1	None	6.5	Handling Fixture = 5 lb
	4	Shell-Mounted Crew Furniture	1	1	1	3	3	1	None	6.5	Handling Fixture = 5 lb
	9	Equipment Abuts Shell-Flex Lines	1	1	2	4	5	3	None	6.5	Handling Fixture = 5 lb
	10	Equipment Abuts Shell-Disconnect Lines	3	1	2	5	5	3	None	8.0	Handling Fixture = 5 lb Parts Stowage Container = 0.5 lb
	12	Structural Member Attached to Shell	1	1	1	5	5	3	2.0	2.0	Parts Stowage Container = 0.5 lb Stowage Fixture = 1 lb Built-In Fasteners = 2 lb

NOTE:

Time:
- < - 1 Min = 0
- 1 - 2 Min = 1
- 2 - 4 Min = 2
- 4 - 8 Min = 3
- 8 - 16 Min = 4
- > - 16 Min = 5

Task Difficulty:
- Inherent Ability = 0
- Minimal Training = 1
- Training in Pressure Suit = 3

Table 6-2 (page 3 of 3)

TRADE OF ACCESS METHODS VS ACCESS RESTRICTION CONDITIONS

Access Method	Identification No.	Access Condition	Tools Required For Access	Stowage Fixture Required	Number Of Crewmen Required	Time Required For Access	Time Required To Reposition Equipment	Task Difficulty	Weight Penalty Built Into Equipment	Weight Penalty For Support Equipment	Remarks
Item Displacement F	5	Shell-Mounted Decor and Crew Protection Padding	None	None	1	1	2	0	0.5	None	Built-In Restraint/Tie Down = 0.5 lb
	6	Liquid Transfer Lines	None	None	1	0	0	0	1.5	None	Flex and Swivel Joints = 1.5 lb (items 6–8)
	7	Gas Transfer Lines and Ducting	None	None	1	0	0	0	1.5	None	
	8	Conduit and Electrical Cable	None	None	1	0	0	0	1.5	None	
Disassemble G	6	Liquid Transfer Lines	2	1	1	3	4	3	2.5	2.0	Built-In Disassemble Capability = 2.5 lb (items 6–8)
	7	Gas Transfer Lines and Ducting	2	1	1	3	4	3	2.5	2.0	
	8	Conduit and Electrical Cable	2	1	1	2	3	3	2.5	2.0	
Partial Disassembly H	6	Liquid Transfer Lines	2	1	1	2	3	3	1.5	2.0	Built-In Partial Disassemble Capability = 1.5 lb (items 6–8)
	7	Gas Transfer Lines and Ducting	2	1	1	2	3	3	1.5	2.0	
	8	Conduit and Electrical Cable	2	1	1	2	3	3	1.5	2.0	

NOTE (Time Required For Access / Time Required To Reposition Equipment):
< - 1 Min = 0
1 - 2 Min = 1
2 - 4 Min = 2
4 - 8 Min = 3
8 - 16 Min = 4
> - 16 Min = 5

(Task Difficulty):
Inherent Ability = 0
Minimal Training = 1
Training in Pressure Suit = 3

NOTE: Weight Allocations as Follows:

Slides, Large—1 Pr = 10 lb; Small—1 Pr = 6 lb

Pivots, Large—1 Pr = 1 lb; Small—1 Pr = 0.5 lb

Tools (Average) = 0.5 lb each; Stowage Fixture = 1 lb

Parts Stowage Container = 0.5 lb; Handling Fixture = 5 lb

Table 6-3
EVALUATION AND RANKING OF ACCESS METHODS

Condition Preventing Access	Access Method Score Evaluation: A — Inherent In Design — Score Raw	A Adj	B — Pivot — Score* Raw	B Adj	C — Slide — Score Raw	C Adj	D — Slide/Pivot — Score Raw	D Adj	E — Unit Removal — Score Raw	E Adj	F — Item Displacement — Score Raw	F Adj	G — Disassemble — Score Raw	G Adj	H — Partial Disassemble — Score Raw	H Adj
Partition Abuts Wall			3 0.5	3 0.5	1 3.0	1 5.5	3 3.5	3 8.0	11 0.5	11 0.5						
1			(1)		2		3		4							
Storage Cabinets Abuts Shell			7 2.5	7 2.5	3 10.0	3 21.25	7 12.5	7 27.5	11 6.5	11 12.5						
2			(1)		3		4		2							
Shell-Mounted Storage Cabinets			7 2.5	7 2.5	3 10.0	3 21.25	7 12.5	7 27.5	11 6.5	11 12.5						
3			(1)		3		4		2							
Shell-Mounted Crew Furniture			7 1.5	7 1.5	3 6.0	3 12.75	7 7.5	7 16.5	10 6.5	10 14.0						
4			(1)		2		3		4							
Shell Mounted Decor and Crew Protection Padding			6 1.0	6 1.75							4 0.5	4 0.5				
5			2								(1)					
Liquid Transfer Lines											1 1.5	1 1.5	14 4.5	14 9.0	12 3.5	12 6.5
6											(1)		3		2	
Gas Transfer Lines and Ducting											1 1.5	1 1.5	14 4.5	14 9.0	12 3.5	12 6.5
7											(1)		3		2	
Conduit and Electrical Cable											1 1.5	1 1.5	12 4.5	12 9.0	12 3.5	12 6.5
8											(1)		3		2	
Equipment Abuts Shell Flex Lines			7 2.5	7 2.5	5 10.0	5 21.25	8 12.5	8 27.5	16 6.5	16 15.0						
9			(1)		2		4		3							
Equipment Abuts Shell-Disconnect Lines			14 3.5	14 3.5	15 11.0	15 26.25	16 13.5	16 38.5	19 8.0	19 19.25						
10			(1)		3		4		2							
Airlock Equipment Protruding Into Access Area	1 0	1 0														
11	(1)															
Structural Member Attached to Shell									16 4.0	16 4.0						
12									(1)							
	A		B		C		D		E		F		G		H	

*The first figure in a column indicates accumulative score, the second figure accumulative weight. The rank is denoted by a circled number. For example, on the Pivot Score, 3 = Accumulative Score, 0.5 = Accumulative Weight, and 1 = Rank.

thickness should be considered if access is not possible using any of the methods identified in this study. In all cases, structural members should be attached to the external pressure shell surface to reduce the number of major problems in leak repair.

For the class of access restriction comprised of partitions, storage cabinets, and equipment attached to the floor and touching the pressure shell, it is recommended that the pivot method of access, if possible, be used in configuration layout and design. Appendix C (Figures C-2 through C-11) illustrates the access methods and summarizes the priority for use in configuration layout and engineering design.

For the class of access restriction comprised of storage cabinets and crew furniture with attach-points on the pressure shell, it is recommended that engineers use the pivot method of access, if possible, in configuration layout and design. This method is illustrated in Appendix C (Figures C-12 and C-13). Appendix C (Figures C-14 through C-18) illustrates less favorable methods of gaining access to the pressure shell from restrictions of storage cabinets and crew furniture.

For the shell-mounted soft decor and crew protection padding, the item displacement access method is recommended and is illustrated in Appendix C (Figure C-19). For the shell-mounted firm decor and crew protection padding, the pivot method of access is recommended and is illustrated in Appendix C (Figure C-20).

For the class of access restriction comprised of gas transfer lines, liquid transfer lines, and conduit or electrical cable adjacent to the pressure shell, it is recommended that engineers use the following priority for access methods in configuration layout and design: item displacement, partial disassembly, and disassembly as shown in Appendix C (Figures C-21 through C-23).

A cursory evaluation of various storage or equipment cabinet sizes in 10.1 m (33 ft) dia, 6.7 m (22 ft) dia, and 4.3 m (14 ft) dia shells was made to maximize the storage, living, and working area during periods when access to the pressure shell is required (Figure 6-1 through 6-6). The 0.38 m (15 in.)

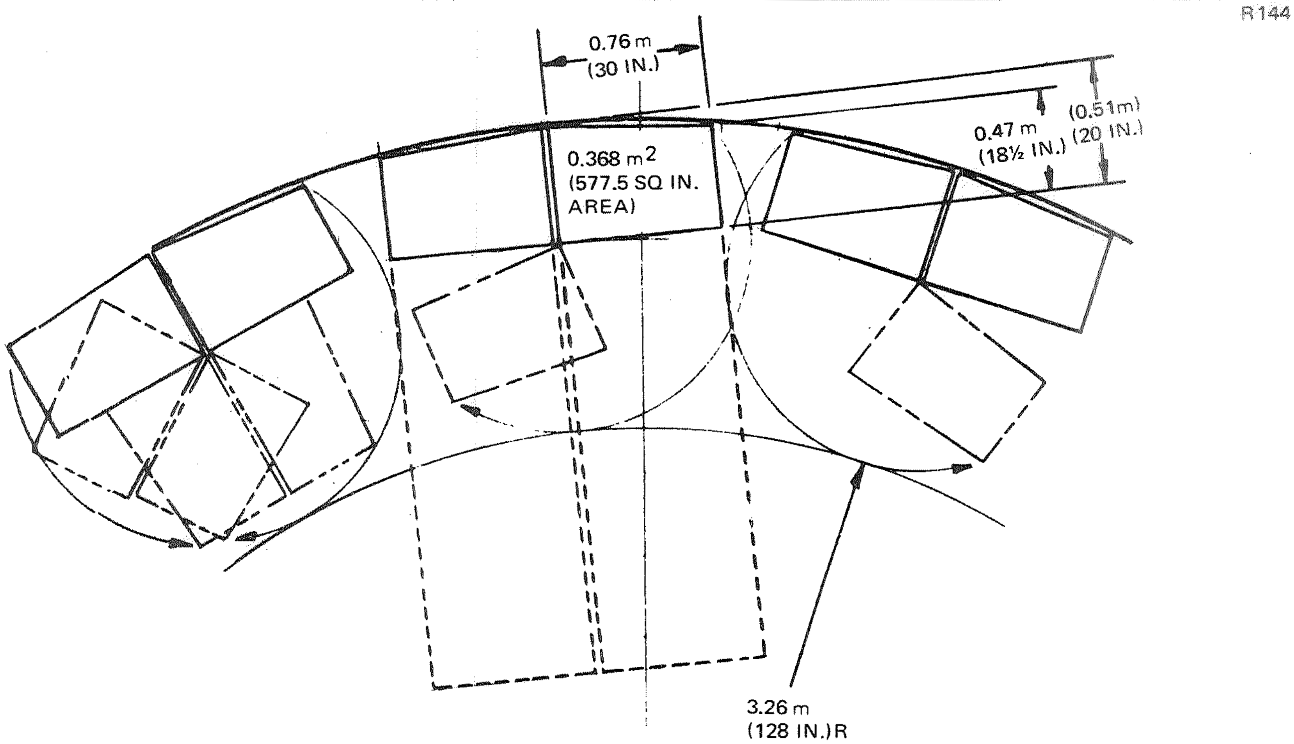

Figure 6-1. 10.1 m (33 Ft) Diameter Shell with 0.51 m (20 In.) Deep by 0.76 m (30 In.) Wide Cabinet

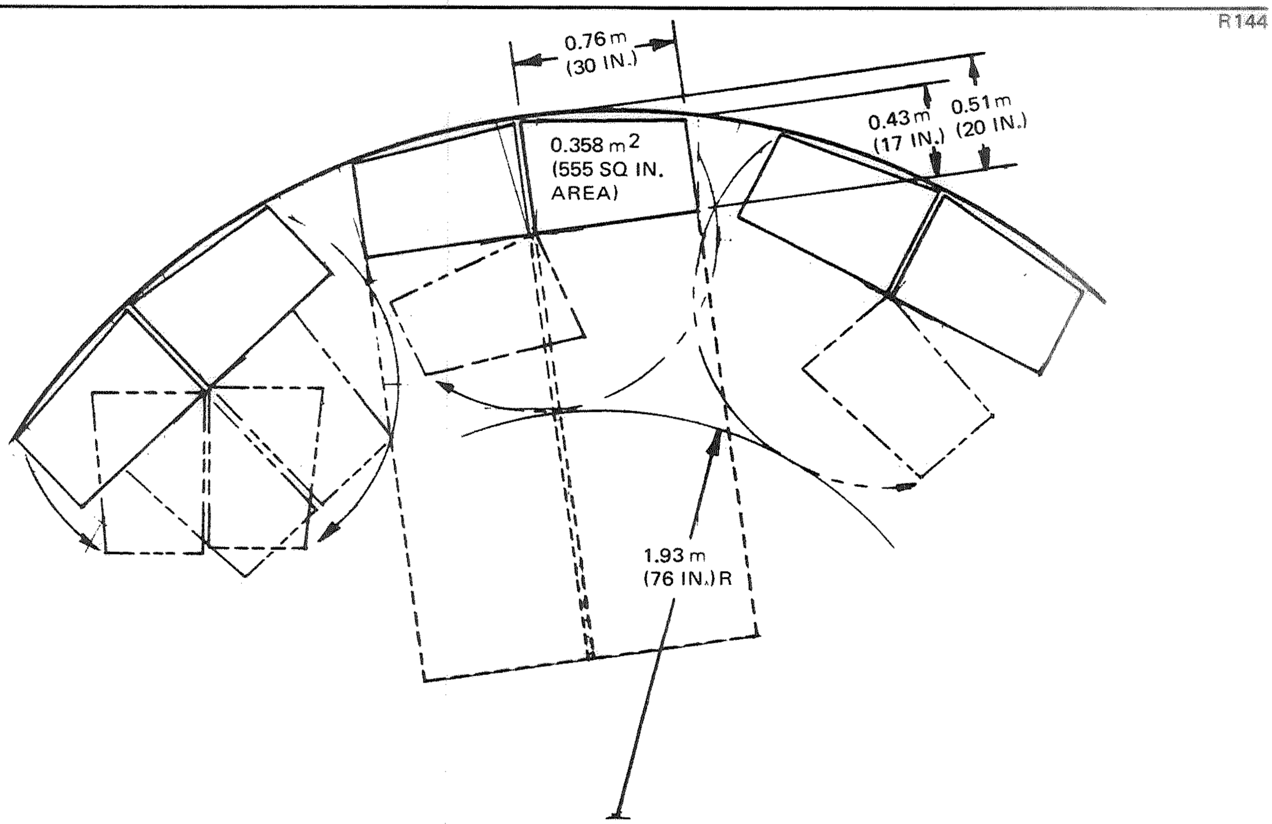

Figure 6-2. 6.7 m (22 Ft) Diameter Shell with 0.51 m (20 In.) Deep by 0.76 m (30 In.) Wide Cabinet

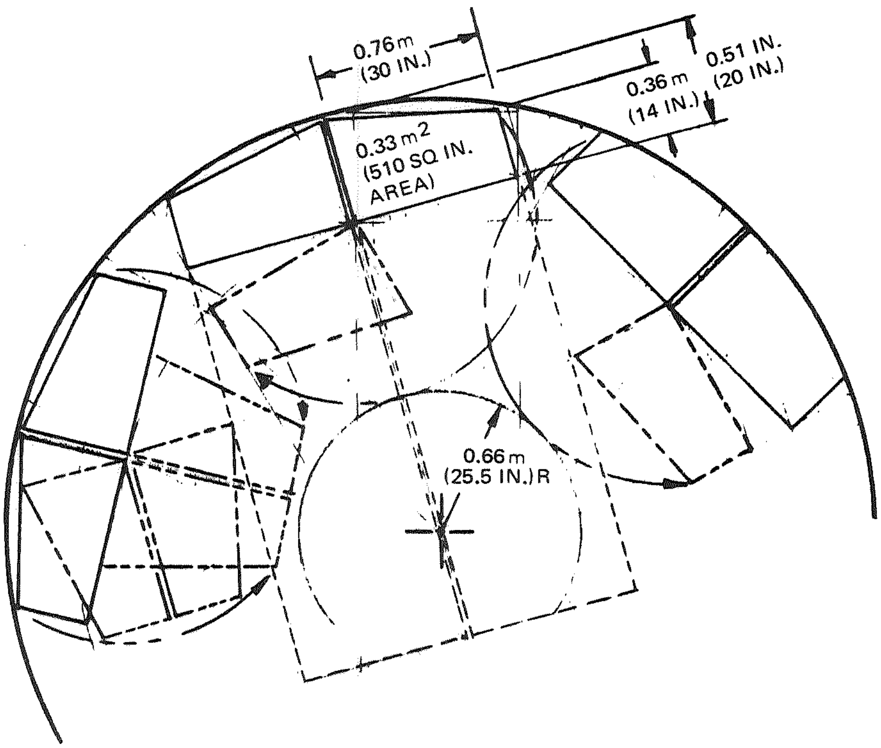

Figure 6-3. 4.27 m (14 Ft) Diameter Shell with 0.51 m (20 In.) Deep by 0.76 m (30 In.) Wide Cabinet

R144

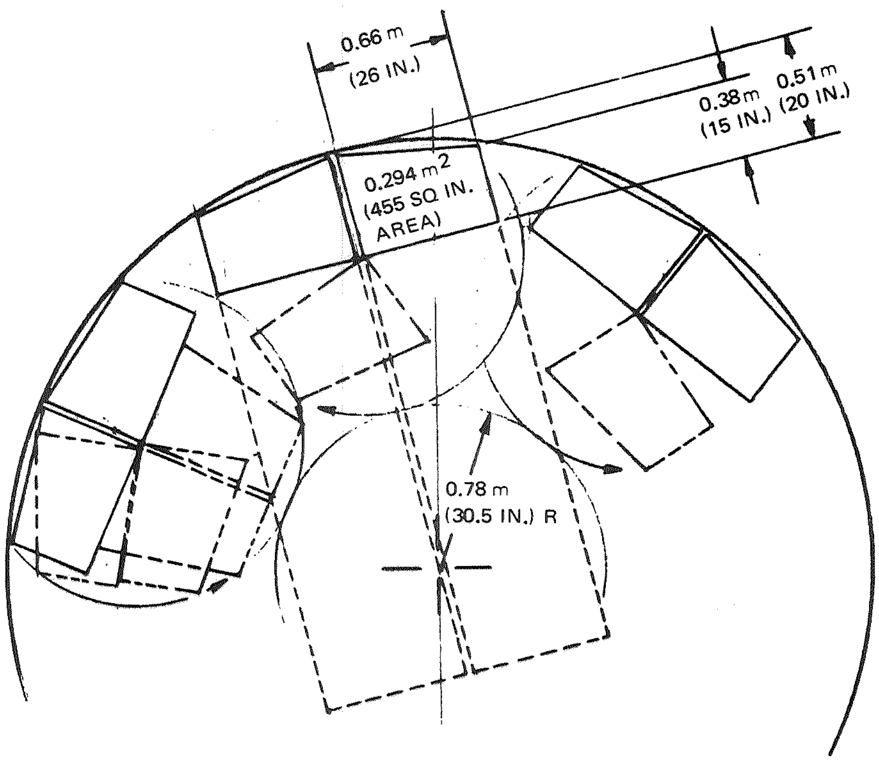

Figure 6-4. 4.27 m (14 Ft) Diameter Shell with 0.51 m (20 In.) Deep by 0.66 m (26 In.) Wide Cabinet

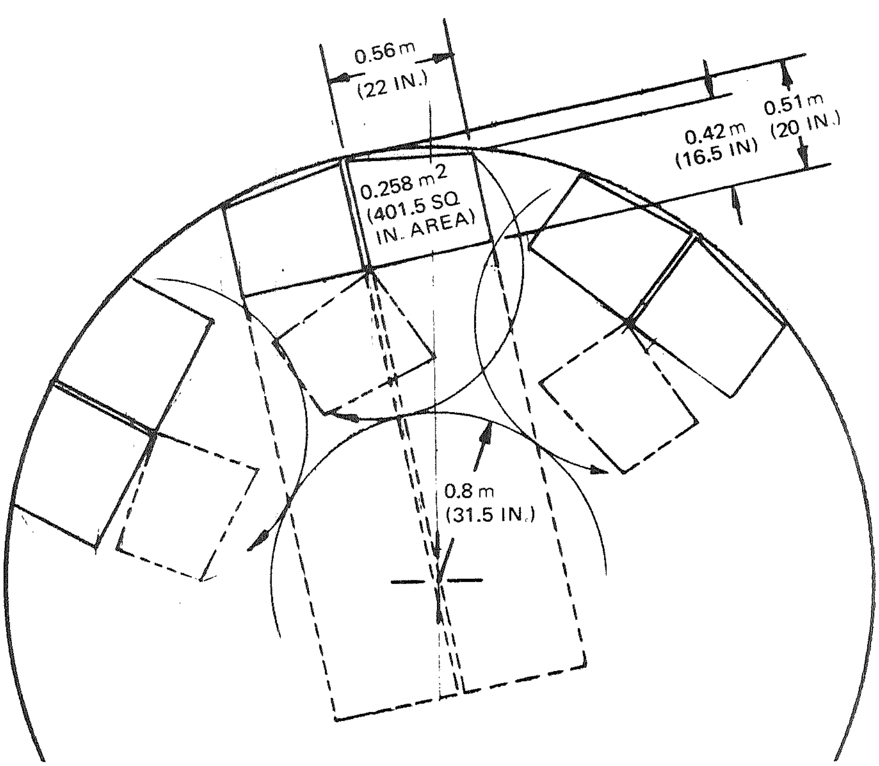

Figure 6-5. 4.27 m (14 Ft) Diameter Shell with 0.51 m (20 In.) Deep by 0.56 m (22 In.) Wide Cabinet

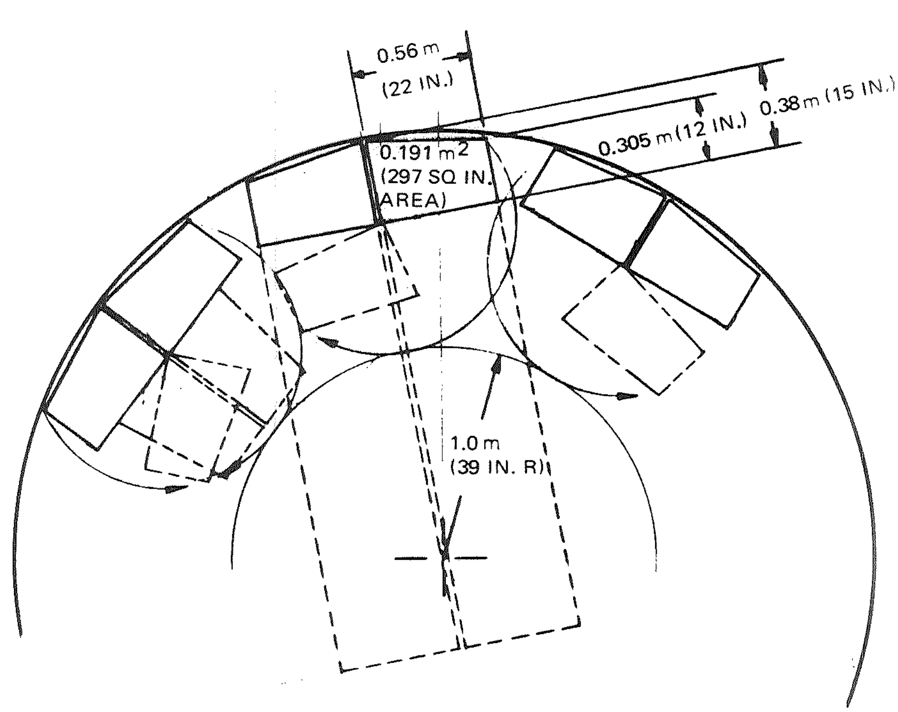

Figure 6-6. 4.27 m (14 Ft) Diameter Shell with 0.38 m (15 In.) Deep by 0.56 m (22 In.) Wide Cabinet

deep by 0.56 m (22 in.) wide cabinet in a 4.3 m (14 ft) dia shell appears to offer an acceptable storage area with the maximum living and working area.

Further detailed studies are recommended to optimize cabinet size and configurations in relation to trade parameters such as total storage space required, type of material to be stored, internal free area required, and weight associated with various size cabinets.

The use of any particular identified access method should be evaluated with respect to all factors influencing configuration layout and design. It is envisioned that the 4.3 m (14 ft) dia modular design and the orbiter design will of necessity employ a combination of access methods to ensure acceptable access for repair of pressure shell leaks. This study provides guidelines to ensure access to all portions of the pressure shell and vehicle systems with the least weight penalty and loss of crew time.

Section 7
LEAK REPAIR SYSTEMS STUDY

The objective of this task was the synthesis of repair systems (procedures, tools, materials) applicable to leak failures from vehicle systems and overboard leaks of atmospheric gases through holes in the vehicle pressure shell. The following approach was employed.

A. Define leak parameters, including fluid, container material, repair conditions, and crew hazards.

B. Define repair or replacement (R/R) methods compatible with the leak parameters and quantitatively evaluate their desirability.

C. Develop and define crew repair procedures employing specified repair methods and quantitatively evaluate their desirability.

D. Combine repair methods with suitable procedures to specify recommended leak repair systems.

The following ground rules are applicable to this study effort:

A. The 10.1 m (33 ft) dia Space Station, as defined by the parallel studies of MDAC and the Space Division of North American Rockwell Corporation, is used as a baseline to identify subsystems and their fluids.

B. Leak repair systems are restricted to onboard R/R at the component level or above (i.e., no repairs will be undertaken within components).

C. Leak detection and location capability is assumed to exist.

D. Leak isolation capability has been provided and has been activated (automatic, manual, or semiautomatic mode).

E. Leak passivation has occurred when the repair is initiated, that is, no hazard exists from pressure or temperature conditions. Toxicity and corrosivity of residual fluids may be an extant hazard.

F. All repair methods require manned activity.

G. Cure time refers to the duration required for an R/R method, once applied, to permit operational reactivation of the subsystem. For purposes of procedure evaluation, cure times are excluded from R/R time, although the maximum expected cure times are stated when applicable. Curing requires continued system downtime for that duration, but requires no further manned activity.

H. All R/R methods studied must be compatible with system operational conditions (e.g., temperature, pressure, corrosivity, or galvanic action).

I. Leak source fluids and materials are limited to those which reflect current Space Station concepts. Thus, certain alternative fluids and container materials which are under consideration as design improvements are not included in this study. Examples of these are Wescodyne (possible urine chemical pretreatment solution), hydrochloric acid (potential urine electrolytic pretreatment fluid), Hastalloy C (a high-nickel-content steel possessing superior corrosion resistance), titanium (high strength-to-weight ratio container material), and Freon (heat transfer medium).

J. This study will be limited to a generic evaluation of leak repair. Unless otherwise stated, evaluation of leak repair systems will be limited to an examination of feasibility and thus will avoid consideration of real or conceptual Space Station component positions and leak failure configurations, such as splits, jagged and irregular-sized openings, and invisible or hairline cracks.

7.1 IDENTIFICATION AND EVALUATION OF R/R METHODS

An R/R method remedies a leak once it has been detected and located and access has been provided. Table 7-1 provides an overview of all systems and subsystems currently conceived to be onboard the 10.1 m (33 ft) dia Space Station and identifies all fluids (gases or liquids) and their containers in each system. This table served as a starting point for the identification of R/R methods.

Table 7-1

LEAK SOURCES

System	Subsystem	Fluid	Container Material
EC/LS	O_2 Generation (Electrolysis)	H_2O	Stainless Steel or Plastic
		O_2	Stainless Steel or Plastic
		H_2	Stainless Steel or Plastic
		KOH	Stainless Steel or Plastic
	Wash Water Recovery (Multifiltration)	H_2O	Stainless Steel
	Potable Water Recovery (Vacuum Distillation)	Urine	Stainless Steel
		H_2O	Stainless Steel
		H_2SO_4	Stainless Steel
		CrO_3	Stainless Steel
		$CuSO_4$	Stainless Steel
	Atmosphere Control	O_2 } Air	Aluminum
		N_2 } Air	Aluminum
	Thermal Control	O_2 } Air	Aluminum
		N_2 } Air	Aluminum
		H_2O	Stainless Steel
	Humidity Control	O_2 } Air	Aluminum
		N_2 } Air	Aluminum
		H_2O	Stainless Steel
	CO_2 Removal (Molecular Sieve)	CO_2	Aluminum
		H_2O	Stainless Steel
		O_2 } Air	Aluminum
		N_2 } Air	Aluminum

Table 7-1

LEAK SOURCES (Continued)

System	Subsystem	Fluid	Container Material
EC/LS (Continued)	Toxin Control (Catalytic Burner)	O_2, N_2 } Air	Stainless Steel or Aluminum
	Sabatier Reactor	CH_4	Stainless Steel
		CO_2	Aluminum
		H_2O	Stainless Steel
		H_2	Stainless Steel
		O_2-traces	Aluminum
		N_2-traces	Aluminum
Reaction Control	Hypergolic (Monopropellant)	N_2H_4	Aluminum
		He	Aluminum
	Resistojet	H_2O	Aluminum
		CO_2	Aluminum
		CH_4	Aluminum
Structure	Pressure Hull	N_2, O_2 } Air	Aluminum, Fiberglass, Teflon
Docking Mechanism	Shock Absorber (Hydraulic)	Unknown	Unknown
	Latch Activator (Pneumatic)	Air?	Unknown
		He?	
Secondary Power*	Batteries (Nickel-Cadmium)	KOH	Stainless Steel

*Considered identical for study purposes to electrolysis subsystem of EC/LS system.

Table 7-2 summarizes available R/R methods which satisfy operational requirements. Although many R/R methods exist, not all are included in Table 7-2. Some were excluded because of an inherent lack of reliability, others because they were in an early or low developmental status, still others because they would impose large amounts of toxic or corrosive substances, and for other reasons relating to feasibility of use under zero-gravity and in semi-closed or closed ecological conditions. Examples of these include electron beam welding, soldering, and thermo-active plastics.

The evaluations of methods of leak repair were performed in the following manner. Nine criteria were identified which appeared to provide a basis for differentiating the various R/R methods and which could seriously affect subsystem performance. The criteria selected were: permanency, reliability, onboard weight, vehicle electrical power requirements, storage volume, requirements for use of special tools, cure time, shelf-life expectancy, and requirements for control of storage environment. These appear across the top of Table 7-2 and are fully defined in Table 7-3.

Within each criterion, subcategories or levels were established to permit evaluation using finer judgments. As an example, for the criterion of permanency, three levels were identified: H, highly permanent, or capable of functioning as a repair after application for one year or more; M, moderate, or capable of functioning for 6 to 12 months; and L, less permanent or capable of functioning for less than 6 months. Next, each criterion was assigned a value on a scale of importance from 1 to 5, with 1 being equivalent to minimum importance and 5 equivalent to maximum importance.

Importance was estimated on the basis of expected impact upon space system operations. For example, repair permanence and reliability were considered of greater importance than shelf life. Thus, shelf life was given a value of 1 while permanency and reliability were each rated 5.

These criterion values were considered to be weighting factors and were used in the determination of overall desirability in the following manner: for each fluid and container combination, applicable R/R methods were

Table 7-2. (Page 1 of 5)

EVALUATION OF REPAIR OR REPLACEMENT (R/R) METHODS

ID No.	Fluid	Container Material and Type	R/R Method	Evaluative Criteria: Permanency (5)	Reliability (5)	Weight (4)	Power (5)	Storage Volume (3)	Special Tools (3)	Cure Time (2)	Shelf Life (1)	Storage Environment (2)	Comments	Desirability of Method $D_{(M)}$
1	H_2O	Stainless tubing	Weld	H	H	M	Y	M	Y	L	H	VAC	Note 1	0.28
2	H_2O	Stainless tubing	Epoxy adhesive	M	M	L	N	L	Y	M	M	EC	Note 2	0.13
3	H_2O	Stainless tubing	Elastomer sealant	L	L	L	N	L	N	H	M	EC	Note 3	0.22
4	H_2O	Stainless valve	Replace	H	H	H	N	M	N	L	H	VAC	Note 4	0.60
5	H_2O	Stainless tank	Weld	H	H	M	Y	M	Y	L	H	VAC		0.28
6	H_2O	Stainless tank	Bolt and seal	H	H	M	N	M	Y	L	H	VAC	Seal of silicone or fluorel	0.44
7	H_2O	Stainless tank	Epoxy adhesive patch	H	M	L	N	L	Y	M	M	EC		0.23
8	H_2O	Stainless tank	Elastomer sealant	L	L	L	N	L	N	M	M	EC		0.22
9	H_2O	Stainless tank	Epoxy adhesive	L	L	L	N	L	N	M	M	EC		0.22
10	H_2O	Stainless condenser	Weld	H	H	M	Y	M	Y	L	H	VAC		0.28
11	H_2O	Stainless condenser	Bolt and seal	H	H	M	N	M	Y	L	H	VAC	Seal of silicone or fluorel	0.44
12	H_2O	Stainless condenser	Epoxy adhesive patch	H	M	L	N	L	Y	M	M	EC		0.25
13	H_2O	Stainless condenser	Elastomer sealant	L	L	L	N	L	N	M	M	EC		0.22
14	H_2O	Stainless condenser	Epoxy adhesive	L	L	L	N	L	N	M	M	EC		0.22
15	H_2O	Polyethylene tubing	Epoxy adhesive	L	L	L	N	L	N	L	M	EC		0.31
16	H_2O	Polyethylene tubing	Elastomer sealant	L	L	L	N	L	Y	M	M	EC		0.13
17	H_2O	Polysulfone tubing	Epoxy adhesive	L	L	L	N	L	N	L	M	EC		0.31
18	H_2O	Polysulfone tubing	Elastomer sealant	M	M	L	N	L	Y	M	M	EC		0.13
19														----
20	O_2	Stainless tubing	Weld	H	H	M	Y	M	Y	L	H	VAC	No residual fluid	0.28
21	O_2	Stainless tubing	Epoxy adhesive	M	M	L	N	L	Y	M	M	EC		0.13
22	O_2	Stainless tubing	Elastomer sealant	L	L	L	N	L	N	H	M	EC		0.22
23	O_2	Aluminum tubing	Weld	H	H	M	Y	M	Y	L	H	VAC	No residual fluid for medium-to-high pressure operations	0.28
24	O_2	Aluminum tubing	Epoxy adhesive	M	M	L	N	L	Y	M	M	EC		0.13
25	O_2	Aluminum tubing	Elastomer sealant	L	L	L	N	L	N	H	M	EC		0.22
26	O_2	Aluminum valve	Replace	H	H	H	N	M	N	L	H	VAC		0.60
27	O_2	Aluminum tank	Weld	H	H	M	Y	M	Y	L	H	VAC		0.28
28	O_2	Aluminum tank	Bolt and seal	H	H	M	N	M	Y	L	H	VAC	Seal of fluorel	0.44
29	O_2	Aluminum tank	Epoxy adhesive patch	M	M	L	N	L	Y	M	M	EC	For low pressure only	0.13
30	O_2	Aluminum walls	Epoxy adhesive patch	H	H	L	N	L	Y	M	M	EC		0.41

Table 7-2. (Page 2 of 5)

EVALUATION OF REPAIR OR REPLACEMENT (R/R) METHODS

ID No.	Fluid	Container Material and Type	R/R Method	Evaluative Criteria: Permanency (5)	Reliability (5)	Weight (4)	Power (5)	Storage Volume (3)	Special Tools (3)	Cure Time (2)	Shelf Life (1)	Storage Environment (2)	Comments	Desirability of Method $D_{(M)}$
31	O_2	Aluminum walls	Elastomer sealant	H	M	L	N	L	N	M	M	EC		0.37
32	O_2	Aluminum walls	Adhesive tape	L	L	L	N	L	N	L	M	EC	For low pressure only	0.31
33	O_2	Aluminum walls	Weld	H	H	M	Y	M	Y	L	H	VAC	No residual fluid	0.28
34	O_2	Polyethylene tubing	Epoxy adhesive	L	L	L	N	L	N	L	M	EC	See 15	0.31
35	O_2	Polyethylene tubing	Elastomer sealant	L	L	L	N	L	Y	M	M	EC	See 16	0.13
36	O_2	Polysulfone tubing	Same as H_2O	L	L	L	N	L	N	L	M	EC	See 17	0.31
37	O_2	Polysulfone tubing	Same as H_2O	M	M	L	N	L	Y	M	M	EC	See 18	0.13
38	O_2	Teflon seals	Replace	H	H	L	N	L	Y	L	H	VAC		0.40
39	O_2	Fiber glass ducts	Epoxy adhesive patch	H	H	L	N	L	N	M	H	EC		0.40
40	O_2	Fiber glass ducts	Elastomer sealant	H	M	L	N	L	N	M	H	EC		0.47
41	O_2	Fiber glass ducts	Adhesive tape	L	L	L	N	L	N	L	H	EC		0.40
42	H_2	Stainless tubing	Same as H_2O	H	H	M	Y	M	Y	L	H	VAC	See 1	0.28
43	H_2	Stainless tubing	Same as H_2O	M	M	L	N	L	Y	M	M	EC	See 2	0.13
44	H_2	Stainless tubing	Same as H_2O	L	L	L	N	L	N	H	M	EC	See 3	0.22
45	H_2	Stainless tanks	Same as O_2	H	H	M	Y	M	Y	L	H	VAC	See 27	0.28
46	H_2	Stainless tanks	Same as O_2	H	H	M	N	M	Y	L	H	VAC	See 28	0.44
47	H_2	Stainless tanks	Same as O_2	M	M	L	N	L	Y	M	H	VAC	See 29	0.13
48	H_2	Stainless valves	Same as H_2O	H	H	H	N	M	N	L	H	VAC	See 4	0.60
49	H_2	Polyethylene tubing	Same as H_2O	L	L	L	N	L	N	L	M	EC	See 15	0.11
50	H_2	Polyethylene tubing	Same as H_2O	L	L	L	N	L	Y	M	M	EC	See 16	0.13
51	H_2	Polysulfone tubing	Same as H_2O	L	L	L	N	L	N	L	M	EC	See 17	0.31
52	H_2	Polysulfone tubing	Same as H_2O	M	M	L	N	L	Y	M	M	EC	See 18	0.13
53	Hydrazine	Steel tubing	Weld	H	H	M	Y	M	Y	L	H	VAC	Requires solvent cleaning (MEK) (Freon) See 1	0.28
54	Hydrazine	Steel tubing	Epoxy adhesive patch	H	H	L	N	L	Y	M	M	EC	Requires solvent cleaning (MEK) (Freon) See 30	0.41
55	Hydrazine	Steel valves	Replace	H	H	H	N	M	N	L	H	VAC	Requires solvent cleaning (MEK) (Freon) See 4	0.60
56	Hydrazine	Steel tanks	Same as O_2	H	H	M	Y	M	Y	L	H	VAC	Requires solvent cleaning (MEK) (Freon) See 27	0.28
57	Hydrazine	Steel tanks	Same as O_2	H	H	M	N	M	Y	L	H	VAC	Requires solvent cleaning (MEK) (Freon) See 28	0.44

Table 7-2. (Page 3 of 5)

EVALUATION OF REPAIR OR REPLACEMENT (R/R) METHODS

ID No.	Fluid	Container Material and Type	R/R Method	Evaluative Criteria: Permanency (5)	Reliability (5)	Weight (4)	Power (5)	Storage Volume (3)	Special Tools (3)	Cure Time (2)	Shelf Life (1)	Storage Environment (2)	Comments	Desirability of Method $D_{(M)}$
58	Hydrazine	Steel tanks	Same as O_2	M	M	L	N	L	Y	M	H	VAC	See 29	0.13
59	N_2	Stainless ducts	Same as O_2	H	H	L	N	L	N	M	H	EC	See 39	0.40
60	N_2	Stainless ducts	Same as O_2	H	M	L	N	L	N	M	H	EC	See 40	0.47
61	N_2	Stainless ducts	Same as O_2	L	L	L	N	L	N	L	H	EC	See 41	0.40
62	N_2	Stainless valves	Same as O_2	H	H	H	N	M	N	L	H	VAC	See 4	0.60
63	N_2	Aluminum tubing	Same as O_2	H	H	M	Y	M	Y	L	H	VAC	See 1	0.28
64			Same as O_2	M	M	L	N	L	Y	M	M	EC	See 2	0.13
65			Same as O_2	L	L	L	N	L	N	H	M	EC	See 3	0.22
66	N_2	Aluminum valves	Same as H_2O	H	H	H	N	M	N	L	H	VAC	See 4	0.60
67	N_2	Aluminum ducts	Same as O_2	H	H	L	N	L	N	M	H	EC	See 39	0.40
68			Same as O_2	H	M	L	N	L	N	M	H	EC	See 40	0.47
69			Same as O_2	L	L	L	N	L	N	L	H	EC	See 41	0.40
70	N_2	Aluminum tanks	Same as O_2	H	H	M	Y	M	Y	L	H	VAC	See 27	0.28
71			Same as O_2	H	H	M	N	M	Y	L	H	VAC	See 28	0.44
72			Same as O_2	M	M	L	N	L	Y	M	M	EC	See 29	0.13
73	N_2	Aluminum walls	Same as O_2	H	H	L	N	L	Y	M	M	EC	See 30	0.41
74	N_2	Aluminum walls	Same as O_2	H	M	L	N	L	N	M	M	EC	See 31	0.37
75	N_2	Aluminum walls	Same as O_2	L	L	L	N	L	N	L	M	VAC	See 32	0.31
76	N_2	Aluminum walls	Same as O_2	H	H	M	Y	M	Y	L	H	VAC	See 33	0.28
77	N_2	Aluminum heat exchanger	Replace coils	H	H	H	N	H	Y	L	H	VAC	See 4	0.22
78	N_2	Aluminum heat exchanger	Weld	H	H	M	Y	M	Y	L	H	VAC	See 1	0.28
79	N_2	Aluminum heat exchanger	Epoxy adhesive	M	L	L	N	L	Y	M	M	EC	See 15	0.31
80	KOH	Polysulfone tubing	Replace	H	H	M	N	M	Y	L	M	VAC	Requires solvent cleaning (H_2O) See 4	0.22
81	KOH	Polysulfone tubing	Elastomer sealant	M	L	L	N	L	Y	M	M	EC	Requires solvent cleaning (H_2O) See 18	0.13
82	CH_4	Stainless tubing	Weld	H	H	M	Y	M	Y	L	H	VAC	No residual fluid. See 1	0.28
83	CH_4	Stainless tubing	Epoxy adhesive	M	M	L	N	L	Y	M	M	EC	See 2	0.13

Table 7-2. (Page 4 of 5)

EVALUATION OF REPAIR OR REPLACEMENT (R/R) METHODS

ID No.	Fluid	Container Material and Type	R/R Method	Evaluative Criteria: Permanency (5)	Reliability (5)	Weight (4)	Power (5)	Storage Volume (3)	Special Tools (3)	Cure Time (2)	Shelf Life (1)	Storage Environment (2)	Comments	Desirability of Method $D_{(M)}$
84	CH_4	Stainless tubing	Elastomer sealant	L	L	L	N	L	N	H	M	EC	See 3	0.22
85	CH_4	Stainless tubing	Elastomer sealant	M	M	L	N	L	Y	M	M	EC		0.14
86	CH_4	Stainless tubing	Epoxy adhesive	M	M	L	N	L	Y	M	M	EC		0.13
87	CH_4	Stainless valves	Replace	H	H	H	N	H	Y	L	H	VAC	See 4	0.60
88	Air (N_2, O_2)	Stainless tubing	Weld	H	H	M	Y	M	Y	L	H	VAC	See 20	0.28
89	Air (N_2, O_2)	Stainless tubing	Epoxy adhesive	M	M	L	N	L	Y	M	M	EC	See 21	0.13
90	Air (N_2, O_2)	Stainless tubing	Elastomer sealant	L	L	L	N	L	N	H	M	EC	See 22	0.22
91	Air (N_2, O_2)	Aluminum tubing	Weld	H	H	M	Y	M	Y	L	H	VAC	See 23	0.28
92	Air (N_2, O_2)	Aluminum tubing	Epoxy adhesive	M	M	L	N	L	Y	M	M	EC	See 24	0.13
93	Air (N_2, O_2)	Aluminum tubing	Elastomer sealant	L	L	L	N	L	N	H	M	EC	See 25	0.22
94	Air (N_2, O_2)	Aluminum valve	Replace	H	H	H	N	M	N	L	H	VAC	See 26	0.60
95	Air (N_2, O_2)	Aluminum tank	Weld	H	H	M	Y	M	Y	L	H	VAC	See 27	0.28
96	Air (N_2, O_2)	Aluminum tank	Bolt and seal	H	H	M	N	M	Y	L	H	VAC	See 28	0.44
97	Air (N_2, O_2)	Aluminum tank	Epoxy adhesive patch	M	M	L	N	L	Y	M	M	EC	See 29	0.13
98	Air (N_2, O_2)	Aluminum walls	Epoxy adhesive patch	H	H	L	N	L	Y	M	M	EC	See 30	0.41
99	Air (N_2, O_2)	Aluminum walls	Elastomer sealant	H	M	L	N	L	N	M	M	EC	See 31	0.37
100	Air (N_2, O_2)	Aluminum walls	Adhesive tape	L	L	L	N	L	N	L	M	EC	See 32	0.31
101	Air (N_2, O_2)	Aluminum walls	Weld	H	H	M	Y	M	Y	L	H	VAC	See 33	0.28
102	Air (N_2, O_2)	Polyethylene tubing	Epoxy adhesive	L	L	L	N	L	N	L	M	EC	See 34	0.31
103	Air (N_2, O_2)	Polyethylene tubing	Elastomer sealant	L	L	L	N	L	Y	M	M	EC	See 35	0.13
104	Air (N_2, O_2)	Polysulfone tubing	Same as H_2O	L	L	L	N	L	N	L	M	EC	See 36	0.31
105	Air (N_2, O_2)	Polysulfone tubing	Same as H_2O	M	M	L	N	L	Y	M	M	EC	See 37	0.13
106	Air (N_2, O_2)	Teflon seals	Replace	H	H	L	N	L	Y	L	H	VAC	See 38	0.80
107	Air (N_2, O_2)	Fiber glass ducts	Epoxy adhesive patch	H	H	L	N	L	N	M	H	EC	See 39	0.40
108	Air (N_2, O_2)	Fiber glass ducts	Elastomer sealant	H	M	L	N	L	N	M	H	EC	See 40	0.47
109	Air (N_2, O_2)	Fiber glass ducts	Adhesive tape	L	L	L	N	L	N	L	H	EC	See 41	0.40
110	CO_2	Aluminum tubing	As in N_2, H_2, and H_2O	H	H	M	Y	M	Y	L	H	VAC	See 1	0.28
111				M	M	L	N	L	Y	M	M	EC	See 2	0.13
112				L	L	L	N	L	N	H	M	EC	See 3	0.22

Table 7-2. (Page 5 of 5)

EVALUATION OF REPAIR OR REPLACEMENT (R/R) METHODS

				Evaluative Criteria										
ID No.	Fluid	Container Material and Type	R/R Method	Permanency (5)	Reliability (5)	Weight (4)	Power (5)	Storage Volume (3)	Special Tools (3)	Cure Time (2)	Shelf Life (1)	Storage Environment (2)	Comments	Desirability of Method $D_{(M)}$
113	CO_2	Aluminum valves	As in N_2, H_2, and H_2O	H	H	H	N	H	Y	L	H	VAC	See 4	0.60
114	CO_2	Aluminum tanks	As in N_2, H_2, and H_2O	M	H	L	N	L	Y	M	M	EC	See 30	0.41
115				H	M	L	N	L	N	M	M	EC	See 31	0.17
116				L	L	L	N	L	N	L	M	VAC	See 32	0.31
117				H	H	M	Y	M	Y	L	H	VAC	See 33	0.28
118	H_2SO_4 (with or without urine)	Stainless tubing	Weld	H	H	M	Y	M	Y	L	H	VAC	Flush with H_2O	0.28
119	H_2SO_4 (with or without urine)	Stainless tubing	Epoxy adhesive	L	L	L	N	L	Y	M	M	EC	Flush with H_2O	0.13
120	H_2SO_4 (with or without urine)	Stainless valves	Replace	H	H	H	N	M	N	L	H	VAC		0.60
121	H_2SO_4 (with or without urine)	Stainless tanks	Weld	H	H	M	Y	M	Y	L	H	VAC		0.28
122	H_2SO_4 (with or without urine)	Stainless tank	Bolt and Seal	H	H	L	N	L	Y	L	H	VAC	Seal must be Teflon	0.44
123	H_2SO_4 (with or without urine)	Stainless tanks	Epoxy adhesive patch	L	L	L	N	L	Y	M	M	EC		0.20
124	CrO_3 and $CuSO_4$ (with or without urine)	Stainless tubing	Same as H_2O	H	H	M	Y	M	Y	L	H	VAC	Flush with H_2O See 1	0.28
125		Stainless tubing	Same as H_2O	M	M	L	N	L	Y	M	M	EC	Flush with H_2O See 2	0.13
126		Stainless tubing	Same as H_2O	L	L	L	N	L	N	H	M	EC	Flush with H_2O See 3	0.22
127	CrO_3 and $CuSO_4$ (with or without urine)	Stainless valves	Same as H_2O	H	H	H	N	M	N	L	H	VAC	Flush with H_2O See 4	0.60
128	CrO_3 and $CuSO_4$ (with or without urine)	Stainless tanks	Same as H_2O	H	H	M	Y	M	Y	L			Flush with H_2O See 5	0.28
129		Stainless tanks	Same as H_2O	H	H	M	N	M	Y	L			Flush with H_2O See 6	0.44
130		Stainless tanks	Same as H_2O	H	M	L	N	L	Y	M			Flush with H_2O See 7	0.25
131		Stainless tanks	Same as H_2O	L	L	L	N	L	N	M			Flush with H_2O See 8	0.22
132		Stainless tanks	Same as H_2O	L	L	L	N	L	N	M			Flush with H_2O See 9	0.22

Notes:

1. Weld: for high O_2 concentrations or vacuum—electron beam, for Space Station environment—arc.
2. Epoxy adhesive—two part system—requires surface roughing.
3. Elastomer sealant—RTV silicone or polysulfide. Polysulfide preferable for nonmetallic substrates.
4. Repair below this level; e.g., valve seal replacement not considered.

Table 7-3

DEFINITION OF CRITERIA FOR EVALUATION OF R/R METHODS, $D_{(M)}$

Criterion	Weighting Factor	Subcategory Evaluation
Permanency	5	*H = 1 year or more
		M = 6 months to 1 year
		L = less than 6 months
Reliability	5	*H = Highly reliable
		M = Requires periodic monitoring
		L = Temporary - expect further R/R
Weight	4	H = more than 9 kg (20 lb)
		M = 2.3 kg (5 lb) to 9 kg (20 lb)
		*L = less than 2.3 kg (5 lb)
Power	5	Y = Requires vehicle electrical power
		*N = Requires no electrical power
Storage Volume	3	H = Requires more than 0.142 m^3 (5 ft^3) onboard
		M = Requires 0.028 m^3 (1 ft^3) to 0.142 m^3 (5 ft^3) onboard
		*L = Requires less than 0.28 m^3 (1 ft^3) onboard
Special Tools (Other than those normally provided onboard for periodic scheduled maintenance)	3	Y = Special Tool(s) Required
		*N = Special Tool(s) Not Required
Cure Time	2	H = Requires 24 hours or more
		M = Requires 4 to 24 hours
		*L = Requires less than 4 hours

Table 7-3

DEFINITION OF CRITERIA FOR EVALUATION OF R/R METHODS, $D_{(M)}$ (Continued)

Criterion	Weighting Factor	Subcategory Evaluation
Shelf Life	1	*H = 6 months to 1 year L = less than 6 months
Storage Environment	2	*VAC = Requires no environmental control EC = Requires environmental control

*Asterisked items are considered to be desirable and thus contribute toward the $D_{(M)}$ values noted in Table 7-2. All other evaluations make no numerical contribution toward the determination of desirability.

identified. Each method was then evaluated in terms of its expected performance within the Space Station and subcategory designations were assigned for each criterion. Certain subcategories were defined as desirable, while others were defined as of no desirability. As an example, taking the criterion of permanency with its subcategories of H, M, and L, it was decided that an evaluation of H was desirable for the Space Station, while any other evaluation was not desirable. Thus, if an R/R method were evaluated as H for permanency, it earned a desirability of 5, the weight for that criterion. If, however, it was judged to be M or L on permanency, it earned no desirability value whatsoever. The use of this system forces an exaggeration of desirability which was thought to be valuable to this analysis.

Once all criterion subcategory designations had been inserted, a count was made of the number of desirable criterion subcategories. This number, multiplied by the weighting factors for the associated criteria, provided a raw score for the desirability of the method for Space Station application. This was converted to a standard score (proportion) by dividing it by the total possible desirability raw score obtainable, which is a value of 270. The value obtained after division was entered as $D_{(M)}$, the desirability of the method.

Table 7-4 presents the mathematical formulas for the calculation of D applicable to methods, $D_{(M)}$. An analogous procedure applies to the calculation of D applicable to procedures, $D_{(P)}$. D is thus considered to be a mathematical index of desirability of methods and procedures assuming consensus on the selection of criteria for each.

Table 7-4

DESIRABILITY INDEX*

Calculation of R/R Method Evaluation Index

$$D_{(M)} = \frac{\Sigma c \times \Sigma w}{MPS} = \frac{RS}{MPS}$$

1. Σ Number of desirable criteria = Σc
2. Σ Weight factors of desirable criteria = Σw
3. $\Sigma c \times \Sigma w$ = Raw Score = RS
4. Divide RS by maximum possible score = MPS = 270

Example:

$$\Sigma c = 9$$

$$\Sigma w = 30$$

$$\Sigma c \times \Sigma w = 270 = RS$$

$$\frac{RS}{MPS} = \frac{270}{270} = 1.00 = D \text{ maximum } (M)$$

$$\frac{RS}{MPS} = \frac{0}{270} \quad 0.00 = D \text{ minimum } (M)$$

Range of $D_{(M)}$ = D max - D min = 1.00 - 0.00 = 1.00

*(M) subscript denotes applicability to R/R method. Subscripts differentiate D applicability. Desirability of R/R procedures is identified by $D_{(P)}$.

7.2 IDENTIFICATION AND EVALUATION OF R/R PROCEDURES

R/R Procedures are defined as the crew activities required to effectively utilize a valid R/R method. A valid R/R method has been defined as one which is evaluated at $D_{(M)}$ of 0.25 or above. Procedures were evaluated in a manner similar to R/R methods. Criteria used as a basis for evaluation were: number of crewmen required, requirements for special skills, presence of hazard necessitating the use of protective equipment, special preparation requirements, waste generation, and repair time requirements. Each criterion was further divided into the subcategories identified and defined in Table 7-5, weighting values from 1 to 5 were assigned, and the subcategories were ranked in terms of their desirability. The calculation of desirability of the procedure for orbital application ($D_{(P)}$) was accomplished in the same way as the $D_{(M)}$. $D_{(P)}$ thus provides a quantitative index of the desirability of each crew procedure.

Utilizing valid [$D_{(M)} > 0.25$] R/R methods from Table 7-2, Table 7-6 demonstrates the evaluation of applicable R/R procedures and provides a quantitative index of their desirabilities. ($D_{(P)}$) is based upon the weighted criteria defined in Table 7-5. Reference identification is seen to both R/R methods (Column 4) and to the detailed procedures (Column 5) which were developed for evaluation.

Crew procedures were developed as logical flows of activities required for men to accomplish an R/R operation. For each fluid and container combination, a sequential activity profile was developed which was consistent with an understanding of the method requirements, leak characteristics, and the operational capabilities of a crew. Fifty-two such procedure profiles were generated of which 11 illustrative examples are presented in Appendix D. These served as the basis for the procedure evaluations and $D_{(P)}$ determinations shown in Table 7-6. Each procedure is identified by a hyphenated number. The first number is identical to the fluid-container combination identification numbers first established in Table 7-2, while the number to the right of the hyphen reflects the category of procedure, e.g., Category 1 = weld, 2 = elastomer sealant, 3 = replacement, 4 = bolt and seal, 5 = epoxy

Table 7-5

DEFINITION OF CRITERIA FOR EVALUATION OF R/R PROCEDURES $D_{(P)}$

Criterion	Weighting Factor	Subcategory Evaluation
Number of Crewmen	5	H = 4 crewmen or more required M = 2 to 4 crewmen required *L = 1 crewman required
Special Crew Skills	2	Y = Special skills and training required *N = Special skills and training not required
Hazard - Protective Equipment	5	Y = Hazard to men or equipment exists. Special precautions or protective equipment required *N = No hazard
Special Preparations (solvent cleaning, surface etching, rounding, surface smoothing of protrusions, isolation, sanding, etc.)	2	Y = Requires unusual preparations *N = Requires no preparation
Special Testing	3	Y = Techniques other than visual inspection *N = Visual inspection only
Waste Material Generation	1	H = Requires special storage for waste generated M = Requires waste storage—no special storage conditions. *L = Generates no waste material

Table 7-5

DEFINITION OF CRITERIA FOR EVALUATION OF R/R PROCEDURES $D_{(P)}$ (Continued)

Criterion	Weighting Factor	Subcategory Evaluation
Repair Time (excluding sealant cure times, if any)	3	H = 20 minutes or more M = 15 to 20 minutes *L = less than 15 minutes

*These contribute toward the calculation of $D_{(P)}$ values. All other evaluations make no numerical contribution toward the determination of desirability.

adhesive, 6 = epoxy adhesive patch, and 7 = adhesive tape. Thus, for each category, one can by use of Tables 7-2 and 7-3, trace its R/R characteristics, evaluation considerations, and desirability.

7.3 REPAIR SYSTEM SYNTHESIS AND RESULTS

Repair systems are defined as an R/R method and the activities (procedures) necessary to accomplish leak repair. Methods and procedures are synthesized in Table 7-7 which provides an overview of the applicability of each of seven identified R/R systems to onboard Space Station leak failures. Table 7-7 provides repair system desirability index ($D_{(S)}$) values for each of the fluid-container combinations previously identified. $D_{(S)}$ was derived by multiplying previously determined $D_{(M)}$ and $D_{(P)}$ values. Identification numbers provided permit ready reference to more detailed information on specific leak situations as available in previous tables.

Table 7-8 represents a summary of R/R systems applicable to all hardware and fluids. It provides average desirability indices for methods and procedures used with each, and multiplying these indices, provides an average desirability index of the R/R system ($\overline{x}D_{(S)}$). Relative ranking of desirability indices for each of the methods ($R_{(M)}$) and procedures ($R_{(P)}$) is provided, as well as a ranking of the desirability of the repair system ($R_{(S)}$). Rankings are based upon the magnitude of the associated average desirability values shown. A rank of 1 is best, while 7 is worst.

Table 7-6
EVALUATION OF R/R PROCEDURES

ID No.	Fluid	Container Material and Type	R/R Method	Procedure ID No.	Criteria: No CM (5)	Spec Skills (2)	Hazard (5)	Spec Prep (2)	Spec Test Req (5)	Waste Matl Gen (1)	Repair Time (3)	$D_{(P)}$	Comments
1	H_2O	Stainless tubing	Weld	1-1	L	Y	Y	N	N	L	M	0.30	
4	H_2O	Stainless valve	Replace	4-3	L	N	N	N	N	M	M	0.58	
5	H_2O	Stainless tank	Weld	5-1	L	Y	Y	N	N	L	M	0.30	
6	H_2O	Stainless tank	Bolt and seal	6-4	M	Y	Y	Y	N	M	M	0.20	
10	H_2O	Stainless condenser	Weld	10-1	L	Y	Y	N	N	L	M	0.30	
11	H_2O	Stainless condenser	Bolt and seal	11-4	M	Y	Y	Y	N	M	M	0.20	
15	H_2O	Polyethylene tubing	Epoxy adhesive	15-5	L	N	Y	N	N	M	M	0.33	
17	H_2O	Polysulfone tubing	Epoxy adhesive	17-5	L	N	Y	N	N	M	M	0.33	
20	O_2	Stainless tubing	Weld	20-1	L	Y	Y	N	Y	L	H	0.16	
23	O_2	Aluminum tubing	Weld	23-1	L	Y	Y	N	Y	L	H	0.16	
26	O_2	Aluminum valve	Replace	26-3	L	N	N	N	Y	M	H	0.38	
27	O_2	Aluminum tank	Weld	27-1	L	Y	Y	N	Y	L	H	0.16	
28	O_2	Aluminum tank	Bolt and seal	28-4	M	Y	Y	Y	Y	L	M	0.01	
30	O_2	Aluminum walls	Epoxy adhesive patch	30-6	L	N	Y	Y	N	M	M	0.20	
31	O_2	Aluminum walls	Elastomer sealant	31-2	L	N	N	N	N	M	M	0.58	
32	O_2	Aluminum walls	Adhesive tape	32-7	L	N	N	Y	N	L	M	0.54	
33	O_2	Aluminum walls	Weld	33-1	L	Y	Y	N	N	L	M	0.30	
34	O_2	Polyethylene tubing	Epoxy adhesive	34-5	L	N	Y	N	Y	M	M	0.18	
36	O_2	Polysulfone tubing	Epoxy adhesive	36-5	L	N	Y	N	Y	M	M	0.18	
38	O_2	Teflon seals—walls	Replace	38-3	L	N	N	Y	N	M	M	0.41	
39	O_2	Fiber glass ducts	Epoxy adhesive patch	39-6	L	N	Y	Y	N	M	M	0.20	
40	O_2	Fiber glass ducts	Elastomer sealant	40-2	L	N	N	N	N	M	M	0.58	
41	O_2	Fiber glass ducts	Adhesive tape	41-7	L	N	N	N	N	L	M	0.73	
42	H_2	Stainless tubing	Weld	42-1	L	Y	Y	Y	Y	L	H	0.08	
45	H_2	Stainless tanks	Weld	45-1	L	Y	Y	Y	Y	L	H	0.08	
46	H_2	Stainless tank	Bolt and seal	46-4	M	Y	Y	Y	Y	L	H	0.01	
48	H_2	Stainless valve	Replace	48-3	L	N	N	N	Y	M	H	0.38	
49	H_2	Polyethylene tubing	Epoxy adhesive	49-5	L	N	Y	N	Y	L	M	0.27	
51	H_2	Polysulfone tubing	Epoxy adhesive	51-5	L	N	Y	N	Y	L	M	0.27	
53	Hydrazine (N_2H_4)	Steel tubing	Weld	53-1	L	Y	Y	Y	N	H	H	0.11	

Table 7-6

EVALUATION OF R/R PROCEDURES (Continued)

ID No.	Fluid	Container Material and Type	R/R Method	Procedure ID No.	Criteria: No CM (5)	Spec Skills (2)	Hazard (5)	Spec Prep (2)	Spec Test Req (5)	Waste Matl Gen (1)	Repair Time (3)	$D_{(P)}$	Comments
54	Hydrazine (N_2H_4)	Steel tubing	Epoxy adhesive patch	54-6	L	N	Y	Y	N	H	M	0.20	
55	Hydrazine (N_2H_4)	Steel valve	Replace	55-3	L	N	Y	N	N	H	M	0.33	
56	Hydrazine (N_2H_4)	Steel tank	Weld	56-1	L	Y	Y	Y	N	H	H	0.11	
57	Hydrazine (N_2H_4)	Steel tank	Bolt and seal	57-4	M	Y	Y	Y	N	H	H	0.02	
59	N_2	Stainless duct	Epoxy adhesive patch	59-6	L	N	Y	N	N	L	M	0.44	
60	N_2	Stainless duct	Elastomer sealant	60-2	L	N	N	N	N	L	M	0.73	
61	N_2	Stainless duct	Adhesive tape	61-7	L	N	N	N	N	L	M	0.73	
62	N_2	Stainless valve	Replace	62-3	L	N	N	N	N	L	M	0.73	
63	N_2	Aluminum tubing	Weld	63-1	L	Y	Y	N	N	L	M	0.30	
65	N_2	Aluminum tubing	Elastomer sealant	65-2	L	N	N	N	N	L	M	0.73	
66	N_2	Aluminum valve	Replace	66-3	L	N	N	N	N	L	M	0.73	
67	N_2	Aluminum duct	Epoxy adhesive patch	67-6	L	N	Y	N	N	L	M	0.44	
68	N_2	Aluminum duct	Elastomer sealant	68-2	L	N	N	N	N	L	M	0.73	
69	N_2	Aluminum duct	Adhesive tape	69-7	L	N	N	N	N	L	M	0.73	
70	N_2	Aluminum tank	Weld	70-1	L	Y	Y	N	N	L	M	0.30	
71	N_2	Aluminum tank	Bolt and seal	71-4	M	Y	Y	Y	N	H	M	0.02	
73	N_2	Aluminum wall	Epoxy adhesive patch	73-6	L	N	Y	Y	N	M	M	0.20	See Procedure 30-6
74	N_2	Aluminum wall	Elastomer sealant	74-2	L	N	N	N	N	M	M	0.58	See Procedure 31-2
75	N_2	Aluminum wall	Adhesive tape	75-7	L	N	N	Y	N	L	M	0.54	See Procedure 32-7
76	N_2	Aluminum wall	Weld	76-1	L	Y	Y	N	N	L	M	0.30	See Procedure 33-1
77	N_2	Aluminum heat exchanger	Replace	76-3	L	N	N	N	N	L	M	0.73	
78	N_2	Aluminum heat exchanger	Weld	78-1	L	Y	Y	N	N	L	M	0.30	
80	KOH	Polysulfone tubing	Replace	80-3	L	N	Y	Y	Y	H	H	0.07	
82	CH_4	Stainless tubing	Weld	82-1	L	Y	Y	N	Y	L	H	0.16	See Procedure 20-1
87	CH_4	Stainless valve	Replace	87-3	L	N	N	N	Y	M	H	0.38	See Procedure 26-3
88	Air (N_2,O_2)	Stainless tubing	Weld	88-1	L	Y	Y	N	Y	L	H	0.16	See Procedure 20-1
91	Air (N_2,O_2)	Aluminum tubing	Weld	91-1	L	Y	Y	N	Y	L	H	0.16	See Procedure 23-1

Table 7-6

EVALUATION OF R/R PROCEDURES (Continued)

ID No.	Fluid	Container Material and Type	R/R Method	Procedure ID No.	Criteria: No CM (5)	Spec Skills (2)	Hazard (5)	Spec Prep (2)	Spec Test Req (5)	Waste Matl Gen (1)	Repair Time (3)	$D_{(P)}$	Comments
94	Air (N_2,O_2)	Aluminum valve	Replace	94-3	L	N	N	N	Y	M	H	0.38	See Procedure 26-3
95	Air (N_2,O_2)	Aluminum tank	Weld	95-1	L	Y	Y	N	Y	L	H	0.16	See Procedure 27-1
96	Air (N_2, O_2)	Aluminum tank	Bolt and seal	96-4	M	Y	Y	Y	Y	L	M	0.01	See Procedure 28-4
98	Air (N_2, O_2)	Aluminum walls	Epoxy adhesive patch	98-6	L	N	Y	Y	N	M	M	0.20	See Procedure 30-6
99	Air (N_2,O_2)	Aluminum walls	Elastomer sealant	99-2	L	N	N	N	N	M	M	0.58	See Procedure 31-2
100	Air (N_2,O_2)	Aluminum walls	Adhesive tape	100-7	L	N	N	Y	N	L	M	0.54	See Procedure 32-7
101	Air (N_2,O_2)	Aluminum walls	Weld	101-1	L	Y	Y	N	N	L	M	0.30	See Procedure 33-1
102	Air (N_2,O_2)	Polyethylene tubing	Epoxy adhesive	102-5	L	N	Y	N	Y	M	M	0.18	See Procedure 34-5
104	Air (N_2,O_2)	Polysulfone tubing	Epoxy adhesive	104-5	L	N	Y	N	Y	M	M	0.18	See Procedure 36-5
106	Air (N_2,O_2)	Teflon seals—walls	Replace	106-3	L	N	N	Y	N	M	M	0.41	See Procedure 38-3
107	Air (N_2,O_2)	Fiber glass duct	Epoxy adhesive patch	107-6	L	N	Y	Y	N	M	M	0.20	See Procedure 39-6
108	Air (N_2,O_2)	Fiber glass duct	Elastomer sealant	108-2	L	N	N	N	N	M	M	0.58	See Procedure 40-2
109	Air (N_2,O_2)	Fiber glass duct	Adhesive tape	109-7	L	N	N	N	N	L	M	0.73	See Procedure 41-7
110	CO_2	Aluminum tubing	Weld	110-1	L	Y	Y	Y	Y	L	H	0.30	See Procedure 63-1
113	CO_2	Aluminum valve	Replace	113-3	L	Y	Y	Y	Y	L	H	0.73	See Procedure 66-3
117	CO_2	Aluminum tank	Weld	117-1	M	Y	Y	Y	Y	L	H	0.16	See Procedure 27-1
118	H_2SO_4 (with or without urine)	Stainless tubing	Weld	118-1	L	Y	Y	Y	Y	H	H	0.03	
120	H_2SO_4 (with or without urine)	Stainless valve	Replace	120-3	L	N	Y	N	N	H	M	0.33	See Procedure 55-3
121	H_2SO_4 (with or without urine)	Stainless tank	Weld	121-1	L	Y	Y	Y	N	H	H	0.11	See Procedure 56-1

Table 7-6

EVALUATION OF R/R PROCEDURES (Continued)

ID No.	Fluid	Container Material and Type	R/R Method	Procedure ID No.	Criteria: No CM (5)	Criteria: Spec Skills (2)	Criteria: Hazard (5)	Criteria: Spec Prep (2)	Criteria: Spec Test Req (5)	Criteria: Waste Matl Gen (1)	Criteria: Repair Time (3)	$D_{(P)}$	Comments
122	H_2SO_4 (with or without urine)	Stainless tank	Bolt and seal	122-4	M	Y	Y	Y	N	H	H	0.02	See Procedure 57-4
124	CrO_3 and $CuSO_4$ (with or without urine)	Stainless tubing	Weld	124-1	L	Y	Y	Y	N	H	H	0.11	See Procedure 53-1
127	CrO_3 and $CuSO_4$ (with or without urine)	Stainless valve	Replace	127-3	L	N	Y	N	N	H	M	0.33	See Procedure 55-3
128	Urine	Stainless tank	Weld	128-1	L	Y	Y	N	N	L	M	0.30	See Procedure 5-1
129	Urine	Stainless tank	Bolt and seal	129-4	M	Y	Y	Y	N	M	M	0.20	See Procedure 6-4
130	Urine	Stainless tank	Epoxy adhesive patch	130-6	L	N	N	N	N	L	M	0.58	

Table 7-7

REPAIR SYSTEM SYNTHESIS

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
		NO. 1 WELD				
Stainless Tubing	H_2O	1	1-1	0.28	0.30	0.08
	O_2	20	20-1	0.28	0.16	0.04
	H_2	42	42-1	0.28	0.08	0.02
	CH_4	82	82-1	0.28	0.16	0.04
	Air	88	88-1	0.28	0.16	0.04
	H_2SO_4	118	118-1	0.28	0.03	0.01
	CrO_2 & $CuSO_4$	124	124-1	0.28	0.11	0.03
Stainless Tank	H_2O	5	5-1	0.28	0.30	0.08
	H_2	45	45-1	0.28	0.08	0.02
	H_2SO_4	121	121-1	0.28	0.11	0.03
	Urine	128	128-1	0.28	0.30	0.08
Stainless Condenser	H_2O	10	10-1	0.28	0.30	0.08
Aluminum Tubing	O_2	23	23-1	0.28	0.16	0.04
	N_2	63	63-1	0.28	0.30	0.08
	Air	91	91-1	0.28	0.16	0.04
	CO_2	110	110-1	0.28	0.30	0.08
Aluminum Tank	CO_2	117	117-1	0.28	0.16	0.04
	O_2	27	27-1	0.28	0.16	0.04
	N_2	70	70-1	0.28	0.30	0.08
	Air	95	95-1	0.28	0.16	0.04
Aluminum Wall	O_2	33	33-1	0.28	0.30	0.08
	N_2	76	76-1	0.28	0.30	0.08
	Air	101	101-1	0.28	0.30	0.08
Aluminum Heat Exch	N_2	78	78-1	0.28	0.30	0.08
Steel Tubing	N_2H_4	53	53-1	0.28	0.11	0.03
Steel Tank	N_2H_4	56	56-1	0.28	0.11	0.03
Mean				0.28	0.20	0.05

Table 7-7

REPAIR SYSTEM SYNTHESIS (Continued)

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
			NO. 2–ELASTOMER SEALANT			
Aluminum Wall	O_2	31	31-2	0.37	0.58	0.21
	N_2	74	74-2	0.37	0.58	0.21
	Air	99	99-2	0.37	0.58	0.21
Stainless Duct	N_2	60	60-2	0.60	0.73	0.44
Fiber Glass Duct	O_2	40	40-2	0.47	0.58	0.27
	Air	108	108-2	0.60	0.58	0.35
Aluminum Tubing	N_2H_4	65	65-2	0.22	0.73	0.16
Aluminum Duct	N_2	68	68-2	0.60	0.73	0.44
Aluminum Wall	N_2	74	74-2	0.37	0.58	0.21
Mean				0.44	0.63	0.28

Table 7-7

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(M)}$	$D_{(S)}$
			NO. 3—REPLACE			
Stainless Valve	H_2O	4	4-3	0.60	0.58	0.35
	H_2	48	48-3	0.60	0.38	0.23
	N_2	62	62-3	0.60	0.73	0.44
	CH_4	87	87-3	0.60	0.38	0.23
	H_2SO_4	120	120-3	0.60	0.33	0.20
	CrO_3 & $CuSO_4$	127	127-3	0.60	0.33	0.20
Aluminum Valve	O_2	26	26-3	0.60	0.38	0.23
	N_2	66	66-3	0.60	0.73	0.44
	Air	94	94-3	0.60	0.38	0.23
	CO_2	113	113-3	0.60	0.73	0.44

Table 7-7

REPAIR SYSTEM SYNTHESIS (Continued)
NO. 3—REPLACE

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
Teflon Seals—Wall	O_2	38	38-3	0.80	0.41	0.33
	Air	106	106-3	0.80	0.41	0.33
Steel Valve	N_2H_4	55	55-3	0.60	0.33	0.20
Aluminum Heat Exchanger	N_2	77	77-3	0.44	0.73	0.32
Polysulfone Tubing	KOH	80	80-3	0.35	0.07	0.02
Mean				0.60	0.46	0.28

Table 7-7

NO. 4—BOLT AND SEAL

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
Stainless Tank	H_2O	6	6-4	0.44	0.20	0.09
	H_2	46	46-4	0.44	0.01	less than 0.01
	H_2SO_4	122	122-4	0.44	0.02	0.01
	Urine	129	129-4	0.44	0.20	0.09
Stainless Condenser	H_2O	11	11-4	0.44	0.20	0.09
Aluminum Tank	O_2	28	28-4	0.44	0.01	less than 0.01
	Air	96	96-4	0.44	0.01	less than 0.01
	N_2	71	71-4	0.44	0.02	0.01

Table 7-7

REPAIR SYSTEM SYNTHESIS (Continued)
NO. 4—BOLT AND SEAL

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
Steel Tank	N_2H_4	57	57-4	0.44	0.02	0.01
Mean				0.44	0.08	0.04

Table 7-7 (e)

REPAIR SYSTEM SYNTHESIS (Continued)
NO. 5—EPOXY ADHESIVE

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
Polyethylene Tubing	H_2O	15	15-5	0.31	0.33	0.10
	O_2	34	34-5	0.31	0.18	0.06
	H_2	49	49-5	0.31	0.27	0.08
	Air	102	102-5	0.31	0.18	0.06
Polysulfone Tubing	H_2O	17	17-5	0.31	0.33	0.10
	O_2	36	36-5	0.31	0.18	0.06
	H_2	51	51-5	0.31	0.27	0.08
	Air	104	104-5	0.31	0.18	0.06
Mean				0.31	0.24	0.08

Table 7-7 (f)

REPAIR SYSTEM SYNTHESIS (Continued)
NO. 6—EPOXY ADHESIVE PATCH

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
Aluminum Wall	O_2	30	30-6	0.41	0.20	0.08
	N_2	73	73-6	0.41	0.20	0.08
	Air	98	98-6	0.41	0.20	0.08

Table 7-7

REPAIR SYSTEM SYNTHESIS (Continued)
NO. 6—EPOXY ADHESIVE PATCH

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
Fiber Glass Ducts	O_2 Air	39 107	39-6 107-6	0.40 0.40	0.20 0.20	0.08 0.08
Steel Tubing	N_2H_4	54	54-6	0.41	0.20	0.08
Stainless Duct	N_2	59	59-6	0.62	0.44	0.27
Aluminum Duct	N_2	67	67-6	0.62	0.44	0.27
Stainless Tank	Urine	130	130-6	0.25	0.58	0.14
Mean				0.44	0.30	0.13

Table 7-7 (g)

REPAIR SYSTEM SYNTHESIS (Continued)
NO. 7—ADHESIVE TAPE

Container Material and Type	Fluid	Method ID No.	Procedure ID No.	$D_{(M)}$	$D_{(P)}$	$D_{(S)}$
Aluminum Walls	O_2 N_2 Air	32 75 100	32-7 75-7 100-7	0.31 0.31 0.31	0.54 0.54 0.54	0.16 0.16 0.16
Fiber Glass Ducts	O_2 Air	41 109	41-7 109-7	0.40 0.40	0.73 0.73	0.29 0.29
Stainless Ducts	N_2	61	61-7	0.40	0.73	0.29
Aluminum Ducts	N_2	69	69-7	0.40	0.73	0.29
Mean				0.36	0.65	0.23

Table 7-8

R/R SYSTEM EVALUATION SUMMARY

No.	Type	Methods $\bar{x}\ D_{(M)}$	$R_{(M)}$	Procedures $\bar{x}\ D_{(P)}$	$R_{(P)}$	Repair System $\bar{x}\ D_{(S)}$	$R_{(S)}$
1	Weld	0.28	7	0.20	6	0.05	6
2	Elastomer Sealant	0.44	2	0.63	2	0.28	1
3	Replace	0.60	1	0.46	3	0.28	1
4	Bolt and Seal	0.44	2	0.08	7	0.04	7
5	Epoxy Adhesive	0.31	6	0.24	5	0.08	5
6	Epoxy Adhesive Patch	0.44	2	0.30	4	0.13	4
7	Adhesive Tape	0.36	5	0.65	1	0.23	3

7.3.1 Methods

Table 7-8 shows that the best available leak repair method is replacement of the defective component ($R_{(M)} = 1$). Where replacement is not feasible or otherwise undesirable, elastomeric sealants or epoxy adhesive patches ($R_{(M)} = 2$) are the preferred repair methods for those fluid-container combinations permitting this approach. A version of the patch concept is shown in Figure 7-1. For remaining fluid-container combinations, an equally desirable repair method is the bolt and seal approach, utilizing a silicone or fluorel seal and a metallic bolt insert ($R_{(M)} = 2$).

Least desirable of the methods is arc-welding ($R_{(M)} = 5$). Its low desirability index reflects its anticipated requirements for significant vehicle electrical power, lift-off weight, and onboard storage volume.

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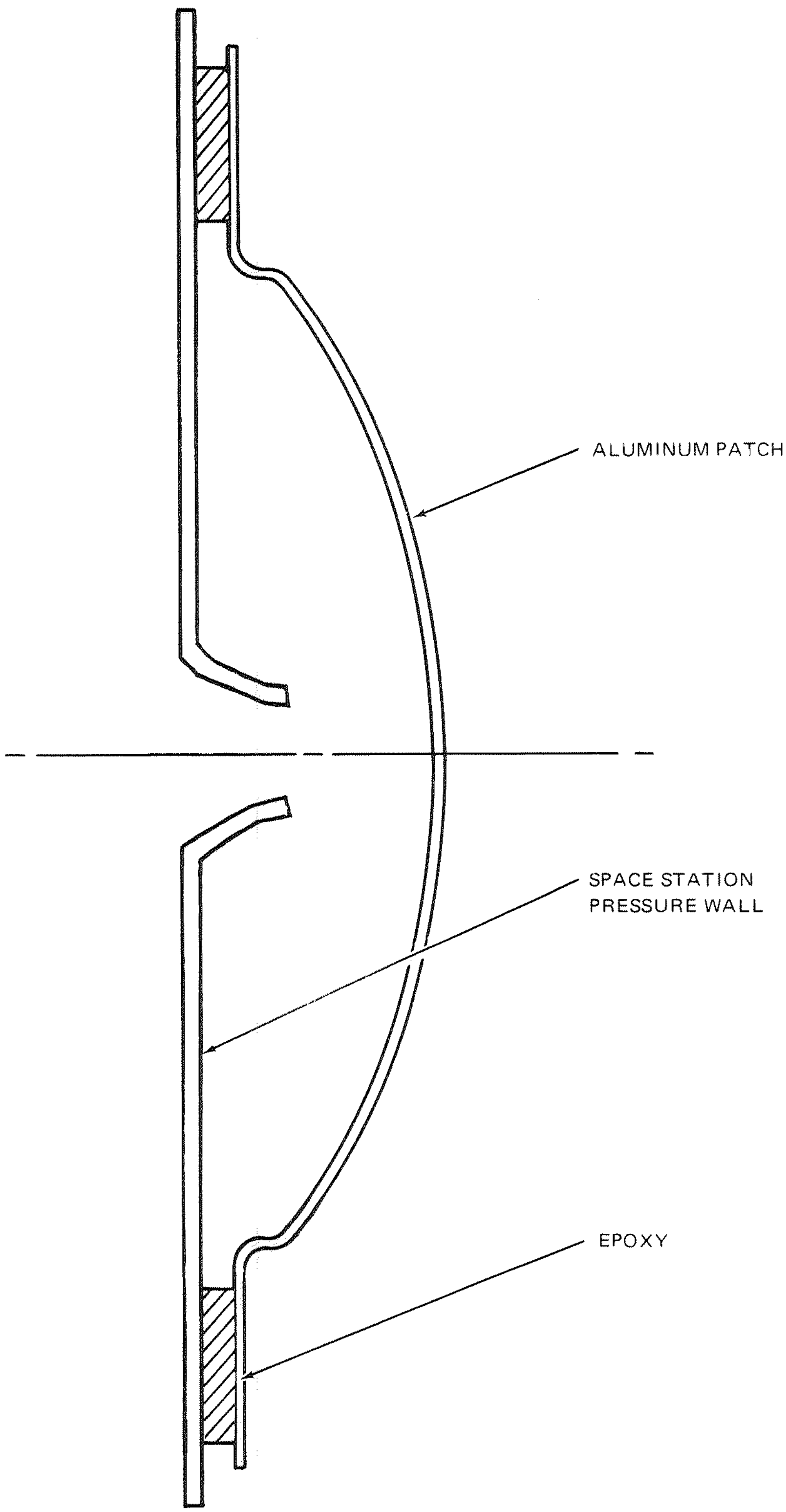

Figure 7-1. Blister Patch Concept for Space Station Pressure Wall

7.3.2 Procedures

Table 7-8 shows that the greatest procedural desirability ($R_{(P)} = 1$) is in the application of adhesive tape which reflects its simplicity. It is undesirable as a method for space systems because of low permanency and reliability. The second alternative procedure ($R_{(P)} = 2$) is the application of an elastomeric sealant, which appears highly desirable because of its relative ease of application. A major drawback to the use of such sealants is significant cure times of up to 24 hours. During cure, systems would be inoperative. Thus, the applicability of elastomers is seriously abridged despite desirability from both the methods and procedures standpoints.

Replacement appears as the next desirable alternative, but of course, is limited again by feasibility for space operations.

Of markedly lower desirability, the next procedural alternative is the use of an epoxy adhesive patch. This is applicable to a wide variety of container materials and fluids, but cannot be readily applied to a wide variety of container configurations. While applicable to pressure hulls and ducting which present flat surfaces for repair, it is not applicable to tubing or other containers possessing more complex surface geometries. The desirable alternative seems to be epoxy adhesive. While overcoming the limitations in applicability of epoxy adhesive patches, epoxy adhesive still suffers from deficiencies in permanency, reliability, and requirements for environmental control during storage, as shown in Table 7-2.

Least desirable from a procedural standpoint is the bolt and seal approach because of its procedural complexity and requirements for special skills and unusual surface preparation. For a description of the bolt and seal procedure, see Procedure 6-4 in Appendix D which is typical of the activities necessary for the accomplishment of a bolt and seal repair.

7.3.3 Systems

On an absolute basis, no one repair system is more than 28 percent desirable for space application. This is a serious potential problem for the repair of onboard leaks on the Space Station by crew members. The two systems exhibiting a 28 percent desirability or a ranking of repair system of $R_{(S)} = 1$ are the use of component replacement and the application of elastomeric sealants.

Somewhat less desirable, but still acceptable, is the use of adhesive tape ($R_{(S)} = 3$), despite low permanency and reliability. The use of this repair system presupposes the willingness to undertake continued periodic leak monitoring of the repair site and will require repeated utilization until a more permanent repair is achieved.

Least desirable of the repair systems are welding ($R_{(S)} = 6$) and bolt and seal ($R_{(S)} = 7$). These are seriously impaired by procedural considerations or methodological difficulties.

7.4 RECOMMENDED SYSTEM DEVELOPMENT

The findings lead to the inescapable conclusion that leak repair systems currently available for Space Station use are less than satisfactory. Their deficiencies relate to procedural difficulties, methodological shortcomings, and limited commonality. It is recommended that repair systems as defined in this study be considered only as secondary systems for Space Station use. Reliance should first be placed on approaches which tend to minimize the probability of leaks, then upon design redundancy for critical system functions, and lastly upon R/R systems.

If leak probability reduction and redundancy cannot be provided or are minimally available, then R/R systems could be relied upon if additional effort is expended in their development. Such development should center upon eliminating difficulties in the repair systems offering the greatest potential commonality for fluid-container combinations. This study indicates that arc-welding has the greatest potential commonality, but is somewhat deficient from both a methods and procedures standpoint. Efforts in welding should thus be directed toward reducing power, size, and special tool requirements and minimizing special skills and hazard protection requirements of future crews.

In the realm of repair systems for nonmetallic containers, development effort might best be spent on epoxy adhesive systems whose major limitations stem from inadequacies in permanency, reliability, and cure time requirements.

The ground rules used in the present study suggest that the results be used with some caution. To improve the applicability of this study to future space systems, it is recommended that a more detailed and comprehensive study effort be undertaken which considers the following aspects: (1) specific leak configurations, (2) procedural time demands, (3) newer container materials, (4) alternative fluids, (5) leak repair response time requirements and (6) full pressure suit operations necessitated by rapid response time situations.

Section 8
DAMAGE CONTROL SYSTEM PRELIMINARY DESIGN

The principal consideration in the preliminary design of the DCS is to provide a compatible interface with the established Space Station design concept. The Phase B Space Station concept (10.1 m dia), as well as the modular design show no significant differences in the method of integration of the DCS. The logical method of integration of the DCS function is through the onboard checkout system, which has the overall responsibility for inflight checkout and fault isolation for all Space Station subsystems and experiments. The following sections present an overview of the preferred approach for the design of the Space Station onboard checkout system and a more detailed examination of the integration of the selected DCS into the onboard checkout system.

8.1 DESCRIPTION OF THE ONBOARD CHECKOUT SYSTEM

The objectives of the baseline onboard checkout system (OCS) design approach are (1) to improve crew confidence and safety by presenting immediate indications of out-of-tolerance conditions in critical subsystems; (2) to ascertain maintenance needs and ensure compliance, and (3) to provide a viable system by requiring an inherent flexibility in the design to accommodate growth and changes in both hardware and software. Item (1) above is accomplished by providing a continuous monitor of life and mission critical functions, alerting the crew through caution and warning indicators when the situation warrants, and by providing automatic safing when there is insufficient time for crew intervention. Item (2) is accomplished by providing a fast, accurate assessment of subsystem performance with isolation of faults to the lowest replaceable unit (LRU) level. Item (3) is accomplished by integrating experiments and subsystems through the use of standard modular interface units as well as providing a capability to generate checkout procedures and software changes on-line to adapt to changing conditions.

The OCS design approach for the Space Station is a highly user-oriented system with maximum automation. The system is designed to minimize crew intervention in routine checkout functions, but provides for a cooperative effort when the capabilities of the crew are needed. The design takes maximum advantage of the data management system capability for data acquisition, distribution, displays, processing, storage, and software.

8.1.1 Data Acquisition

Two methods are used in the OCS for data acquisition. One method is called indirect and is typical of equipment which contains internal data-formatting circuitry such as special test and monitoring circuitry or an integral dedicated data processor. Direct data acquisition is utilized when the equipment does not contain this capability. In this case, the test points or transducer outputs are connected directly to a standard interfacing module which is referred to as a remote data acquisition unit (RDAU). The principal circuits in the RDAU, shown in Figure 8-1 are: (1) a 32-channel analog multiplexer which is controlled by the channel sequencer and selects the channel of interest, (2) a programmable gain amplifier which adapts to the gain levels stored for each analog multiplexer channel, (3) an A-D converter which changes the analog input signal to digital format, (4) a digital comparator circuit which performs high and low limit checking between the incoming data and stored limits, and (5) the input/output buffer which receives command messages from the data bus terminal and is used to transmit data words back to the data bus terminal under direction of the control logic. In addition to the analog channels, the RDAU can also accept 32 digital inputs (logic 0 or logic 1 functions). These inputs are also checked in the comparator for changes with respect to their stored nominal level.

Operation of the RDAU is under control of the OCS processor which transmits control information via the data bus subsystem. A standard word format containing the address of the appropriate RDAU and an instruction code are used for control. Several modes of operation are provided, including a compare mode in which each input channel is scanned sequentially and

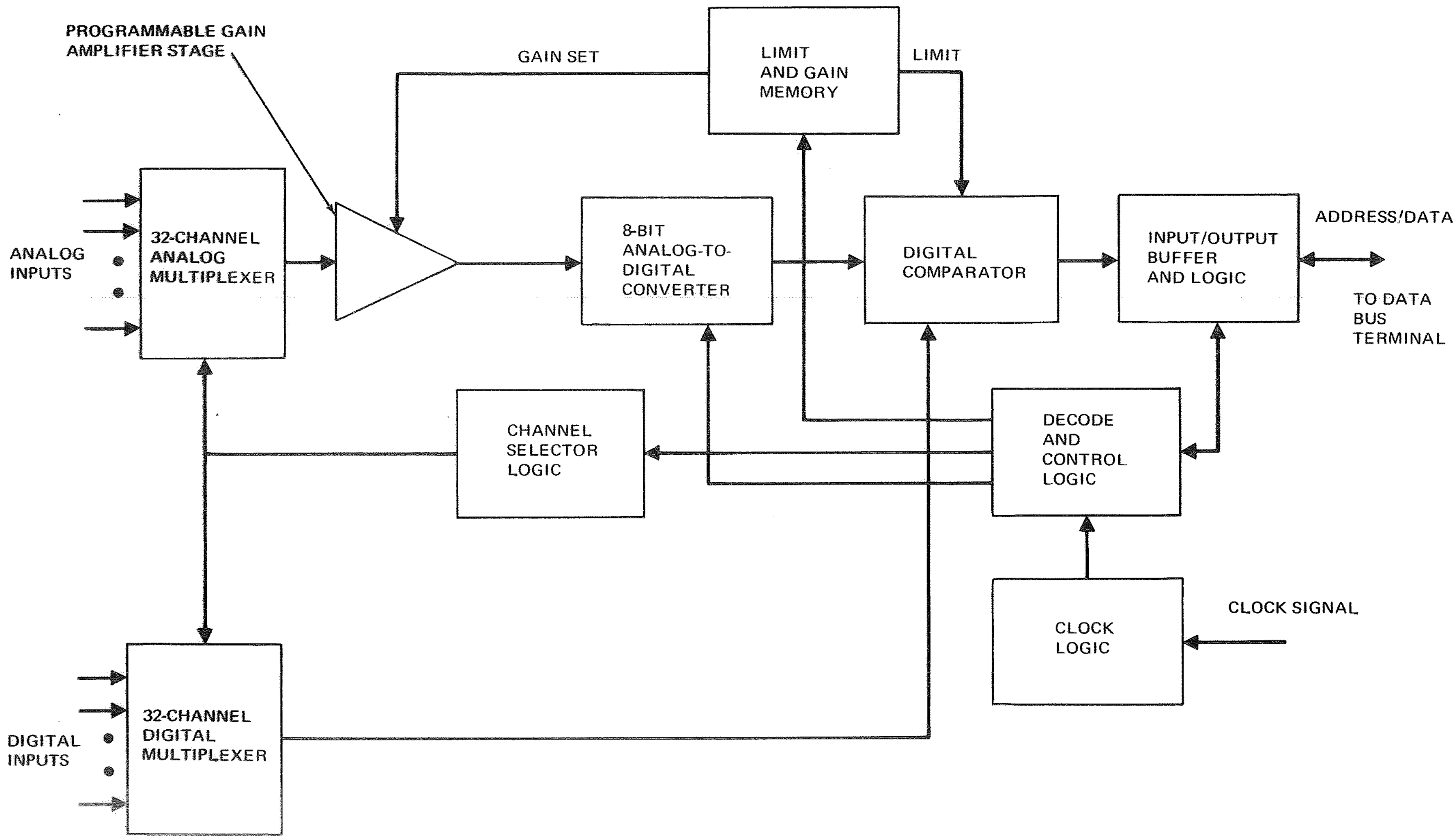

Figure 8-1. Remote Data Access Unit Block Diagram

compared to its stored limits. If an error is detected, a message is formatted for transmission to the OCS processor. The stored limits are under control of the processor and can be altered as required to accommodate changing conditions. A sequential output mode of operation is also provided where the limit checks are inhibited and the binary coded output of each channel is transmitted to the OCS processor for further analysis or storage. The RDAU can also be operated in a single-channel output mode where data from a specific channel is transmitted (once or repetitively, as desired).

8.1.2 Stimuli Generation

The following conclusions have resulted from the Space Station Phase B studies:

A. At present, requirements can be identified for only a few specialized stimuli.

B. The design approach will provide flexibility for future growth and changes.

C. Test stimuli should be located near the using equipment and made integral to the equipment where possible.

D. External sources will be supplied when built-in stimuli are not practical or a common use can be identified.

8.1.3 Data Distribution

The data bus system has been selected to perform the data distribution for the Space Station. It has been determined that the OCS data distribution requirements are relatively simple with respect to the data management subsystem (DMS). In addition, the DMS and OCS frequently require access to common data points; therefore, a shared data bus system for the DMS and OCS is preferred. The main data bus system consists of a coaxial cable and a combined time division-frequency division multiplexing scheme. The OCS digital data information is time-multiplexed onto a specified carrier frequency, which is then frequency multiplexed with other carriers on the common bus system. It is expected that the OCS command and control signals and measurement data will be partitioned by use of separate carriers which will allow full duplex operation. Provisions for clock synchronization will be made through a separate clock carrier or the use of self-clocking codes.

The data bus terminal shown in block diagram form in Figure 8-2 provides the interface between the data bus and all other systems. This unit has the capability to transmit specific commands to any or all of its terminated devices (e.g., RDAU's, displays, or processors) through its input/output switching unit. It also provides 512-bit buffer storage for accommodating data that is to be transmitted to the data bus. This feature is included to accommodate irregular data rates; it provides a means of assembly of data for block transfer to the bus.

8.1.4 Processing

Data processing and control for the OCS are accomplished in the subsystem control computer and the subsystem backup/experiment computer. These units are part of the DMS and contain the executive programs which control the OCS data acquisition and perform the arithmetic, logic, and analysis required to detect malfunctions, control reconfiguration, and prepare data for storage and display updates. Operation of the data transfer from terminal to processor will be accomplished through a polling mode; that is, each data terminal will respond with data only when requested by the supervisory program. The data transfer sequence will be as follows:

A. An encoded command from the supervisory program to the terminal via the data bus requesting status.
B. A response from the terminal to the supervisor indicating status.
C. A command from the supervisor to the terminal to initiate data transfer.
D. The data transfer from terminal to supervisor.

8.1.5 Storage

The bulk storage capability of the DMS is also shared with the OCS. The selected subsystem uses ultra-high-density magnetic tape recording techniques and is designed to meet large-volume data storage requirements with a relatively slow access time. This storage subsystem will be used

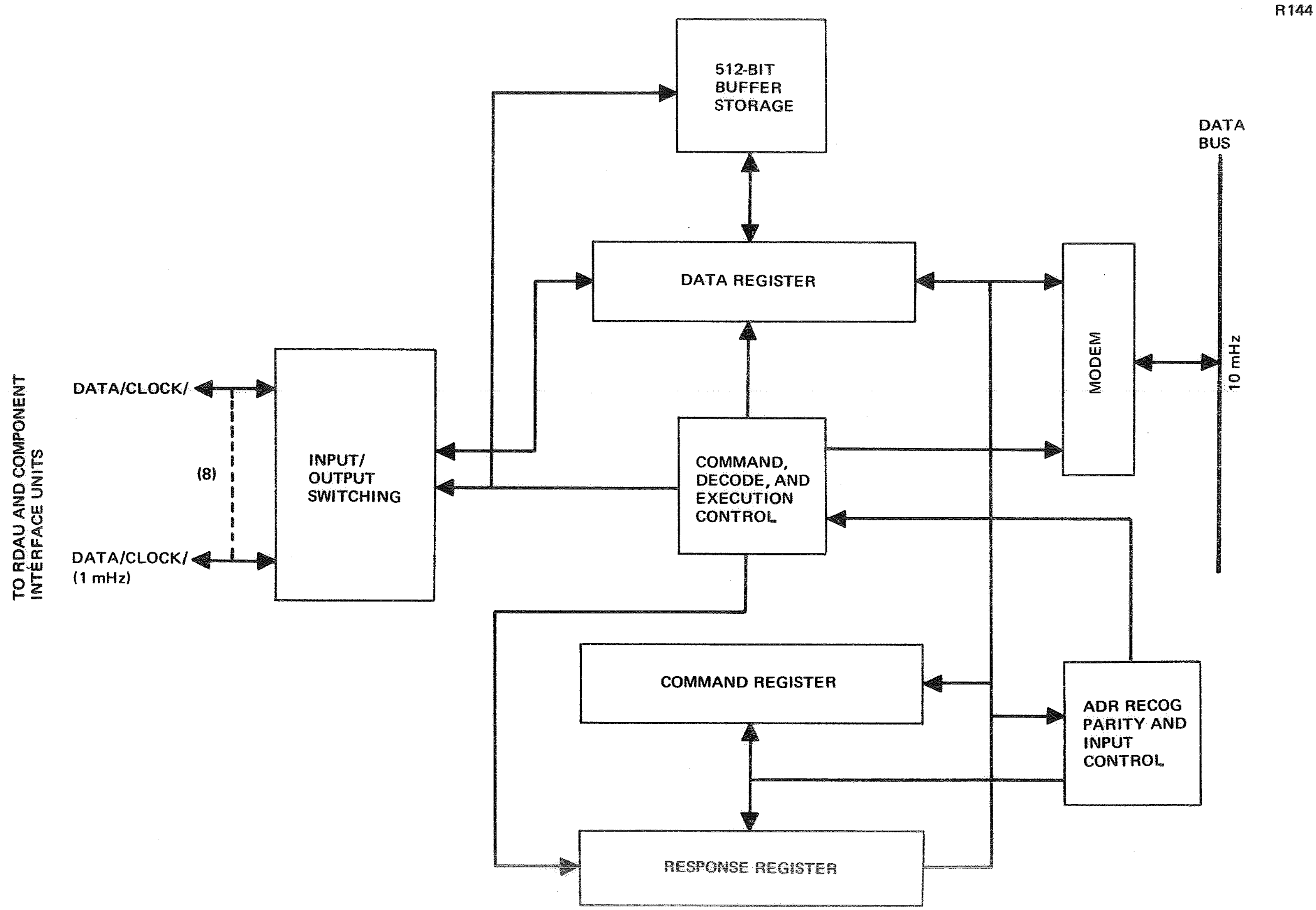

Figure 8-2. Data Bus Terminal Block Diagram

primarily for recording digital data before onboard processing or before return to ground station for processing. The data storage is under control of the DMS computer. Data from various subsystems and locations are tagged and stored in addressed locations. Access to data from the memory location upon a command initiated by the DMS computer.

8.1.6 Display and Control

Onboard checkout display and control requirements have been reviewed as part of the Phase B Space Station study. The conclusions indicate that OCS and operational controls and displays should be located at a central location. The position of these units shall be such that during normal operation, a single crew member can observe OCS displays and maintain access to the OCS switches and keyboard inputs while maintaining operational control; however, sufficient space will be provided for optional two-man operation (one at OCS controls and one at operational controls) during critical periods. Provisions are made in the Space Station design for a primary control center and a backup secondary control center located in an area maintained by an independent EC/LS system. The key features of the display and control console are as follows:

A. Dedicated displays are provided for high-priority functions such as the caution and warning signals.

B. The primary display device is a cathode ray tube which presents alphanumeric and graphic information pertinent to subsystem, mission, and experiment operation.

C. Control functions are provided by keyboards and multi-mode switching arrays.

A concept of a Space Station command and control center is shown in Figure 8-3. The block diagram shown in Figure 8-4 shows how a typical cathode ray tube display system, using local memory, interfaces with the DMS through the data bus distribution system.

8.1.7 Caution and Warning

The primary requirement of the OCS is to continuously monitor and provide status indications of all life support and mission parameters that are defined

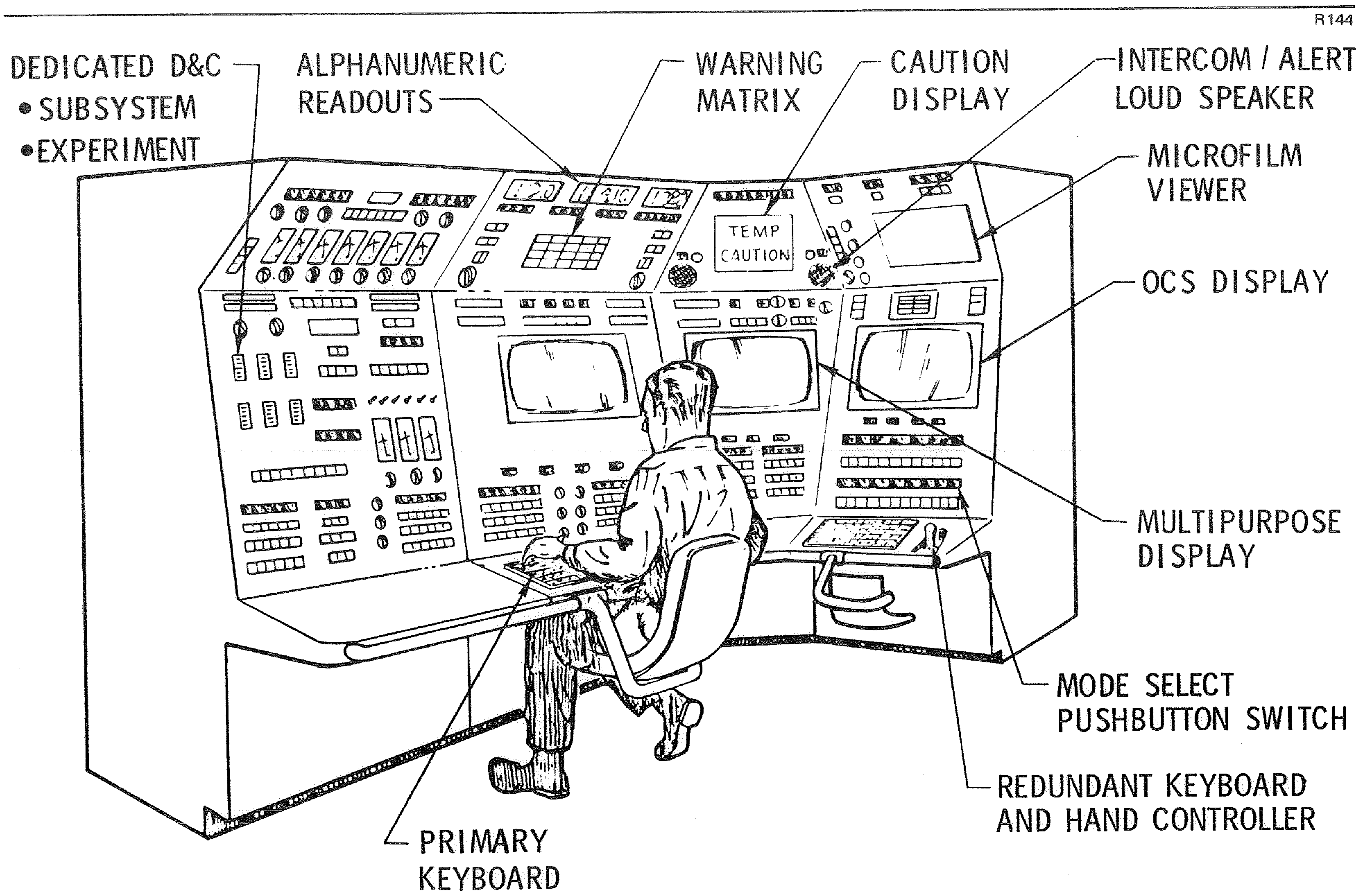

Figure 8-3. Command and Control Center

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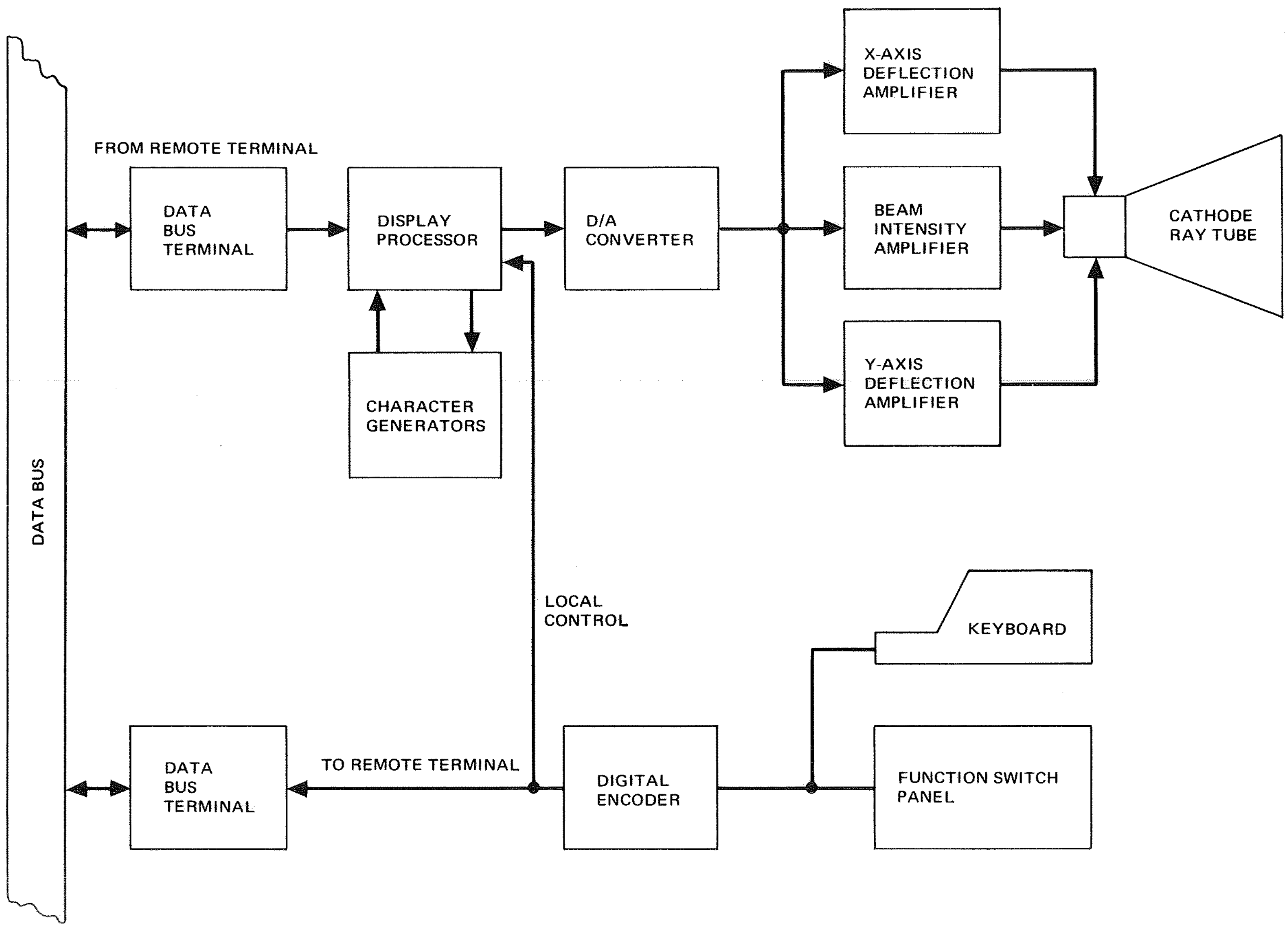

Figure 8-4. Space Station Control and Display Block Diagram

as critical. Two levels of alarm have been defined for the Space Station. Warning level alerts are activated when out-of-tolerance conditions are detected which indicate an immediate threat to crew life. Examples of these include: (1) a rapid decay of atmospheric pressure, (2) fire, and (3) high levels of toxic contaminants. Caution level alerts are to be displayed whenever immediate crew action is necessary to prevent major degradation of Space Station performance. Caution level functions are derived from the analysis of sensor outputs which might indicate, for example, (1) increased fire or explosion hazard, (2) excessive nitrogen or oxygen resupply rate, (3) excessive humidity, (4) high or low cabin temperature levels, or (5) rising CO_2 level. Analysis of the overall Phase B Space Station system caution and warning requirements have been made. The results were that approximately 135 caution functions and 15 warning functions are identified.

Integration of the caution and warning level signals into Space Station displays has been considered. The preferred method used to convey caution level information to the crew members is through the use of dedicated display panels capable of presenting alphanumeric messages. A typical panel contains 8 rows of 32 characters each. Each character is presented in a 5 by 7 dot matrix format. The panel display unit contains the electronics including drivers, memory, timing, and character generators as well as the parallel plate, gas discharge type display. There are three advantages to this type display: (1) information is displayed in English language message rather than a coded format on the source of the malfunction, (2) as many as five or six individual messages can be displayed simultaneously when required, and (3) the physical characteristics of this type of display are attractive with respect to the amount of information transferred. Warning level information will be conveyed by means of dedicated lights which will be redundantly located at the primary and secondary control centers as well as locally. A tone or audible attention-getting signal will also be generated to ensure crew response. The identification of the warning sources is not considered essential since they are few, and the crew reaction will be the same regardless of the cause—retreat to the tunnel or other designated safe area and don space suit.

8.2 INTEGRATION OF SELECTED DCS SYSTEM INTO THE OCS

The following sections contain the descriptions of the data acquisition process between selected DCS subsystems and the preferred Phase B Space Station baseline OCS. Also included is an analysis of the requirements of the DCS and the estimated impact of this system on the overall Space Station design. The emphasis is on providing insight into the systems integration problem.

Signal conditioning and preprocessing requirements are discussed in this section for the selected DCS. Sensors include (1) the two-gas atmosphere controller for nitrogen gas use rate, (2) the impact gage array for detecting and locating meteoroid-type impacts on the inner pressure shell, (3) the acoustic emission sensors which monitor formation growth of flaws or microcracks in solid material (pressure shell) under stress, (4) the seal leak detectors which monitor leaks across seals due to improper seating or degradation, (5) the active ultrasonics subsystems which utilize an array of transponder-receivers to locate flaws or cracks in the pressure shell structure, and (6) the onboard leak subsystem based on the Space Station EC/LS system as a typical representation.

8.2.1 Data Acquisition Requirements

8.2.1.1 Two-Gas Atmosphere Controller

As discussed previously, the nitrogen gas resupply rate can be used to detect an onboard nitrogen gas or overboard atmosphere leak. Changes in the nitrogen resupply rate can also be analyzed to determine the order of magnitude of the leak.

Planned atmospheric losses will be known. Verification will be obtained during initial operation of the Space Station. Therefore, the pulse rate modulated two-gas atmosphere control system will normally admit a fixed number of pulses per hour. Short-term anomalies such as those due to temperature cycling will be known and allowances made for the nitrogen resupply rate monitor. The following is a description of a method of acquiring data based upon a modification of the two-gas atmosphere controller used in the 90-day manned space simulation test (Reference 17).

The nitrogen resupply rate can be monitored by adding an accumulator circuit to the basic pulse rate modulated two-gas atmosphere controller. This accumulator is assumed to be incorporated into the controller design and the input and output signal requirements are as shown in the block diagram of Figure 8-5. The basic operation is as follows:

A. A high limit check is controlled by an 8-bit binary word arbitrarily called LIMIT. The value of LIMIT is determined by operator input or by program control, and is input to the two-gas controller from the subsystem multiprocessor via the data bus and data terminal.

B. The LIMIT input word is stored in a latch register in the controller. The contents of this register are used to reset the accumulator during the normal limit check cycle.

C. The integrator reset pulses from the nitrogen channel of the controller are used to increment the accumulator. If the input pulse rate exceeds the value determined by LIMIT, a TERMINAL COUNT output is generated. This output is the digital input to a RDAU. If no TERMINAL COUNT occurs, the accumulator resets and begins counting input pulses for the next cycle. This operation results in a continuous upper limit monitoring of the nitrogen gas resupply rate.

D. When a TERMINAL COUNT is input to the RDAU, the subsystem multiprocessor is notified via the standard Space Station interface (the RDAU to data bus terminal to data bus to multiprocessor). The multiprocessor then sends an instruction word to the gas controller through the data bus terminal. The accumulator is then reset to zero (rather than the LIMIT used for upper limit monitoring) and permitted to count for one timing period. At the end of this timing period, the accumulator contains the nitrogen gas resupply rate integrated over the period. This information

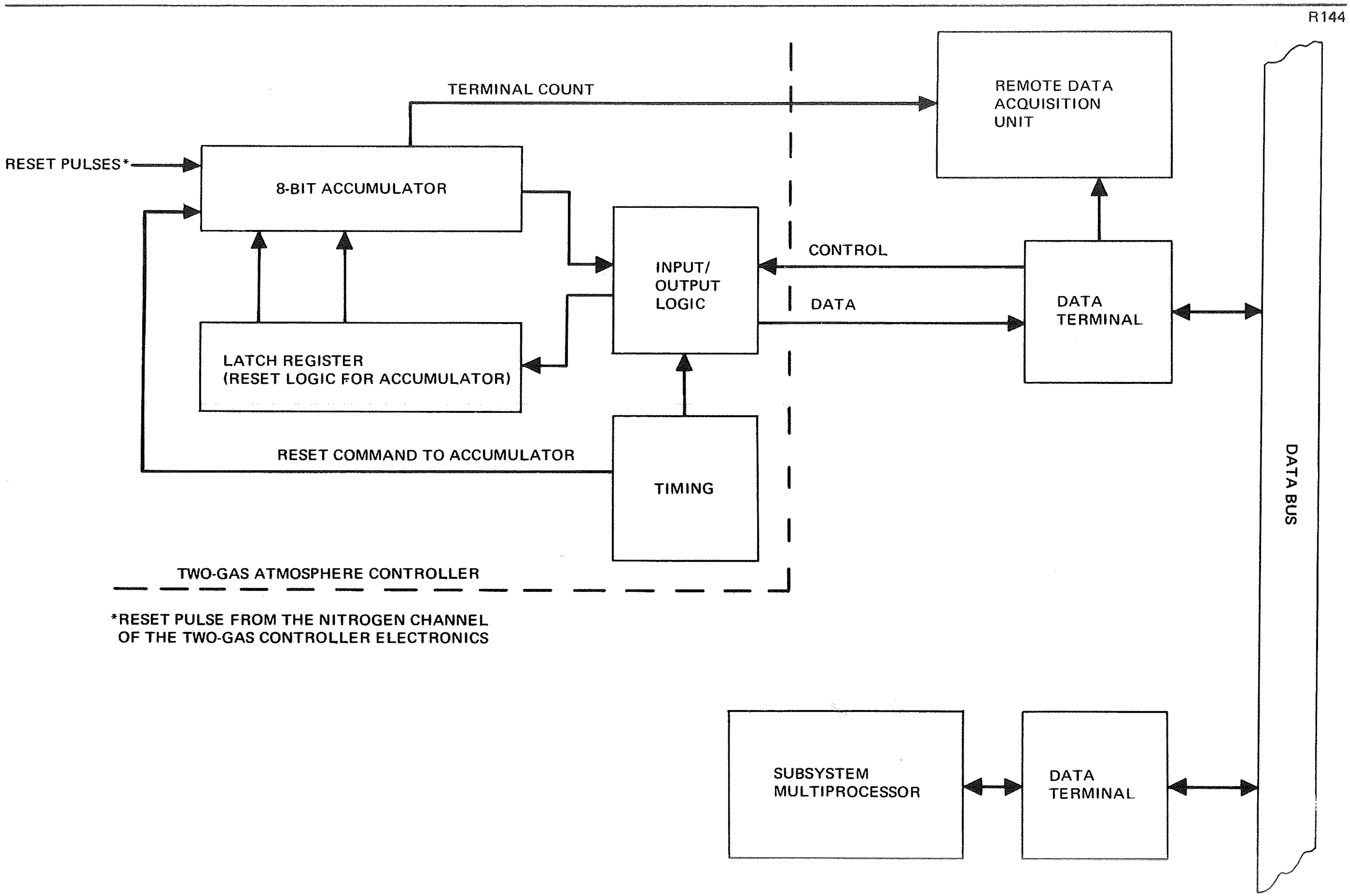

Figure 8-5. System Block Diagram for Acquistion of Data from Two-Gas Controller

is formatted into a data word which is transmitted to the multiprocessor via the data bus terminal. Operation in the continuous monitor mode is then restored if desired. The LIMIT word may be the same as before or a new LIMIT based upon analysis of the present nitrogen resupply rate may be input by the multiprocessor.

E. Periodically, the main checkout program will request data on the nitrogen resupply rate. These data are acquired for the multiprocessor in the same manner as described above. The data acquired from this routine will be checked for lower limit (internal nitrogen leak evaluation). The data will be analyzed for deviations from previously acquired data and stored if significant changes relevant to long or short-term trends are discernible.

A modification to the existing two-gas atmosphere controller with respect to the frequency of the integrator reset pulses is required to accommodate the leak detection scheme within the 15-second period. This change would not affect the operational characteristics of the present design and would offer some advantages in component selection for the integrator circuit.

In summary, the following items are considered to be of importance:

A. This system will provide continuous upper limit monitoring of nitrogen gas resupply rate.
B. Out-of-tolerance limits on the high side can be monitored by one digital input to the RDAU.
C. High limits to detect out-of-tolerance operation are under the control of the main checkout program (adjustable limits).
D. Approximately 15 seconds after the leak is detected, data on the nitrogen gas resupply rate will be available for display at the control monitor.
E. The operator at the control monitor may request continuous update information for analysis. This can be supplied at a rate of 4 updates per minute.
F. The basic design of pulse rate modulated two-gas atmosphere controller is retained with very minor modifications.
G. The data acquisition method is compatible with the Space Station interface.

8.2.1.2 Impact Gage Subsystem

The impact gage subsystem will be used to monitor, classify, and locate damage to the external pressure shell as it occurs. The impacts which can cause damage to the pressure shell include those from the exterior such as collisions with meteoroids or space debris, docking collisions, or malfunctioning equipment external to the pressure shell. Damage to the external pressure shell may also result from shrapnel-type impacts from explosion caused by malfunctioning onboard equipment.

The impact gage subsystem consists of a set of transducers, mounted in contact with the inner side of the outer pressure shell. Energy from any significant impact will be sensed in one or more of these transducers. For this portion of the study, it will be assumed that transducers are mounted at approximately equidistant intervals on the wall of the outer pressure shell. Spacing is expected to be 4.6 m (15 ft) minimum.

This subsystem can be operated in the following manner:

A. Continuous upper limit testing shall be performed on sensor outputs for each transducer in the impact gage subsystem.
B. In the event an impact occurs, the acoustic energy in the form of stress waves propagates through the pressure wall and is initially detected by the transducer nearest the point of impact. The velocity of propagation is assumed to be 5 mm/μsec (wave travels approximately 0.3m in 60 μsec).
C. The output of the sensors resulting from an impact on the pressure shell wall can be classified as follows:
   1. Using a frequency discrimination technique on the sensor output signals, it should be possible to distinguish between an impact from a high-velocity source such as meteoroid or space debris and impacts from other sources (see Appendix B).
   2. The amplitude of the sensed signal resulting from the impact should provide information relative to the extent of damage incurred. For example, a three-level detection system could

be implemented whereby the first detection level is designed to be at that point which just exceeds the damage threshold, the highest detection level may be at that point where penetration of the pressure wall is fairly certain, and another level about half way between. This system would be able to provide quantitative information on severity of the impact.

D. The impact may be located by analyzing the time relationship of the transducer signals in the area of the impact. Location resolution is obviously a function of system complexity.

1. First-order resolution is accomplished simply by determining which transducer was first excited by the impact. With the assumed spacing of 4.6 m, this would place the impact within a 22.2 m^2 area.

2. Improved resolution of the impact area can be achieved by relating the time between the initial transducer pickup and subsequent transducer outputs due to the same impact. If this information can be determined for the second and third transducers to record the impact, sufficient resolution should be possible.

3. A method of resolving the impact area based on digital data could be incorporated. Consider the array shown in Figure 8-6. Assume that an impact has occurred within the bounded area and energy has propagated to the B2 transducer. Use this incident to trigger a timing period, t_1, and monitor the adjacent transducer. If the energy imparted to the pressure wall does not propagate to other transducers during time t_1, it can be concluded that the impact must have occurred in Area 9 shown in the figure. If other transducers record the impact during t_1, these data can be used to locate the area as shown in the logic table in Figure 8-6.

E. Due to the design of the data acquisition system for the Space Station, it is not easy to determine the time relationship for signals input from widely dispersed transducers such as are required in the impact gage subsystem. It is therefore appropriate

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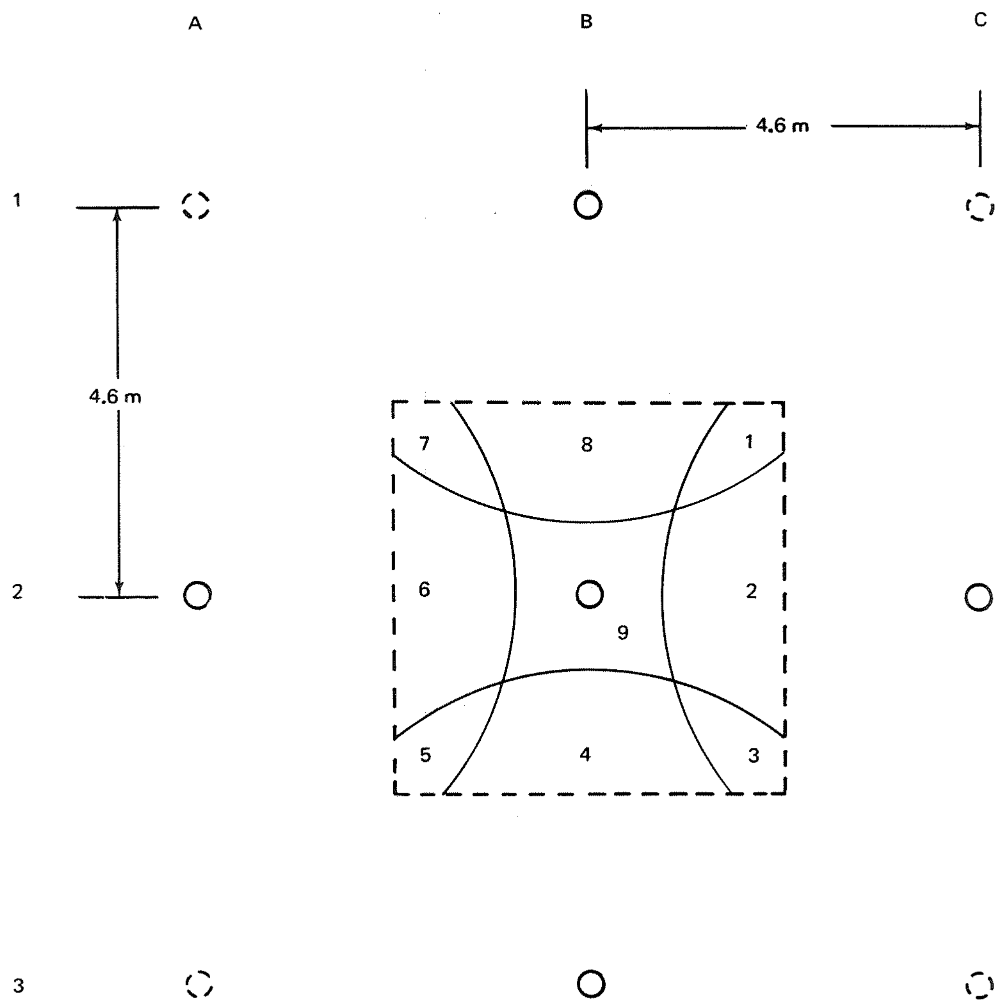

B1	A2	C2	B3	AREA
1		1		1
		1		2
		1	1	3
			1	4
	1		1	5
	1			6
1	1			7
1				8
				9

A "1" IN THE ABOVE TABLE INDICATES THAT AN IMPACT WAS RECORDED BY THE INDICATED TRANSDUCER WITHIN 360 μSEC OF THE TIME THAT TRANSDUCER B2 RECORDED THE IMPACT.

Figure 8-6. Impact Gage Subsystem Transducer Array to consider the feasibility of determining the area of impact utilizing amplitude data only. One such system has been suggested and is described as follows:

1. Assume a transducer system is dispersed as described in the previous example.
2. Assume the sensor signal for each transducer is conditioned so that two outputs are derived. Output 1 may be a digital output (0 of 1) which signifies the result of the frequency discrimination. A second analog output could be provided with the amplitude proportional to the peak input sensor signal. This analog voltage would be automatically reset to zero by the transducer after a time period which is long with respect to the data acquisition time of the Space Station OCS.
3. Assume that the outputs from each transducer are monitored by standard analog and digital inputs to remote data acquisition units. When an impact occurs, amplitude data from each transducer that exceeded the limit is acquired by the system. Analysis of this peak amplitude data should locate the impact with an acceptable area resolution.

8.2.1.3 Acoustic Emission Monitor Subsystem

Acoustic emission in a solid material occurs as a result of energy release caused by plastic deformation or fracture within the solid. This phenomenon can be used as a basis for a technique to detect the formation and growth of flaws or microcracks in the Space Station pressure shell. It is also theoretically possible to locate the source of the emission by time correlation of several transducer/sensor signals.

This subsystem is similar to the impact gage subsystem relative to the expected dispersion of sensors on the Space Station pressure structure. However, the signal characteristics are significantly different. It should be possible to utilize the same sensing element for pickup of the signal for both the impact gage subsystem and acoustic monitor and then branch out to individual signal conditioning channels for further processing.

A block diagram of an acoustic emission monitor sensor/transducer which can be integrated into the Space Station OCS-DCS is presented in Figure 8-7. The operational concept of this subsystem is as follows:

A. The acoustic signals are detected by the sensor, amplified, and filtered. The requirements for this portion of the signal processing are a function of the sensor characteristics.

B. The discriminator and pulse shaper circuit selects the significant signals (e.g., amplitude or pulse width discrimination) and provides an output pulse compatible with the accumulator requirements.

C. The n bit accumulator sums the pulses. When the accumulator is full, a terminal count signal is generated and input to the RDAU (digital input). The value of n will be a function of the critical rate information requirements.

D. The subsystem multiprocessor will acquire the information about the accumulator terminal count via the RDAU data bus link. This information will be analyzed relative to elapsed time from the previous terminal count to derive rate information and a summation of all previous terminal counts will provide total count information. The subsystem multiprocessor will compare this information to stored limits and notify the crew or take other appropriate action as the situation warrants.

The location of the developing flaw or microcrack by time correlation of several sensor signals is difficult to integrate into an automatic system when a large sensor array is required. Several possible approaches should be investigated to determine the feasibility of methods other than time correlation. For example, analysis of the amplitudes, emission rates, or total emission counts of various transducers within the array may provide a satisfactory method. If further study indicates that time correlation is the only feasible approach, the design effort should be directed toward utilization of the same system as the impact gage subsystem.

8.2.1.4 Seal Integrity Monitor Subsystem

This subsystem will monitor the performance of each of the pressure shell-space vacuum interfaces that depends upon seals such as neoprene O-rings

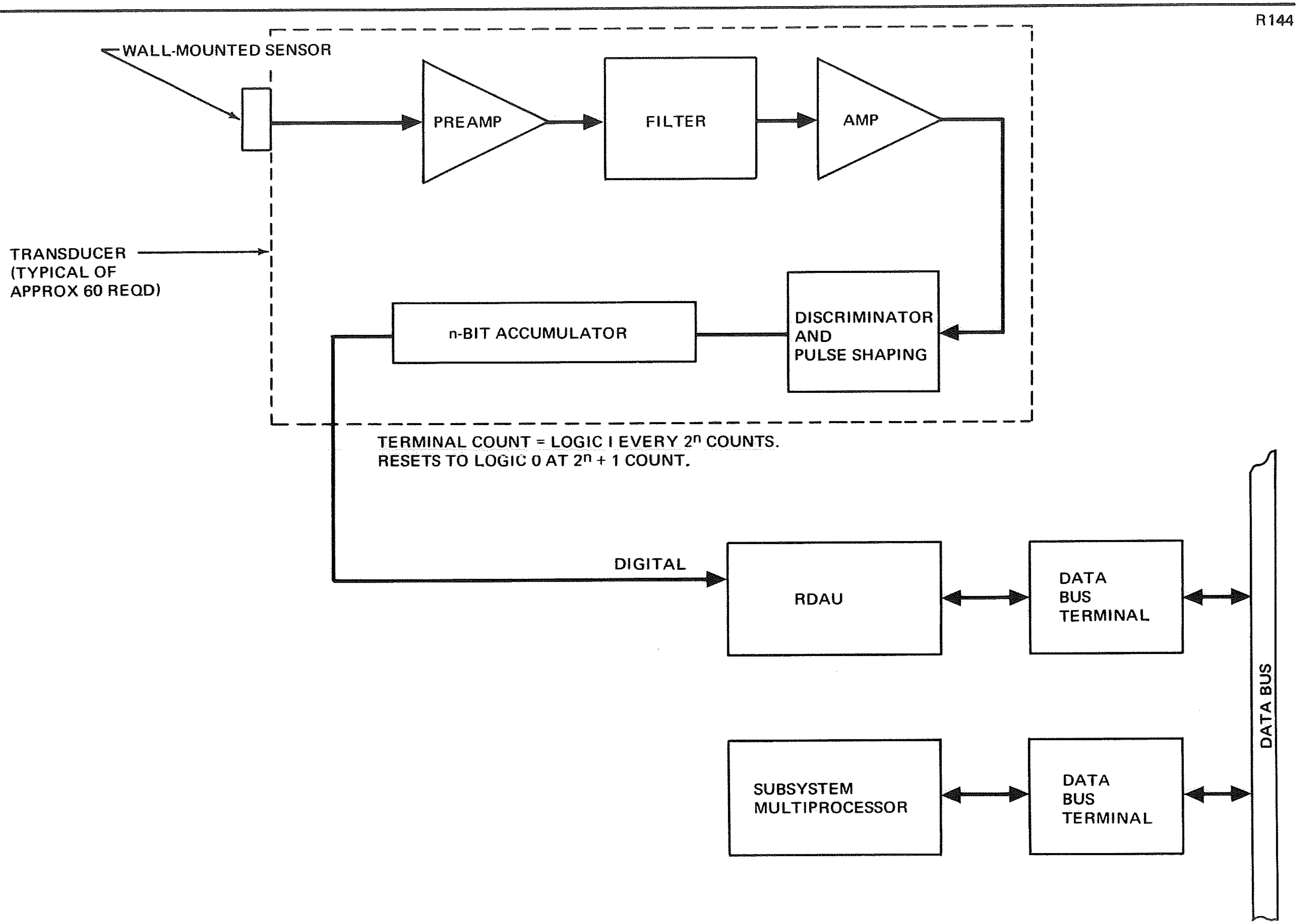

Figure 8-7. Acoustic Emission Monitor Data Acquisition Block Diagram

or inflatable gaskets. The DCS will provide a continuous monitor of the integrity of each seal through this subsystem. It will be capable of locating a faulty seal and determining the quantity of gas flow past the seal. No requirement has been established to provide for further partitioning of large seals such as the 10.1 m (33 ft) dia seal on the toroidal dome covers.

Table 8-1 contains a compilation of information on seals included in the MDAC Phase B Space Station concept. This listing is intended to be used as a general guide to the overall design of the interface between the seal integrity monitor subsystem and the Space Station onboard checkout-data management system. This subsystem will consist of one leak detecting transducer for each of the seals in Table 8-1. Each transducer in the subsystem will output a voltage proportional to the flow of atmospheric gas across the seal. The leak rate limit for each seal will be established initially by design analysis and subsequently upgraded by monitoring actual seal performance. This information will be used to establish upper and lower limits for each seal. The monitor function will be performed by the OCS through the remote data acquisition unit which is physically located closest to a specific transducer in the subsystem. The RDAU has high-low limit check capability and is polled periodically by the supervisory OCS program to detect out-of-limit performance. Upon detection of an out-of-tolerance condition, the output voltage from the malfunctioning seal is input to the OCS through standard RDAU operation. These data are then processed to ascertain the quantity of the leakage and formulate possible solutions; that is, to revise limits, or inspect, repair, or replace the seal. Information about the condition of malfunctioning seals can be presented to the crew in various formats for decisions.

Under normal conditions, defined as no seal leak rate exceeding its preset limit, a periodic check of each transducer output will be performed. The data thereby acquired can be used to compare actual performance with that predicted by analysis of previously acquired data. It may also be used to update trend analysis information if significant changes are observed.

Table 8-1

SPACE STATION PHASE B SEAL SUMMARY

Total Number Reqd/System	Description	Comments
4	O Ring Seal between Pressure Cylinder and Toroidal Dome—10.1 m dia	Static seal
4	O Ring Seal between Tunnel Cylinder and Toroidal Dome (4), and (1) at Forward Cone and Tunnel Interface—3.4 m	Static seal
25	O Ring View Port Seal—0.254 m	Static seal
7	Inflatable Seal for Docking Ports—1.7 m	Double seal for redundancy, inflatable by hand pump in emergency
1	Inflatable Seal for Airlock—1.07 m dia	
5	Tunnel to Deck Access Ports—1.7 m dia	Normal operation with hatches open or with zero pressure differential across seals
4	Rotating Hub, 3.4 m dia, 4 rpm	Dynamic Seals on Space Base only
9	Solar Array Gimbal—1 m dia	Dynamic seal on modular Space Station only

8.2.1.5 Active Ultrasonic Subsystem

This subsystem utilizes a pulse-echo concept to locate defects in the pressure wall which may have been caused by cracks, punctures, or flaws. The sensing transducer operates as a two-way device to translate an electrical excitation into an acoustic energy pulse that is coupled into the structure as well as a receiver that is capable of detecting any energy reflected from the transmitted pulse. Continuous operation of each element of an array of these transducers cannot be achieved because of the effect of cross-coupling of transmitted pulses. Therefore, it is anticipated that the testing sequence will be controlled by the OCS-DCS executive program so that each transducer in the system can be sequentially pulsed and monitored for reflected signals.

A number of assumptions and simplifications have been made so that an estimate can be made of the impact of integrating this subsystem into the baseline Phase B Space Station electronics system. These are:

A. The sensors are mounted in physical contact with the inner surface of the outer pressure shell structure.

B. Sensors are spaced equidistant from each other at 3.1 to 3.7 m (10 to 12 ft) intervals.

C. The area monitored by a specific transducer overlaps the areas monitored by adjacent transducers so that cracks aligned with the transmitted signal from the nearest transducer can be detected.

D. Each transducer operates as a transmitter-receiver and can detect reflected pulses of energy within a relatively short period of time after the transmitted pulse so that flaws close to the transducer can be detected.

E. The energy coupled into the structure by excitation of a transducer will disperse within 20 ms after generation. (Signals arriving at transducers are below threshold.)

F. Control of a sensor (excitation and receive mode) can be accomplished through hard wire at distances to 6.1 m (20 ft).

In the following discussion of the interface between OCS-DCS and the active ultrasonic subsystem, the data acquisition method and the information flow are emphasized. The validity of the data acquired relative to the location of the flaw is assumed. The method described herein is not intended to represent an optimum means of locating the flaw, but does typify the expected system complexity.

The requirement for alternately exciting a transducer and monitoring response exceeds the capability of the standard RDAU. It is therefore expected that a specialized data acquisition unit (DAU) would be developed for this purpose. A concept of this is shown in block diagram form in

Figure 8-8. The similarity with the RDAU is evident and a parts commonality of 50 percent or greater is estimated between the two units. The actual dispersion of the sensors, sensitivity, maximum signal path lengths, minimum hole size, total area, overlap, and other factors will ultimately determine the number of sensors each DAU will control. For the purpose of this study, it is assumed that each DAU will have eight associated sensors capable of operation as either transmitters or receivers. A total of eight DAU's are required to implement the active ultrasonic subsystem in the Phase B baseline Space Station by present estimates.

Referring to the DAU block diagram shown in Figure 8-8, a typical data acquisition sequence is as follows:

A. The memory block for the DAU contains high and low amplitude limits for peak reflected signals at each sensor. These limits are programmable and can be changed by the DMS executive program, as required. Initial limits will be estimated based on ground testing and analysis. The limits will be updated as additional data are acquired and analyzed.

   In addition to amplitude limits, the memory also contains limits for starting and terminating the variable gate for the peak voltage detector. Initially, these gate limits are set to admit to the peak voltage detector all reflected pulses from its associated scan area. The capability to program these limits is used in a second operational mode to resolve the distance from the detector to the reflected pulse.

B. Assuming that the proper amplitude limit and gate time data are stored in the memory, the unit will periodically receive a digital control signal from the OCS-DCS executive program requesting the DAU to poll each of its transducer inputs.

C. Decoding of the incoming request is performed in the control and decode logic block. An address register is set up and an excitation pulse is input to the appropriate transducer through the output multiplexer.

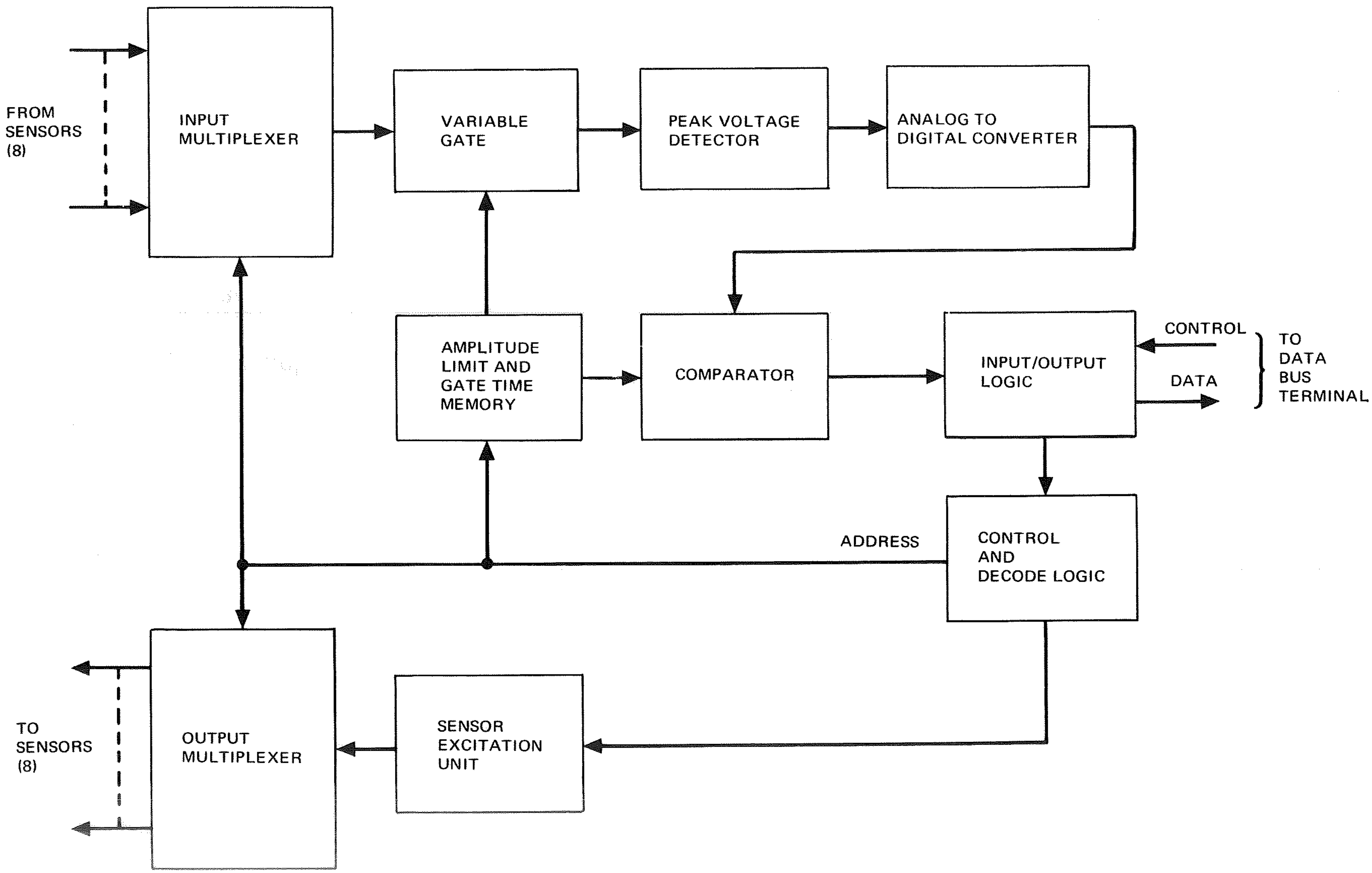

Figure 8-8. Data Acquisition Unit for Active Ultrasonics Block Diagram

D. The input multiplexer selects the appropriate sensor (In Figure 8-8, this has been shown to be the same as the address of the transmitter sensor.)

E. The incoming signal is blanked for selected periods of time by the variable gate circuit. This feature is used to block the initial transmitted pulse and to terminate the receiver at the appropriate boundary so that the test sequence can be reiterated within a nominal time frame.

F. The peak voltage detector circuit is used to sense and hold the peak value of the reflected energy pulse during the gating period. This circuit is necessary due to the transient nature of the reflected signal. The peak voltage detector circuit in this operating mode is acting as a gross check on the area scanned; that is, there may be several reflected signals of significant amplitude during the gate period. Resolving this information is accomplished at a later time.

G. The DAU sequentially repeats the test described above on each of its sensors by incrementing the address register. Upon completion of the polling, the DCS-OCS multiprocessor is notified via the data terminal. Information in this transmission would include the address of any sensor or sensors whose output exceeded the programmed limits.

H. All remaining DAU's will be sequentially polled in a like manner under the control of the OCS-DCS program in the multiprocessor.

I. When the polling process described above is completed, the addresses of all sensors which received significant reflected signals are available for further processing. This information will be analyzed and specific sensors selected for further testing.

J. A command signal is sent to the DAU of which the selected sensor is a subset. This command signal is decoded and the following subroutine is used to isolate further the fault which apparently caused the reflected signal.

    1. The programmed limits for the variable gate are changed so that further resolution of the distance from flaw to transducer can be achieved. For example, a method of successive

approximations analogous to a technique used in some A-D converters may be employed. The gate period would be divided in half and the excitation pulse applied. If the out-of-tolerance reflection is received, then the remaining gate period is again divided by two and the process repeated until sufficient resolution is achieved.

2. Multiple reflections caused by more than one flaw in the area checked by a particular transducer can be detected by actively checking the gating periods that are assumed to contain no flaws.
3. Upon conclusion of this test sequence, information on the gate periods and amplitudes of the related reflected pulses are formatted and transmitted to the OCS-DCS executive program.

K. The routine described in J is repeated for other selected transducers as required for triangulation of the reflected signals.

L. Information regarding the flaw or flaws detected by the active ultrasonic subsystem is then presented to the crew via the control panel. Information would contain location as well as estimated size or degree of imminence. This information could be related with previously acquired data, if a history exists, so that the crew could be made aware of changes.

M. Based upon the estimated 20 millisecond damping time requirements, a scan of all sensors (and therefore the total area under consideration) can be accomplished in 1.28 seconds. When flaws are detected, some additional time is required for acquiring the data for triangulation of the fault. It is estimated that the total elapsed time would not exceed 2.5 seconds.

The advantages of the described method for acquiring data from the active ultrasonic transducers are; (1) using the DAU concept, fewer direct transmissions are required between the data management system and the active ultrasonic subsystem; (2) transmission of signals between the DAU and its associated sensors are kept to reasonably short paths; (3) complex timing circuits are avoided; and (4) the acquisition of pulse-echo data is divided into two categories. Overall surveillance is accomplished in a straightforward manner with a minimum amount of programming requirements. This would be the preferred mode of operation and will constitute most of the impact of the active ultrasonic subsystem on the DCS-OCS multiprocessor.

8.2.1.6 Onboard Leakage Detection

The primary purpose of this subsystem is to provide sufficient data to the DCS-OCS so that the presence of critical atmospheric contaminants can be detected and the location of the malfunctioning component, storage container, pressure line, or equipment can be determined. This subsystem will consist of a set of various types of sensors located within the EC/LS system at critical points where leaks of process fluids or gases could occur. Similar leaks in other systems (for example, propulsion or onboard experiments) may also result in contamination; however, the EC/LS system contains a number of gases and fluids in various equipment. It is expected that the instrumentation problems encountered in this system are similar to those in other systems.

The operation of this system is described in Section 4 of this report. The block diagram of the Space Station EC/LS system (Figure 4-1) shows the location of some of the sensors that are required to perform the onboard leakage damage control function. The sensor-system interface requirements for the acquisition of data pertinent to specific contaminants are as follows:

A. Hydrogen gas, H_2, is a product of the water electrolysis process. The buildup of hyrdogen in the atmosphere results in an increase in the potential combustion and explosion hazard, and thereby represents a critical damage control function. Hydrogen gas, under positive pressure with respect to the cabin environment, is contained in the water electrolysis unit and the Sabatier as well as the connecting plumbing, as indicated in the functional block diagram, Figure 8-9. Several sensors are therefore required to isolate a malfunction which causes H_2 gas buildup in the controlled atmosphere. These include transducers in the Sabatier and electrolysis unit for detecting leaks inside this equipment. Additional

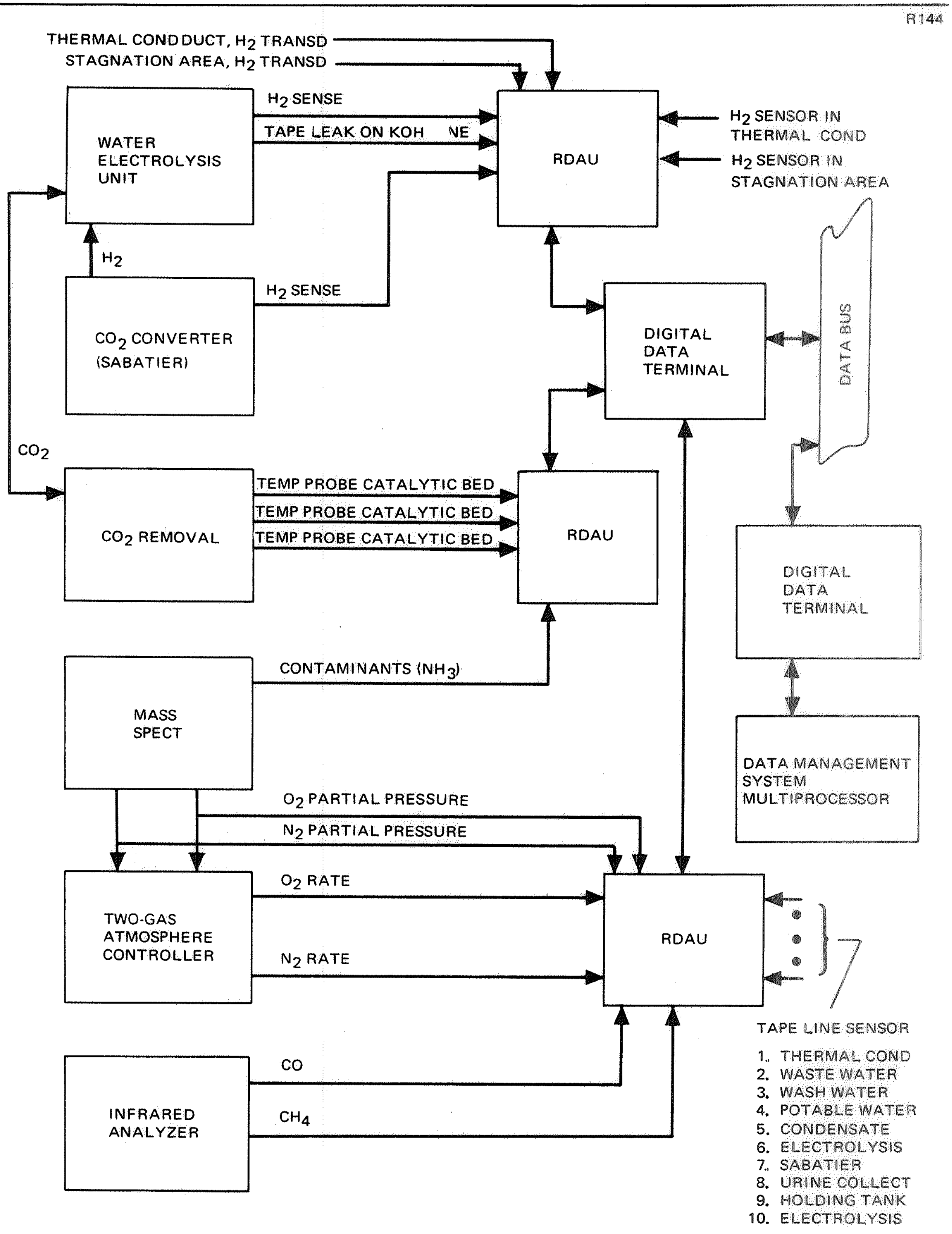

Figure 8-9. Onboard Leak Subsystem Data Acquisition

sensors are located in the thermal conditioning return duct and stagnation area so that leaks in the connecting plumbing can be isolated. The sensor used for detection of H_2 gas is a combustible gas detector. The output voltage of the sensor is monitored by the standard RDAU, as shown in Figure 8-1. Initial limits will be determined by analysis and limits will be updated by the OCS-DCS program as the mission progresses. Typical operation is expected to be as follows:

1. Initial limits are set as follows: 2 percent at Sabatier, electrolysis, and thermal conditioning duct; 0.2 percent at stagnation area sensor. (Assuming nominal level is about 0.05 percent, 4 percent is flammability limit, 6 percent is detonation limit.)
2. The H_2 sensor located in the stagnation area should be the first to exceed its limit. The DCS program then requests data from the remaining H_2 sensors and isolates the malfunction to the electrolysis unit, the Sabatier, or the plumbing by analyzing relative levels.
3. In case of isolation to the electrolysis unit, a check for leaks in KOH lines is also accomplished (part of an existing sensor system discussed in a later section). This provides further resolution of the faulty component.
4. The results of the above analysis are displayed for crew action. Short-term trend analysis may be performed to assess the criticality of the situation.

B. Ammonia (NH_3) contamination of the atmosphere may occur as a result of leaks or malfunctions in the waste collection and disposal system. The nominal level of NH_3 is expected to be 0.5 mg/m^3. A maximum safe level is estimated to be about 10 mg/m^3. It is anticipated that the high limit for a sensor monitoring this gas should be about 2 mg/m^3. The mass spectrometer is used to detect the presence of NH_3 in the atmosphere. This unit will provide an output voltage proportional to the NH_3 partial pressure. Isolation of the malfunctioning component is accomplished by utilizing tape line sensors which are designed to detect and approximately locate a leaking fluid. Three tape lines are utilized, one each on the urine collector, the holding tank, and the feedline to the wicks. The sensors and their relationship to the OCS-DCS data acquisition are shown in the block diagram, Figure 8-9. Out-of-limit detection, analysis of sensor input data, and display of results are accomplished in a similar manner to that used for the H_2 gas contamination.

C. Carbon monoxide gas is present in the Space Station environment from crew metabolic generation. It is also a product of any combustion that may occur. Removal of CO is accomplished in the catalytic oxidizer. Improper operation of this unit can result of a buildup of CO levels. Nominal levels are approximately 18 to 20 mg/m^3, and an unsafe limit is on the order of 50 to 60 mg/m^3; therefore, an upper limit of about 28 mg/m^3 would indicate an abnormal condition which requires further analysis. The detector used to monitor CO is an infrared analyzer. This device provides an output voltage proportional to the CO concentration. Figure 8-9 shows the relationship of the CO detector to the OCS-DCS with respect to the acquisition of the required data. When the sensor output exceeds the high limit, the OCS-DCS program will correlate the data with the CH_4 detector (to be discussed in the next section). A simultaneous increase in both levels would indicate combustion; otherwise, the malfunction must be related to the catalytic reactor. In this case, stored data would be used to extrapolate the time to an unsafe level and the crew notified.

D. Methane, CH_4, is a biowaste product of CO_2 conversion in the Sabatier. Toxic levels of hydrocarbons will result if leaks into the Space Station atmosphere continue undetected. The total hydrocarbon analyzer is used for detection of CH_4. The output of this sensor will be a voltage proportional to the concentration of CH_4. The nominal level in the Space Station atmosphere is approximately 500 mg/m^3 and an unsafe level is estimated to be 2,000 mg/m^3. An upper limit on the detector monitoring this gas would initially be on the order of 1,000 mg/m^3. Detection of an out-of-limit condition would result in a correlation with CO level for possibility of combustion. Otherwise, the leak is assumed to be in the

Sabatier. A possibility exists that the CH_4 gas would be compressed and stored for use in the guidance and propulsion resistojet system. This would necessitate some additional sensors for fault isolation. The possibility of leaks from the CH_4 exhaust plumbing is small, since these lines are normally at a negative pressure with respect to the cabin atmosphere.

E. Water vapor is not considered an atmosphere contaminant. However, water is present in several of the EC/LS units and is plumbed to various locations within the Space Station. An undetected water leak is a potentially serious problem due to overloading of the humidity control unit, depletion of water reserves, and possible damage to experiments. Additionally, a water leak would indicate a malfunction in the critical EC/LS system and may be a precursor to degradation of the atmosphere control loop. For these reasons, it has been included as part of the onboard leak monitor required for the DCS.

Essentially, this subsystem consists of tape line leak detectors attached to each unit and plumbing which contains water. Each of these detectors is interfaced with the nearest RDAU analog input channel. An output voltage from this sensor is an indicator of a leak and the amplitude of the output voltage is proportional to the distance along the tape line where the leak has penetrated the tape. This sensor therefore acts as a detector and also isolates the faulty component or connection. The tape line sensors are shown in the functional schematic, Figure 8-9. Continuous monitoring of these sensors is provided by the RDAU. When a leak is detected, the amplitude of the sensor signal is converted to digital format and transmitted to the multiprocessor. The data are then compared with previously stored information for probable faults along the tape line and the crew notified via the display and control terminal.

F. Potassium hydroxide (KOH) is a working fluid in the water electrolysis process. Leaks in the KOH system can result in contamination of the atmosphere with an increase in the hydrogen content (flammability and explosion hazard), as previously discussed. In addition, KOH leaks can cause severe damage by the corrosive effect on materials found within the water electrolysis unit. The sensor used to detect and locate leaks in the KOH system is a tape line similar to those described for use for water leak detection. The data acquisition and analysis are identical to that described for the water leak detectors.

G. Freon is present in the Space Station in the refrigeration and deep freeze systems and will also be used in the heat exchanger of the thermal control system. A limited amount of Freon is also released by outgassing from components and hard surfaces that have absorbed cleaning fluids. The release of Freon into the atmosphere results in contamination of catalyst bed in the CO_2 removal system. This requires premature maintenance on the charcoal filter on the CO_2 inlet line. Freon contamination can be detected by monitoring temperatures in several places along the catalyst bed. The temperature changes can be updated for nominal contamination utilizing the OCS-DMS executive control and the RDAU programmable limits. Excessive temperature changes along the bed would indicate contamination by Freon. This information would be displayed for crew information and could be correlated with a gas chromatograph analysis.

H. The atmosphere control system normally regulates the oxygen partial pressure. This is accomplished by detecting the O_2 partial pressure with a mass spectrometer and comparing this level with a reference in the two-gas controller assembly. When a deficiency exists, make-up O_2 is supplied by a pulse rate modulated orifice supplied from a pressure regulated oxygen supply or by modulating electrolyzer current. Oxygen leaking into the cabin upstream of the pressure regulator and solenoid controlled orifice could leak to an oxygen-rich environment; therefore, the monitor of oxygen partial pressure is included as part of the damage control function. Nominal levels of oxygen partial pressure are expected to be on the order of 160 ± 5 mm Hg. The minimum allowable limit (due to hypoxia) is considered to be 85 mm Hg. A high limit of

180 mm Hg is defined as an increase in fire hazard. As shown in Figure 8-9, the oxygen partial pressure sensor is the mass spectrometer. The output is monitored by the RDAU utilizing the high and low limit capability. If the output voltage deviates from its window limits, the OCS-DCS executive program is notified via the data bus. A short-term trend analysis is then performed to project the rate at which a critical limit is being approached and the crew notified of the situation. Additional sensors such as a hand-held ultrasonic detector could then be used to isolate the leak.

8.2.2 Damage Control System Requirements for Stimuli Generation

The stimuli generators enable the operational status of a particular subsystem to be determined by providing a calibrated or known input signal or stimulus. This input will also be used by the OCS diagnostic program to help isolate a malfunction to the lowest replaceable unit, or in the case of the DCS, to the repairable level. The use of stimuli generators for each selected DCS is discussed in the following paragraphs.

8.2.2.1 Two-Gas Controller

The design of the two-gas atmosphere controller for Space Station application will include provisions for utilizing the available stimuli to provide fault isolation to the LRU level. The addition of the accumulator circuit discussed in previous sections should provide a valuable test point since quantitative data can be obtained by this method. A typical test would be accomplished by providing an input signal equivalent to a known nitrogen partial pressure error signal and monitoring all test points for proper response. Other than to maintain operational status of the two-gas controller, no additional requirements for test stimuli are anticipated. Existing stimuli required to ensure the normal EC/LS function will be adequate.

8.2.2.2 Impact Gage

The checkout of the impact gage transducer array can be accomplished by excitation through the active ultrasonics transponders. A method to produce several levels of excitation from these transponders would provide several levels of energy for the impact gage transducers. The conclusion, therefore, is that no requirement for direct stimuli generators is presently identified for the impact gage transducer array.

8.2.2.3 Acoustic Emission Monitoring

The requirements for controlled checkout of the acoustic emission transducer array are basically the same as for the impact gage system. Since the two subsystems will probably share the same sensor elements, the above described method can be extended to provide transponder signals of the required amplitude and frequency levels to be compatible with this system.

8.2.2.4 Seal Integrity Monitor

The ideal stimulus for checking this transducer would consist of a method of electrically controlling an atmosphere flow past a seal. However, the inherent complexity and accompanying reduction of reliability may preclude this kind of approach. An alternate method is to insert an electrical offset in the differential amplifier loop to provide a known calibration point. This offset can be inserted conveniently into the reference thermocouple circuit. Due to the low level of the signal, the control of this signal would be accomplished by a digital input.

8.2.2.5 Active Ultrasonics

Maintenance of the active ultrasonics transducer array and signal conditioning can best be accomplished by utilizing the built-in test capability of this system. This would be achieved by providing a variable-level stimulus signal through an adjacent transducer in the array and programming the gating and amplitude limits to the appropriate receiver-transducer. Utilization of this concept is an extension of the method used for testing the impact gage and acoustic monitor transducer arrays.

8.2.2.6 Onboard Leaks

The requirements for stimuli generation for the sensors used to detect onboard leaks are of two types. Sensors such as the hydrogen detector and mass spectrometer will accommodate the analog signal substitution method used to simulate a known input offset level. The tape line sensors described in a previous section will utilize electrically controlled switches at discrete intervals along the length to simulate leaks. These simulated leaks will be detected and analyzed for location and the results compared to the known location.

8.2.3 Processing Requirements for Selected DCS Subsystems

The processing requirements for selected DCS subsystems have been estimated using the methods evolved in the Phase B Space Station study. The results of this analysis and an estimate of the impact of the DCS requirements upon the overall Space Station data management system processing requirement are presented in Tables 8-2 and 8-3. The criteria used to formulate the quantitative information presented in these tables are next discussed. This information is intended to be used as a basis for updating these estimates as additional definitive DCS requirements are established.

8.2.3.1 Test Point Monitoring/Limit Checking

This function is normally performed on-line by the RDAU. However, the ability to check for proper operation of the total system may require duplication of this capability by the subsystem multiprocessor as well. The status monitoring function logic was estimated to be 100 and an upper and lower limit as well as the current value are required for each test point. Therefore, 100 + 3 n storage locations will be required for monitoring and limit checking n test points.

8.2.3.2 Trend Analysis

A discussion of the method of performing computerized trend analysis for Space Station applications is contained in Reference 30. The results of analysis show that the memory requirements for trend analysis can be estimated by $200 + 23\, n_t$ words, where n_t is the number of test points being examined for trends. The factor of 200 in the preceding expression is an estimate of the number of instructions required to perform the least squares fit subroutine.

Table 8-2

FACTORS USED TO ASSESS DCS PROCESSING REQUIREMENTS

Damage Control Subsystem	Test Point Monitoring n	Trend Analysis n_t	Diagnostics n_r	Executive Control n_s, n_t, n_a
Two-Gas Controller	2	2	2	1, 2, 0.25
Impact Gage	80	0	80	1, 0, 1.94
Acoustic Emission	80	0	Modified Impact Gage Routine	1, 0, 1.94
Seal Integrity	38	10	38	1, 10, 0.8
Active Ultrasonics	64	8	64	1, 8, 10.0
On-board Leaks	38	10	38	1, 10, 0.8

Table 8-3

SUMMARY AND COMPARISON OF DCS-OCS MEMORY REQUIREMENTS FOR ONBOARD PROCESSING

	DCS (Words)	Total Data Mgmt System (Words)	DCS Impact (%)
Test Point Monitor	1006	15×10^3	7.1
Trend Analysis	890	11.6×10^3	7.7
Diagnostics	4870	48×10^3	10
Executive Control	606	4.8×10^3	12.6

8.2.3.3 Diagnostics

The diagnostics requirements are a function of the number of replaceable units in a specific assembly. Each diagnostic structure is expected to be fairly unique and an average approach is difficult to predict. The expression used to determine total storage requirements for the Space Station was n_a $(486 + \bar{n}_r 11)$ where n_a is the number of assemblies and $\bar{n}_r$ is the average number of replaceable units per assembly. For the purpose of evaluating the diagnostics requirements for the DCS subsystems, the data in Table 8-2 were used to derive $\bar{n}_r$ for the five subassemblies.

8.2.3.4 Executive Control

The checkout executive storage allocation is comprised of 10 program elements (discussed in Reference 30) and weighted by the following expression: Total words = $310 + 42\ n_s + n_t + n_a$, where n_s is the number of subsytems, n_t is the number of test points being examined for trends, and n_g is the number of assemblies.

8.2.4 Storage Requirements

Storage requirements for the DCS other than those previously determined for data processing are limited to those required for long-term trend analysis. The present Space Station preferred design concept indicates that long-term trend analysis will be performed by transferring the data to ground stations; therefore, no estimate of storage allocations has been made. It is sufficient to assume that the 30 parameters indicated in Table 8-2 would also be candidates for long-term trend analysis. The temporary storage requirements for the transfer of these data are a function of transmission capability, the sample rate, and the amount of data compression accomplished.

8.2.5 DCS Control and Display Requirements

The DCS control and display functions are integrated with that of the onboard checkout system. As previously discussed, the primary method of control will be through keyboard entry. The display mechanism generally used other than caution and warning will be a cathode ray tube. The following paragraphs discuss the control and display requirements for each of the selected DCS subsystems.

8.2.5.1 Two-Gas Controller

The DCS parameter being monitored at the two-gas controller is the nitrogen gas use rate. When the OCS indicates an out-of-tolerance condition, the operator will need to display information relative to the historical use rate. This can best be accomplished by a graphic display on a cathode ray tube plotting nitrogen addition rate vs time. Figure 8-10 shows data of this type as recorded during the 90-day manned test.

In addition to the trend analysis, a requirement exists to modify the program and to change or check limits at the RDAU. Modifications can also be accomplished with a keyboard entry and an alphanumeric display on the cathode ray tube. This display would be similar to those encountered when using a computer graphic terminal in an edit mode.

8.2.5.2 Impact Gage

The impact gage display requirements for program editing and changing RDAU limits are the same as for the two-gas controller. In the event an impact is recorded by the system, a matrix-type display of the transducer outputs in the areas of concern would be beneficial. This display would contain identification numbers and relative magnitude for each of the sensors. This can also be accomplished by keyboard entry and cathode ray tube display.

8.2.5.3 Acoustic Emission Monitor

The principal display for this subsystem will probably consist of graphic display of count rate vs time and total count vs time. Magnitude and identification numbers provided by a matrix-type alphanumeric display similar to that for the impact gage may also be useful in locating the detected fault.

8.2.5.4 Seal Leak Monitor

Two types of displays may be utilized to present information from this subsystem. A tabular output showing the current leak rate through each of seals and a total leak rate for the vehicle may be useful for an overall monitor of leak performance. The second type of display required will be a long-term trend analysis similar to the others. It is assumed that most seals will

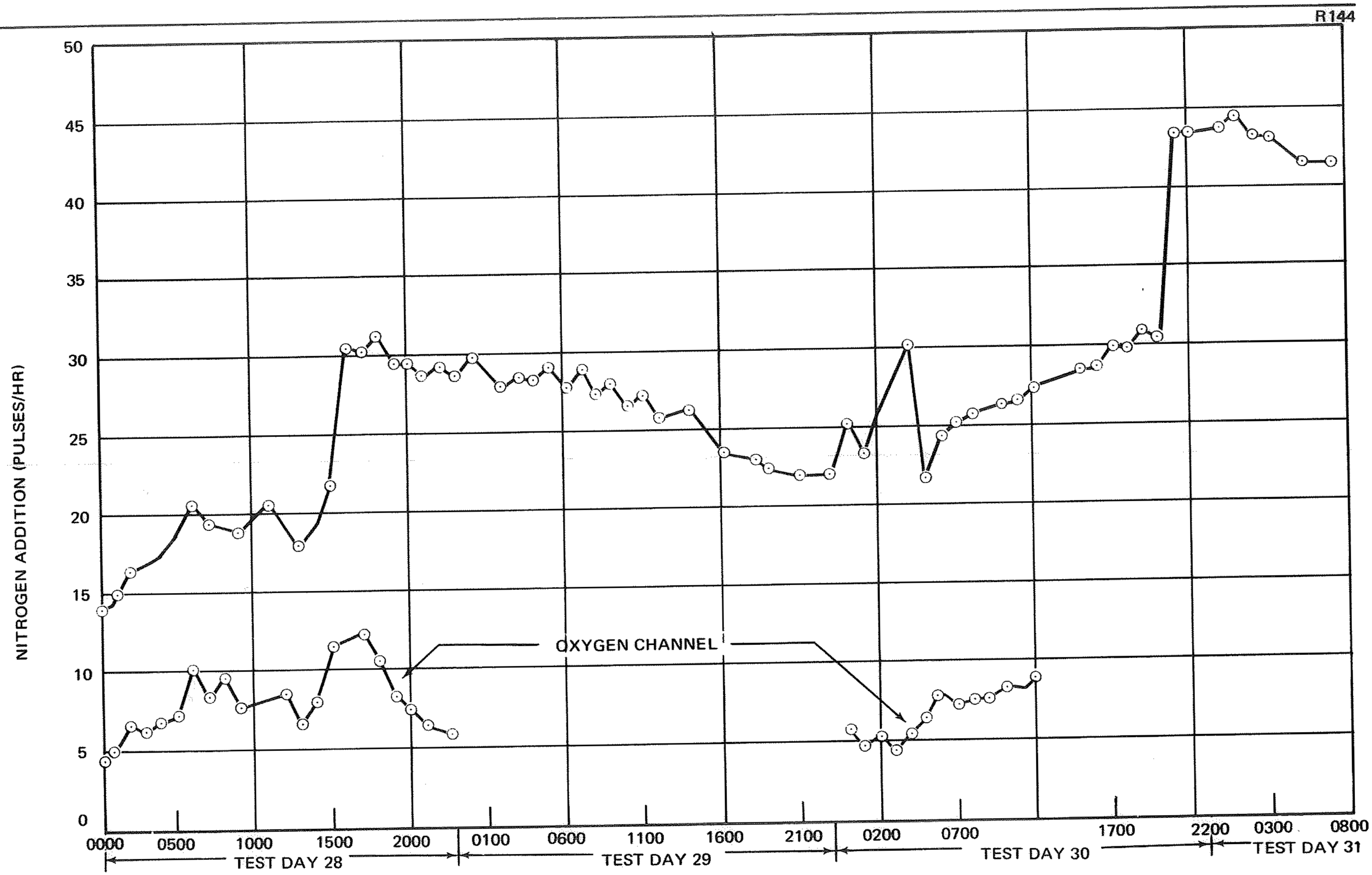

Figure 8-10. Graphic Display Showing Trend Analysis of Nitrogen Resupply Rate

deteriorate gradually and the trend analysis presentation should be useful for predicting seal maintenance or replacement.

8.2.5.5 Active Ultrasonics

The display system will constitute an important part of the active ultrasonics subsystem since the operator might be required to perform an integral part in the flow isolation. This sytem is especially adaptable to the cathode ray tube graphic type display because checkout consists of applying a controlled stimulus and monitoring the response at one or more selected transducers. Information can be displayed in a matrix-type presentation of amplitude and location identification.

8.2.5.6 Onboard Leaks

The onboard leak monitor subsystem control and display requirements can be implemented in the same manner as those previously discussed. In addition to the normal functions displayed on demand at the terminal, most EC/LS functions will be monitored by the caution or warning monitors.

8.2.6 Caution and Warning Requirements for DCS

The DCS subsystem parameters that are considered sufficiently critical to include in the caution and warning displays for the Space Station system are summarized in Table 8-4. Caution level signals are assumed to be displayed in English language format on an alphanumeric dedicated panel, while warning-level signals indicate immediate crew action and are signified by appropriately located lights and audible warnings.

8.3 DCS WEIGHT ANALYSIS

The weight penalty associated with each selected DCS have been estimated and the results are summarized in Table 8-5. Unit weights shown for transducers are based upon estimates of designs optimized for Space Station application. The weight factor used for the Digital Data Terminal (DDT) input is derived from Space Station study reports (Reference 30) and is based upon a total weight of 2.275 kg for an 8-input unit. A factor is also included for wiring based upon Douglas Specification No. 7869679 (modified MIL-W-27300). A pair of wires 4.6 m long, 0-600V, AWG-24, Teflon-insulated, was assumed for each input. The RDAU weight per input is based

Table 8-4

CAUTION AND WARNING LEVEL REQUIREMENTS

DCS Subsystem and Measured Parameter	Caution Level Requirement	Warning Level Requirement
Two Gas Controller Nitrogen use rate	Nitrogen use rate has increased to 2 times its normal rate	Use rate has increased to its maximum level (approximately 36 times normal level).
Impact Gage Significant damage to pressure shell	Caution indication whenever impact is recorded. Expected to be relatively rare occurrence.	None. If impact results in loss of atmosphere, the nitrogen gas use rate above will initiate warning level signal at critical time.
Acoustic Emission Monitor Microcracks or flaws forming in structure	Emission rate of total emission monitored at a particular location has reached a predetermined critical level.	Not established for main pressure shell structure.
Seal Integrity Monitor Loss of atmosphere to space	A faulty seal should be flagged whenever a leak rate becomes significant with respect to the total planned outboard leak (for example, 10 percent).	None. Critical atmosphere degradation as a result of seal failure will be monitored for warning by the nitrogen gas use rate.
Active Ultrasonics Presence of cracks or flaws in pressure structure	This function will probably be used to complement the acoustic emission monitor.	Not defined.
Onboard Leaks		
Hydrogen gas	Hydrogen gas is about 4 times its nominal level	At approximately 10 times nominal level, the detonation limit.
NH_3	2 mg/m^3	10 mg/m^3
CO	30 mg/m^3	50 $^{+0}_{-60}$ mg/m^3
CH_4	1,000 mg/m^3	2,000 mg/m^3
H_2O leaks	Any	None
Freon	Not determined	None
Oxygen	Two to 3 times normal rate	Maximum resupply rate (saturation).

Table 8-5

WEIGHT ASSESSMENT SUMMARY FOR SELECTED DAMAGE CONTROL SUBSYSTEMS

	Transducers			Data Terminal Inputs		RDAU Inputs			
Damage Control Subsystem	Number Required	Unit Weight (kg)	Total Weight (kg)	Number Required	Total Weight (kg)	Number Required	Total Weight (kg)	Overall Weight (kg)	Remarks
Two-Gas Atmosphere Controller (N_2 resupply rate)	2	0.07	0.14	2	0.64	2	0.08	0.86	Sensor weight based on estimated modifications to EC/LS requirements
Impact Gage	60	0.091	5.46			60	2.46	7.92	Spacing assumed to be 4.6m
Acoustic Emission	60					60	2.46	2.46	Uses same transducer as impact gage
Seal Integrity	38	0.091	3.46			38	1.56	5.02	Detectors assumed to be on replaceable seals such as view-ports or hatches
Active Ultrasonics	64	0.091	5.82	8	2.57	See Remarks	4.18	12.57	The special purpose DAU is assumed to be equivalent in weight to the RDAU
Onboard Leaks									
H_2	8	0.223	1.78			8	0.33	2.11	
NH_3	35m	0.0262 kg/m	0.92			8	0.33	1.25	Mass spectrometer weight not factored
CO						2	0.08	0.08	IR analyzer weight not factored
CH_4						2	0.08	0.08	IR analyzer weight not factored
H_2O	61m	0.0262 kg/m	1.60			10	0.40	2.00	
KOH	12m	0.0262 kg/m	0.31			2	0.08	0.39	
Freon	6	0.027	0.16			2	0.08	0.24	
O_2	2	0.07	0.14	2	0.64	2	0.08	0.86	Same as N_2 channel above
N_2									Data acquired above for outboard leaks

Total DCS 35.84 kg

on a similar analysis using a total weight of 0.223 kg and 64 inputs. The weight analysis is carried through the OCS to the data terminal only. It is assumed that the DCS integration does not impose an appreciable weight increase on existing OCS-DMS equipment beyond that point.

8.4 COMPATIBILITY WITH SPACE STATION

The preliminary design effort has been performed with the objective of defining the interfaces between the DCS and the Space Station OCS. Processing, storage, transmission and display of information generated relative to the DCS sensors are compatible with existing Space Station concepts and should have a relatively small impact on the sizing of these systems. At present, the data acquisition system and the preprocessing of sensor signals presents the most imposing problem from the systems integration viewpoint. For example, Figure 8-11 shows the overall data acquisition method for overboard leak damage control systems. Conclusions reached in the preliminary design study are as follows:

A. Caution and warning signals are compatible with the Space Station concept and can be integrated into the present concept without significant impact.

B. Display and control requirements are compatible with the planned system for onboard checkout.

C. Processing and storage requirements for the DCS represent about 10 percent of the total requirements for onboard checkout.

D. Most of the DCS sensor inputs can be monitored by the existing data acquisition system. The method described to locate cracks and flaws in the impact gage subsystem and acoustic emission monitor is not proven; the present method of time-correlating signals would be very difficult to implement. The data acquisition method for locating defects in the active ultrasonic subsystem is also untested and should be investigated.

E. The total weight for the acquistion of DCS sensor signals is estimated to be 35.8 kg, not including controls and displays and other facilities that are time-shared with other systems.

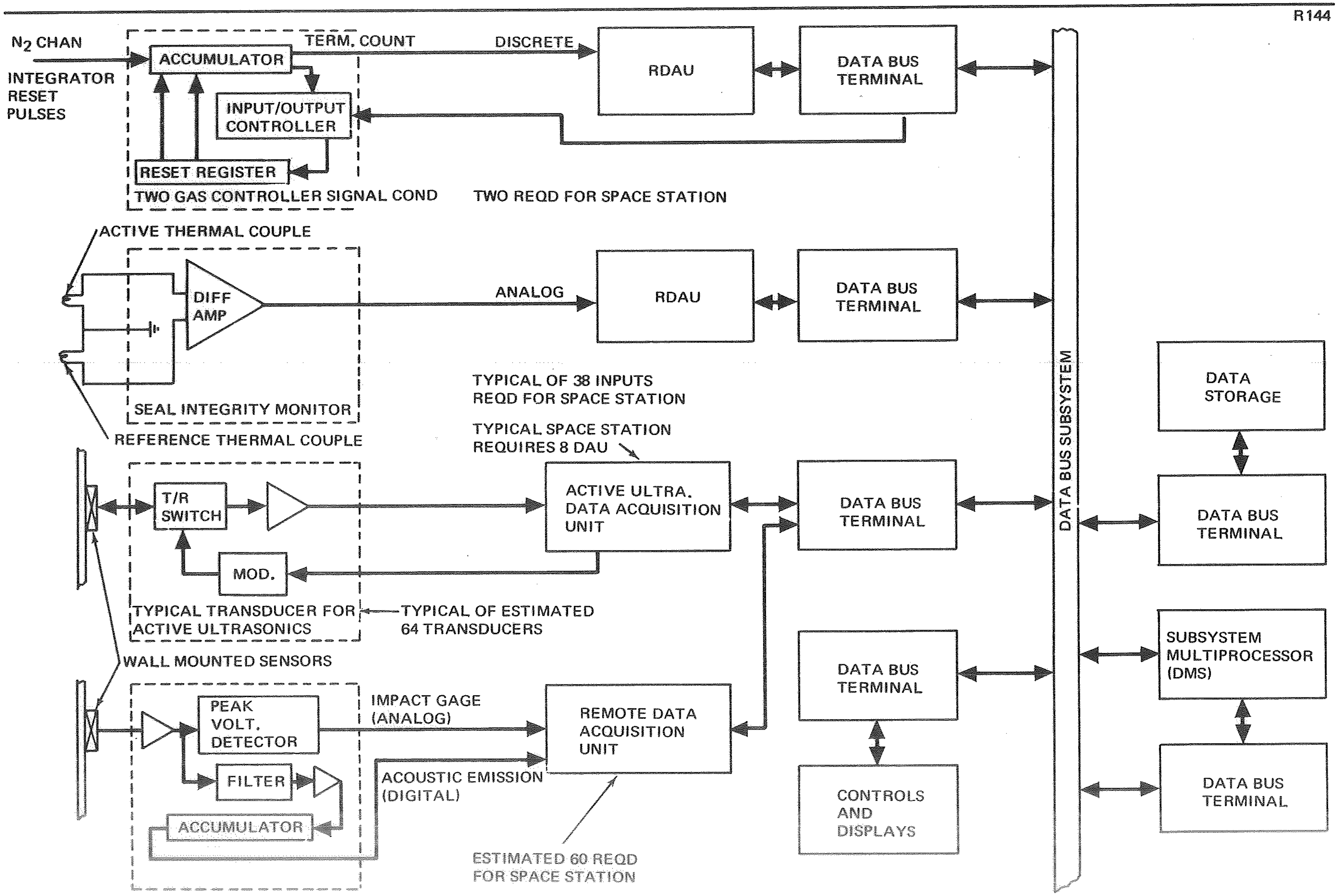

Figure 8-11. Data Acquisition for Overboard Leak Damage Control Systems

Section 9
RECOMMENDATIONS

Overboard damage control systems are in an early stage of development compared with onboard systems which have been studied extensively for trace contamination and control. It is recommended that major emphasis be placed on evaluating promising overboard damage control sensing detection and location techniques. Recommendations for study of specific subsystems follow:

A. Nitrogen Use Rate Monitor.

The pulse rate modulated two-gas controller is in a relatively advanced state of development. To integrate the leak detection function into the controller, four additional circuit functions should be added. These are: temperature compensation, bilevel integration limits, timing circuit, and a function generator. Performance tests should be carried out on the modified controller.

B. Passive Ultrasonics.

Parametric properties of an impact gage should be investigated as a function of type of impact, velocity of impact, and damage mode. Triangulation techniques for predicting point of impact should be verified for realistic Space Station structures. The concept of a dual function passive ultrasonic gage combining the functions of an acoustic emission monitor and an impact gage should be explored.

C. Active Ultrasonics.

Pulse echo techniques should be studied with realistic model structures to define sensitivity parameters such as range and flaw-crack discrimination techniques. A dual-function gage providing both pulse echo and impact gage capabilities should be investigated.

D. Seal Leak Detector.

Electrolytic hygrometry, capacitance, and thermal conductivity techniques should be investigated for prototype development of static, dynamic, and make-and-break seal leak detectors.

E. Portable Leak Detector.

A study of detection techniques based on differential air flow techniques is recommended. The thermistor bridge sensor shows particular promise and should be carried through a prototype development stage if feasibility is demonstrated. A portable leak detector should be versatile enough to be useful for both overboard and onboard leak detection.

The development of flight-type mass spectrometers, gas chromatographs, and supporting analyzers is well advanced. However, the applications of these subsystems to onboard leakage detection remains to be demonstrated. Leak-detection procedures should be studied in a closed atmosphere environment with simulated leak sources as provided by a damage control simulator.

In addition to simulator evaluation of major subsystems, the development of the following support type sensors is recommended: (1) resistive-tape leak detector; (2) solid-state polymeric leak detector; and (3) quartz resonator sorbtion detector.

Access to the pressure walls of the Space Station for leak detection and repair should be designed into the Space Station during configuration layout. The evaluation study and ranking for various access methods indicated that pivot and displacement methods are favored for the majority of conditions preventing access to the walls.

The weight tradeoff analysis between selected damage control systems and the added weight of atmosphere supply reserves to compensate for unplanned leakage resulted in the firm conclusion that the weight penalty for the damage control systems is exceeded by the weight of required gas reserves in short periods of time compared to the projected ten-year life of the Space Station.

Leak repair subsystems currently available for the Space Station are deficient from the standpoints of methods, commonality, and procedures. Reliance should first be placed on approaches which minimize the probability of leaks, then on design redundancy for critical system functions, and finally on leak repair systems.

Where practical, a defective component should be replaced. When replacement is not feasible, elastomeric sealants or epoxy adhesives are the preferred repair methods for fluid-container combinations permitting this approach. For remaining fluid-container combinations, a bolt and seal method is favored.

Arc-welding processes offer the greatest potential commonality for leak repair, but are deficient from both a methods and procedures standpoint. Future effort on space welding research should be directed toward reducing power, size, special tool requirements, and minimizing special skills required for welding operations.

It is recommended that a more comprehensive leak repair study be undertaken which considers specific leak configurations, newer container materials, alternate fluids, and procedural leak-repair response time requirements.

Section 10

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Appendix A
POSSIBLE SOURCES OF NOISE FROM A CHOKED ORIFICE OR CRACK

Possible noise sources are the following:

A. Turbulence in the jet downstream of the orifice. This noise could enter the cabin only by transmission through the wall.

B. Transition in a separation – reattachment region.

C. Fluctuation of the shock structure in the jet, due to turbulence or separation – reattachment instability.

The flow structure depends importantly on the orifice geometry, in particular its length – diameter ratio L/d.

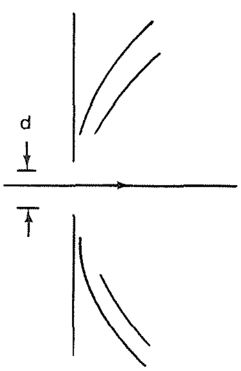


FIGURE A

For $L/d = 0$ and $p_i/p_e \gg 1$, we have a highly underexpanded jet with the classical structure (see sketch).

Assuming $p_i = 1$ atm, it is not quite clear for what minimum d, the shear layers will become turbulent just after expansion. This will depend on the Reynolds number based on diameter. Fluctuations associated with this transition could be transmitted through the wall near the edge of the orifice.

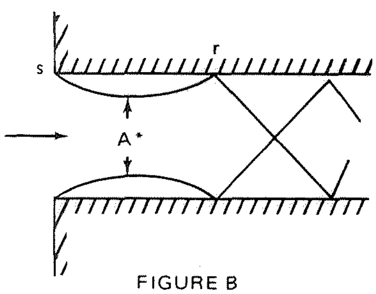


FIGURE B

$L/d \gg 1$ (channel or pipe)
Separation will occur at the inlet edge (s) of the orifice. A free jet will go sonic at a minimum area (A*) then expand and reattach to the channel wall (r), from which point oblique shocks will originate.

At the separation points, the flow will still be laminar, due to the favorable pressure gradient up to that point; but soon after, the separated free shear layer will go turbulent (again depending on the Reynolds number).

The unsteadiness of this transition (which can cause a band of amplified unsteadiness of the whole separated flow region) could produce sound by transmission through the wall or by direct coupling with the upstream region, since the separated region and the flow upstream of the jet throat are subsonic.

In addition, the same possibilities as in Figure A exist for the flow on the exit side.

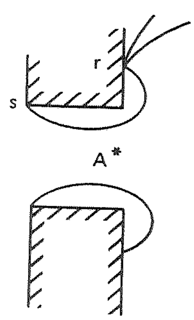


FIGURE C

Intermediate L/d ~ 1
The flow will still separate at the inlet edge and must form a throat somewhere. Where it reattaches, whether inside the channel or on the external wall, is not clear. But the same possibilities for transition etc. as in Figure B are present

A. 1 TRANSITION CONDITIONS

There is a possibility that the free shear layer will become turbulent after separation and before reattachment, i. e., between s and r. To estimate under what conditions this might occur, the thickness of the boundary layer, δ_s, at separation will be of order

$$\delta_s \sim \sqrt{\frac{\nu d}{U}}$$

where ν is the kinematic viscosity, d the hole diameter, and U the velocity at separation, which will be, for all practical purposes, sonic.

The distance to reattachment is a few diameters, say

$$\ell \sim 2d$$

and transition will occur if $\ell > 10\,\delta_s$.

Thus the critical conditions are

$$\delta_s < \frac{\ell}{10} < \frac{d}{5}$$

$$\frac{\delta_s}{d} = \sqrt{\frac{\nu}{Ud}} < \frac{1}{5}$$

$$\boxed{\frac{Ud}{\nu} > 25}$$ Reynolds number based on hole diameter.

Assuming standard atmospheric condition inside the cabin,

$$U = \sim 3 \times 10^4 \text{ cm/sec}, \quad \nu \sim 0.15 \text{ cm}^2\text{/sec}$$

$$\text{gives } d_{cr} \cong 10^{-4} \text{ cm}$$

This estimate may be off by as much as a factor of 10, but it seems clear that the possibility of transitional separated flow exists for very small holes.

A. 2 FREQUENCIES

It is also very difficult to make anything but a crude, order-of-magnitude estimate. The most likely relation for a dominant frequency is

$$f = S\frac{U}{d}$$

where S is a coefficient which may be dependent on Reynolds number. Its numerical value is probably less than unity.

For $S = 1$ and $d = 1$ mm, $f = 3 \times 10^5$/sec.

A. 3 RESEARCH OBJECTIVES

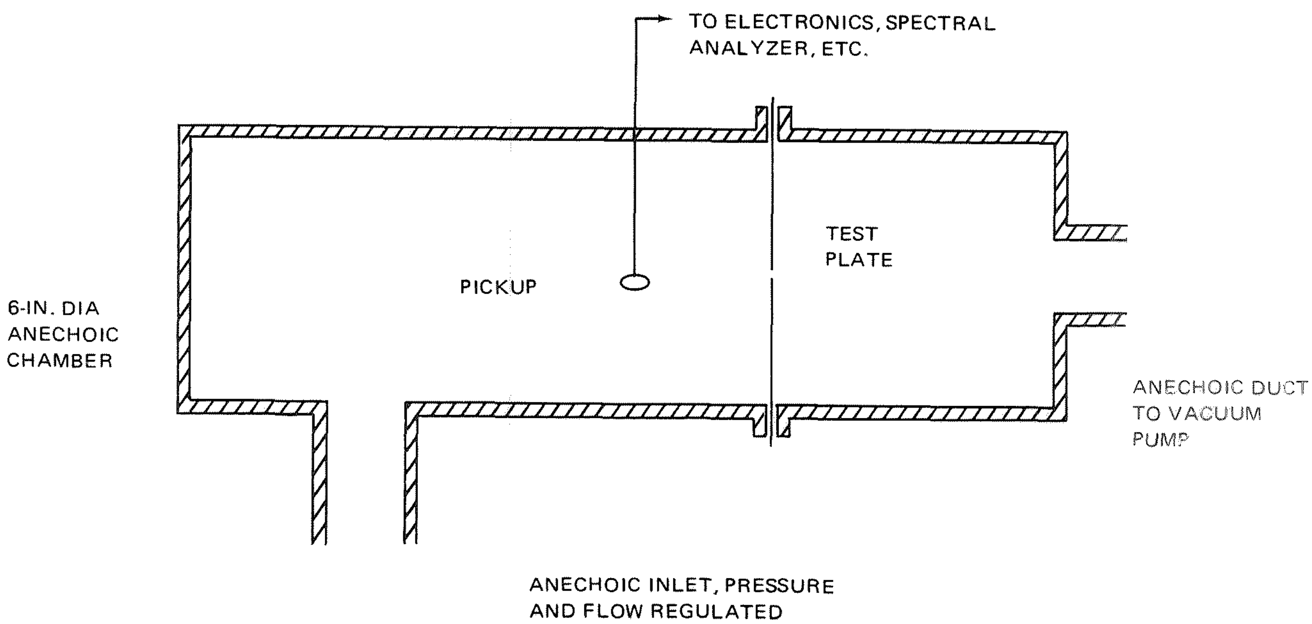
Some of the objectives of a research program would be the following.

A. Spectral content of the sound and its dependence on Reynolds number (i.e., p or d). Latter would furnish scaling information. A thorough investigation and determination of spectral distribution for at least one diameter (about 3 mm) would be desirable. A circular hole and a slot should be investigated. Identification of any peaks (whistles).

B. Intensity (I) Once some idea of spectral distribution were available, one might rationally be able to get some idea of intensity dependence on diameter (d^2, d^3, ?). For example, decrease d and increase p to keep Reynolds number constant, measure total output on center line at a fixed number of diameters from the hole. Then study I/p as function of d.

C. Sound radiation field.

A. 4 EXPERIMENTAL SETUP



A. 5 FLOW RATES

$d = 1$ mm, $p_o = 1$ atm, $\dot{m} = 0.30$ g/sec $\doteq 300$ cc/sec
(Probably one half this for the long hole)

$d = 3$ mm $\rightarrow$ 1 g/sec $\sim$ 1 liter/sec NTP.
To maintain $p_e = 0.001\ p_o$ (1 mm Hg) $\rightarrow$ 1,000 liters/sec.

Upstream pressure: vary up to 3 atm?
Then mass pumping rate up by another factor of 3.

A pumping system with a capacity of about 1,000 liters/sec at about 1 mm Hg is needed (35 cfm). More capacity needed for cracks, depending on aspect ratio.

Alternatively, one might go to lower-volume flow rates, e.g. 3 to 4 cfm, using smaller d but higher p_o.

$$\text{Max } d = \frac{1}{2} \text{ mm (down to } \frac{1}{10} \text{ mm).}$$

At $p_o = 10$ atm, $\dot{m} = 0.75$ g/sec $\doteq$ 0.6 standard liters/sec

$p_e = 10^{-2}$ atm $\rightarrow$ 60 liters/sec $\sim$ 2 cfm

Another possibility to consider is the use of gases other than air, e.g. heavier gas to scale down the frequencies.

A. 6 PARAMETERS

The primary investigation would best be done for large L/d (both circular hole and channel or crack), with sharp, clean, inlet edges. Cases with L/d = 1 and L/d = 0 could follow. Once some insight into these clean cases is obtained, further complications in geometry could be investigated, e.g., effect of noncircularity, inlet edges not sharp, "real" holes produced by particle impact in the ballistic range, real fracture cracks, etc.

Appendix B

EXPERIMENTAL STUDY OF A METEOROID IMPACT GAGE FOR A SPACE STATION

As part of a MDAC IRAD program on impact physics, the feasibility of a meteoroid impact gage for Space Station was studied in 1970.

Sections of a space station wall with a meteoroid bumper and thermal insulation (Figure B-1) were impacted by a light gas gun in the MDAC Aerophysics Laboratory Ballistic Range. A special transducer (Figure B-2) that could detect acoustic waves at frequencies in excess of 10 MHz was mounted to the inner wall. The output was recorded by a Tektronix 502A oscilloscope writing at a rate of 100 μsec/cm and a Tektronix 545A oscilloscope writing at 20 μsec/cm. The transducer was connected to the oscilloscopes by nearly 30.5 meters of coaxial cable, attenuating the signal by about 60 db.

Nine impacts were made using aluminum projectiles with velocities from 6 to 7 km/sec. Projectile masses were selected to bracket the ballistic limit of the cabin wall (Table B-1). Three impacts were made using a cadmium bumper and a cadmium projectile. To determine difference between normal and high velocity inputs, each shot was preceded by a test consisting of striking the wall with small hand-held objects such as a plastic screwdriver handle, a steel bar, and a wrench. Figures B-3 through B-9 show the main signal components as reduced from oscillograms. The periods and amplitudes of the higher frequencies were read with a microscope. It was concluded that the signal from the B48-54 test (Figure B-8) was transmitted through the wooden spacer. Consequently, the spacer was removed for the next shot (B48-55)(Figure B-9). Only a gas cloud struck the plate in this shot, producing a weak signal and no damage. An unresolved instrumentation problem prevented any data from being recorded on six of these shots. In all but one case, high-frequency oscillations were detected

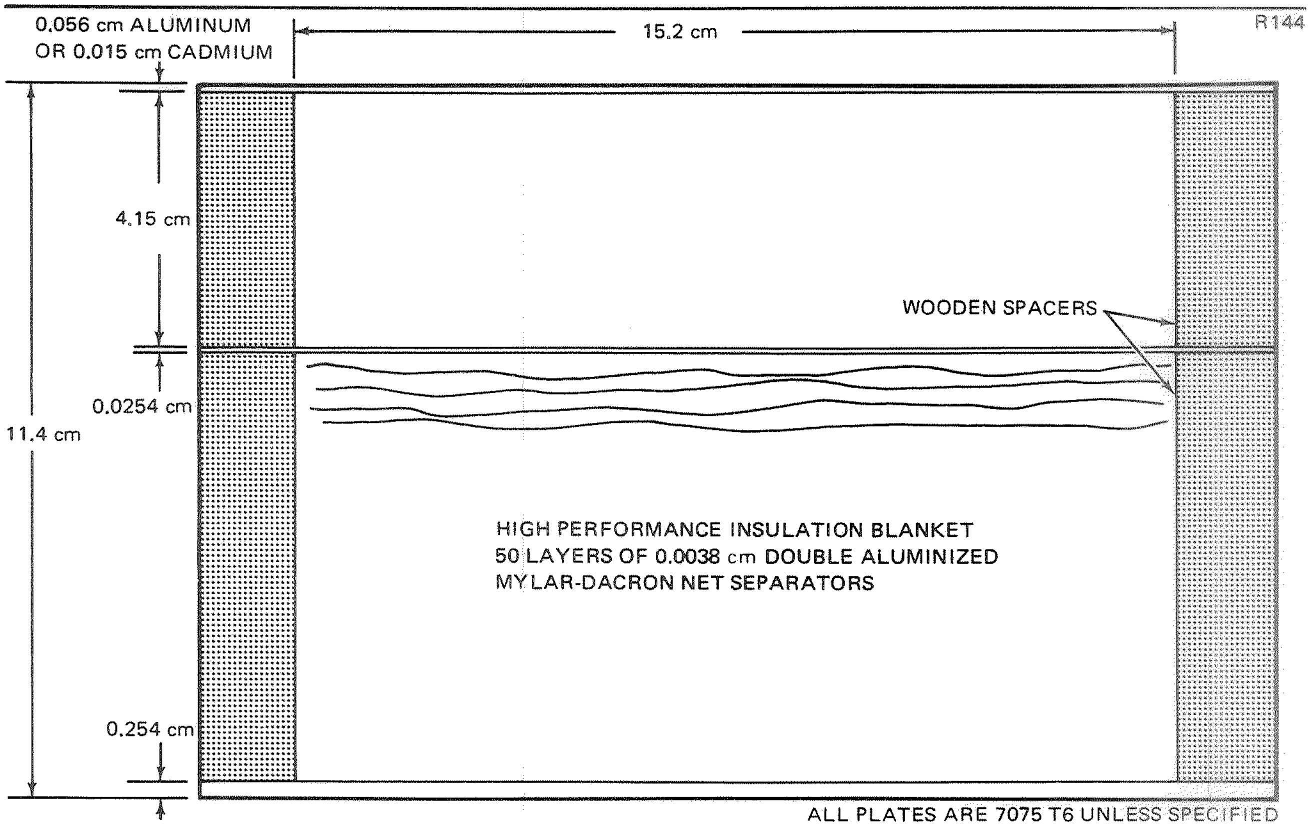


Figure B-1. Space Station Wall Configuration

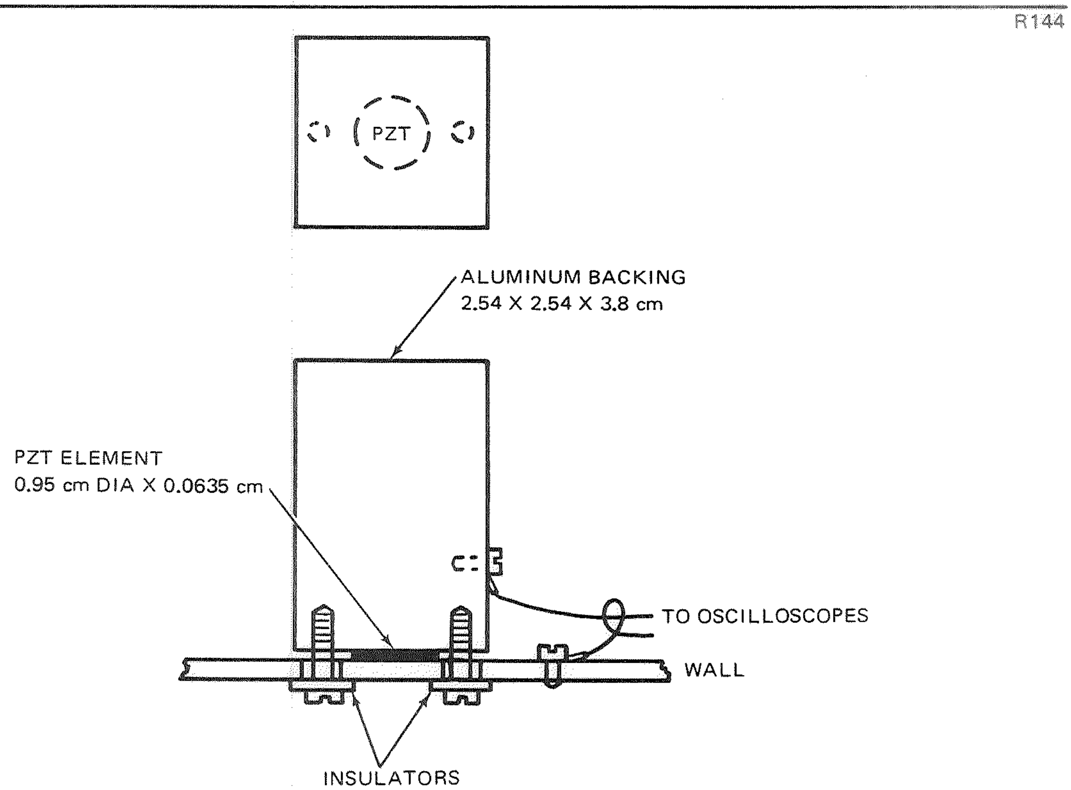


Figure B-2. Meteoroid Impact Transducer

Table B-1

SIGNAL ANALYSIS TEST CONDITIONS

Run	Projectile	Mass (grams)	Velocity (km/sec)	Comment
B48-45	Al	0.380	6.8	Penetrated
46	Al	0.375	6.65	Penetrated
47	Al	0.048	--	No signal
48	Al	0.165	--	Bad shot
49	Al	0.165	6.8	
50	Al	0.048	7.4	No signal
51	Al	0.075	--	Bad shot
52	Al	0.075	7.55	--
53	Al	0.048	7.43	--
54	Cd	0.006	7.45	--
55	Cd	0.012	7.7	--
56	Cd	0.700	6.8	No signal

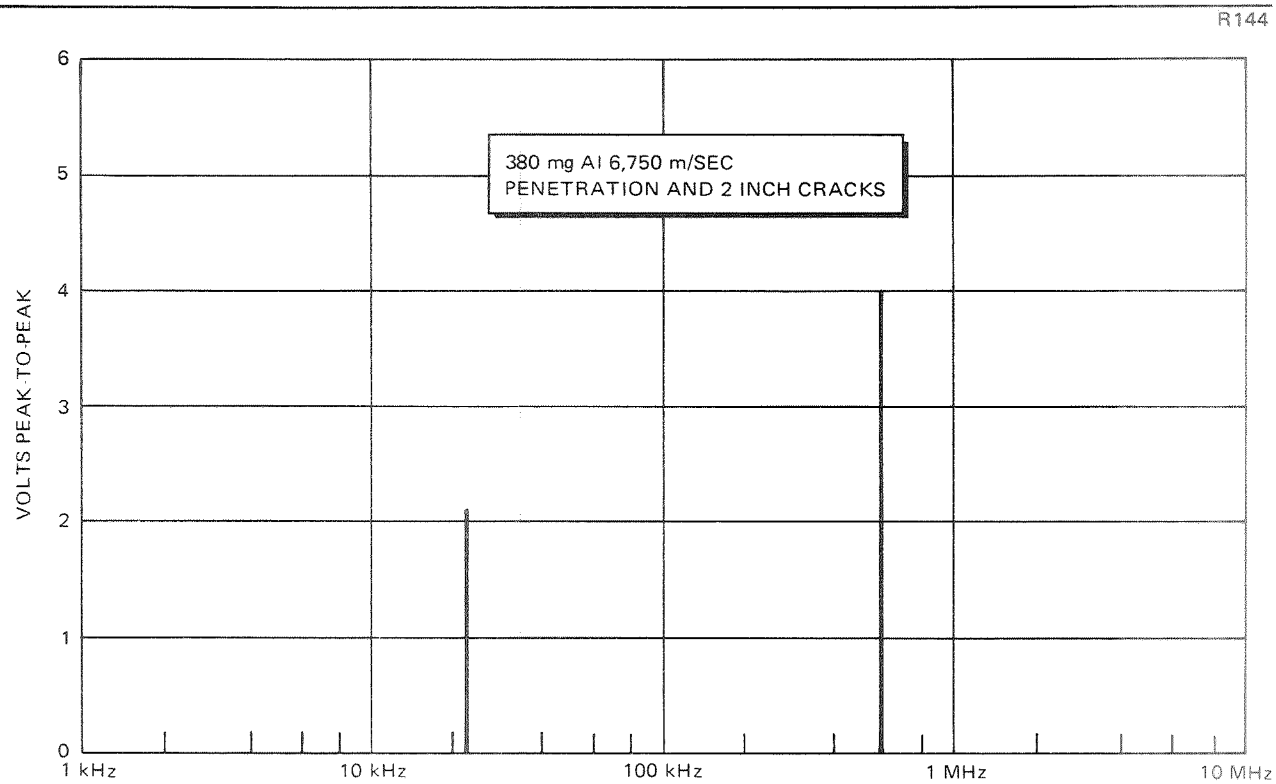


Figure B-3. Shot B48-45 Impact Signature

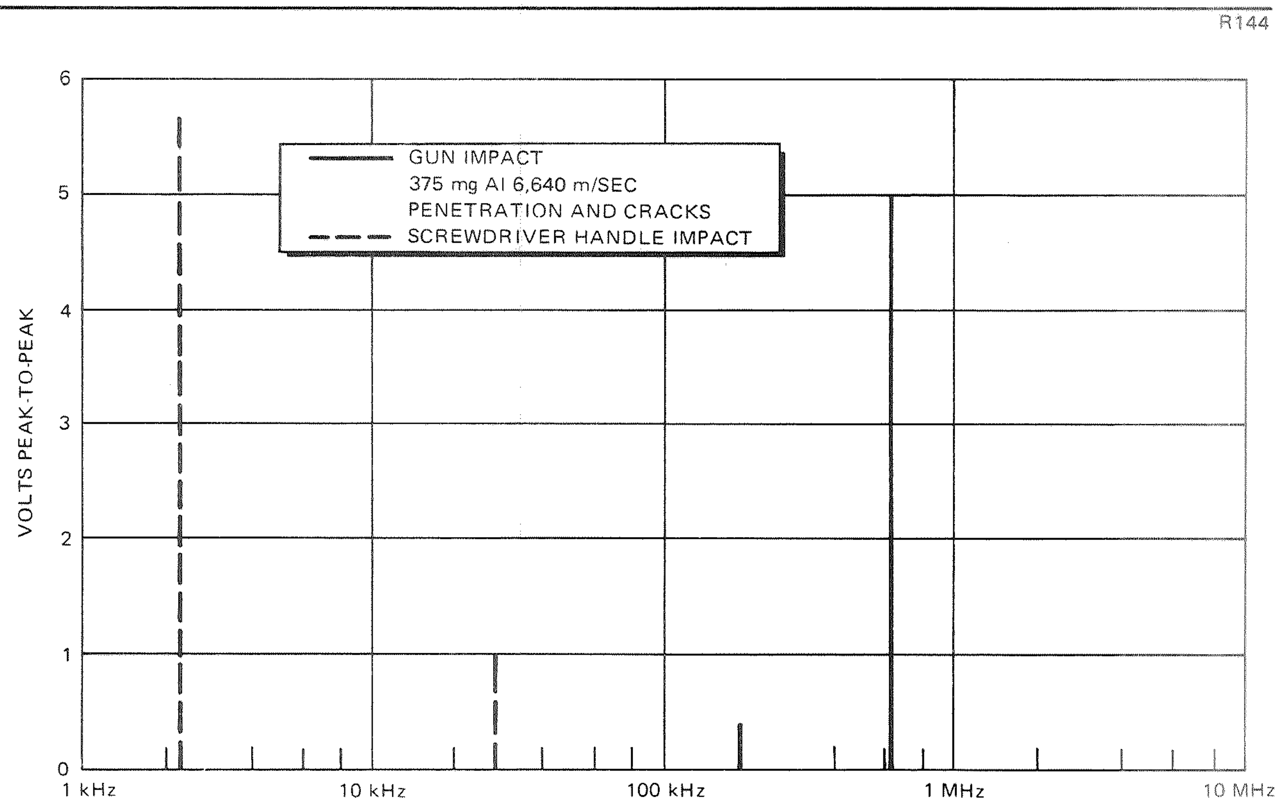


Figure B-4. Shot B48-46 Impact Signature

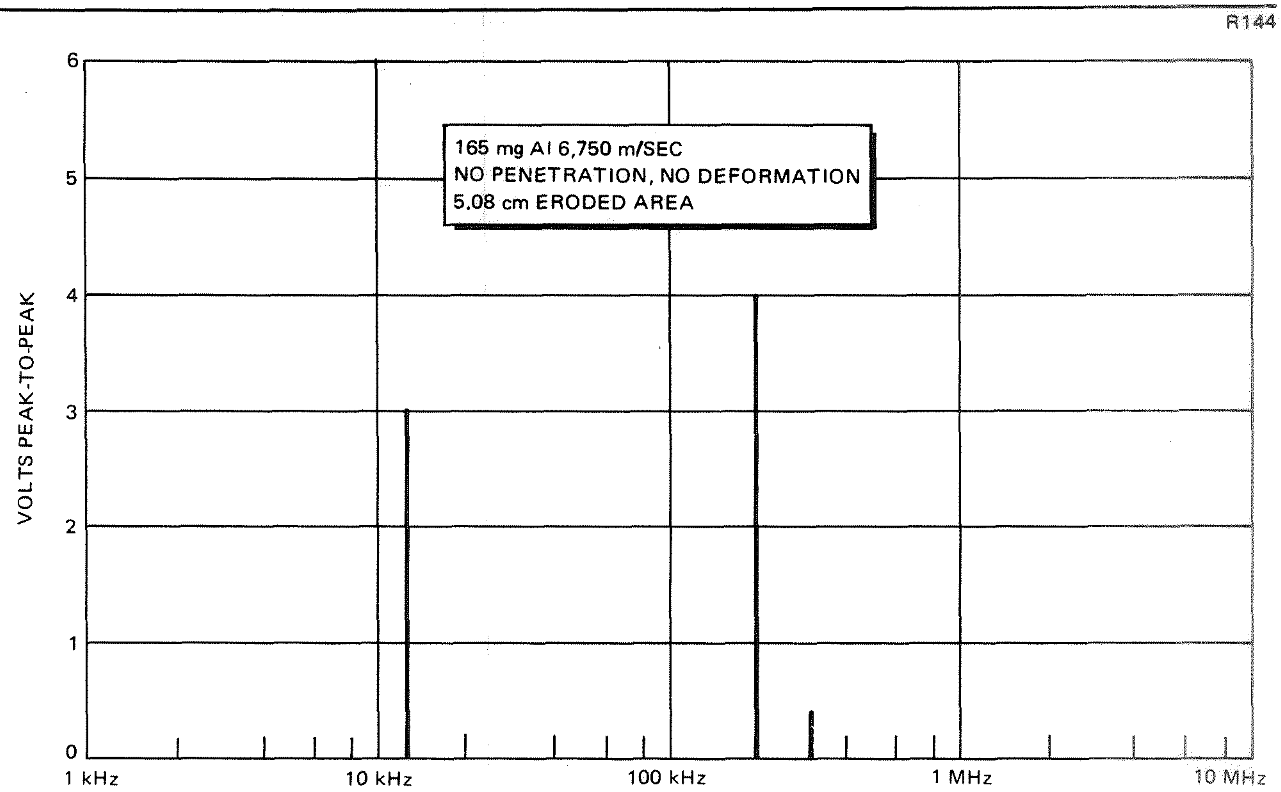


Figure B-5. Shot B48-49 Impact Signature

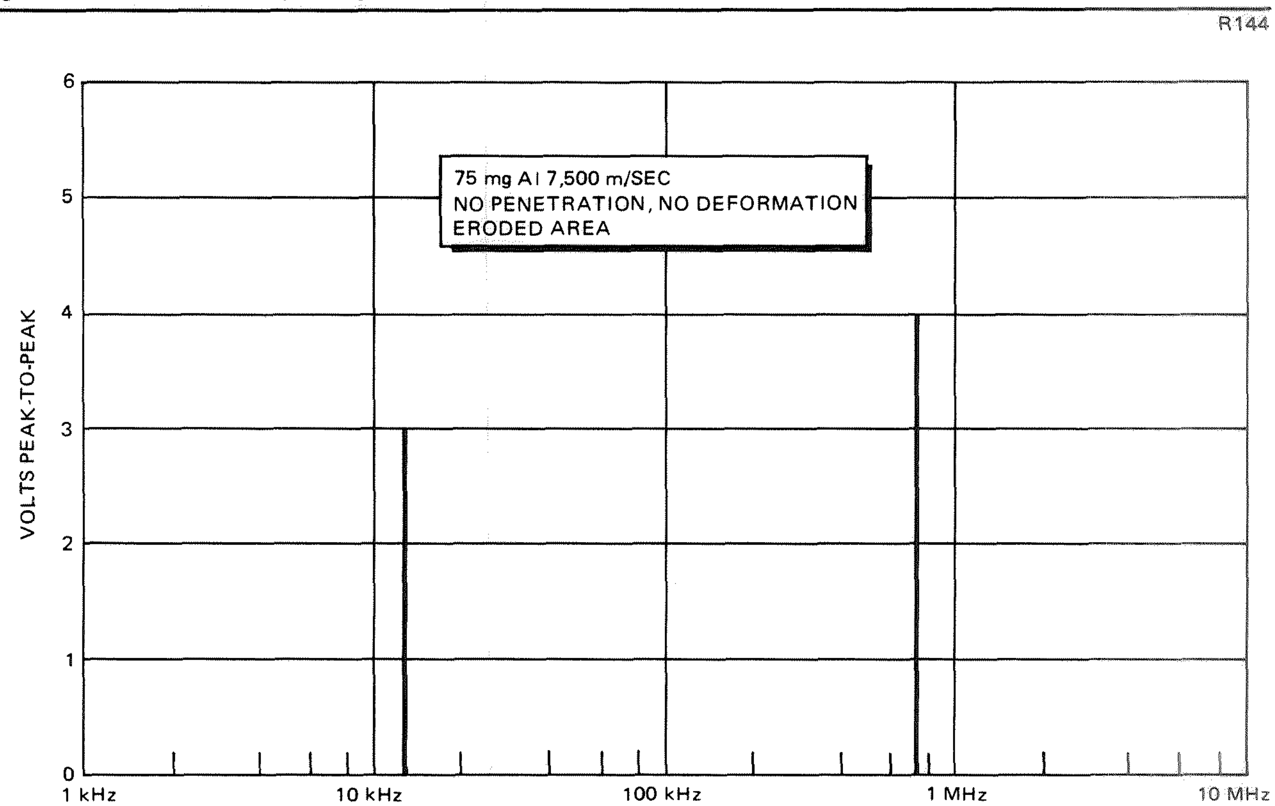


Figure B-6. Shot B48-52 Impact Signature

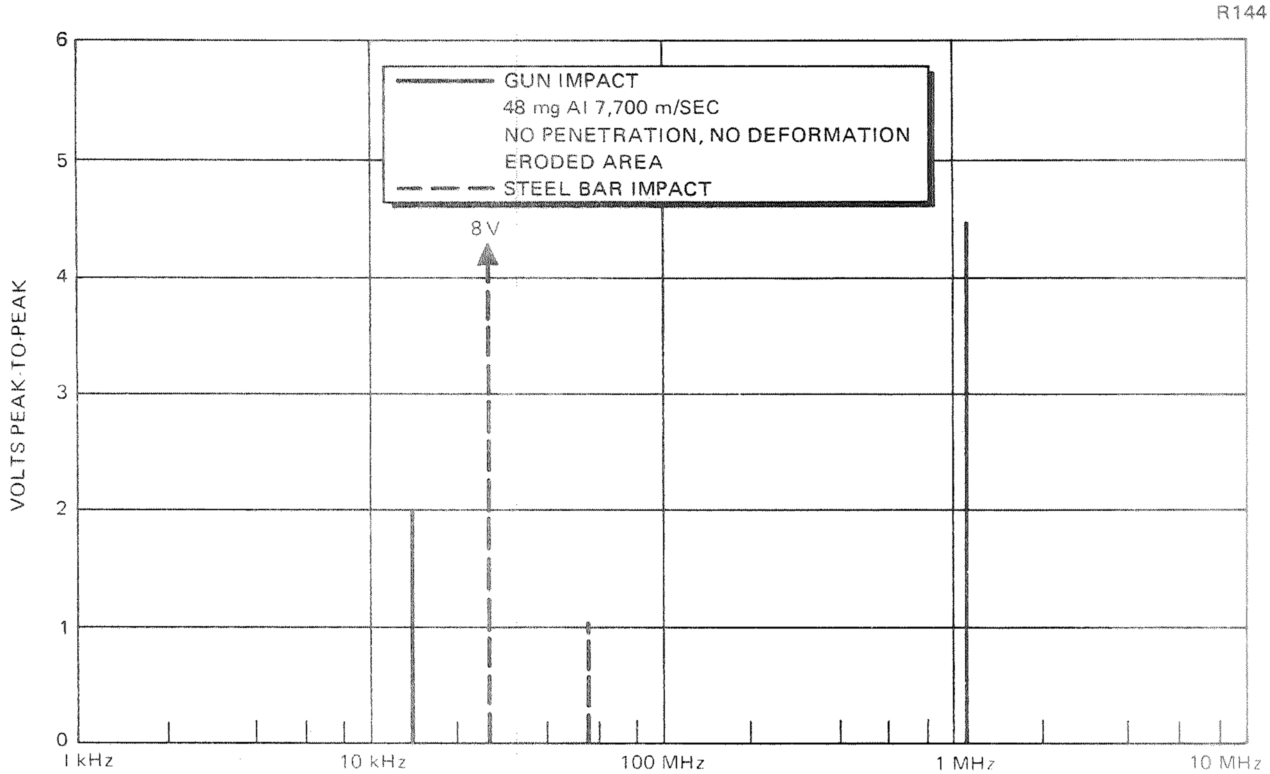


Figure B-7. Shot B48-53 Impact Signature

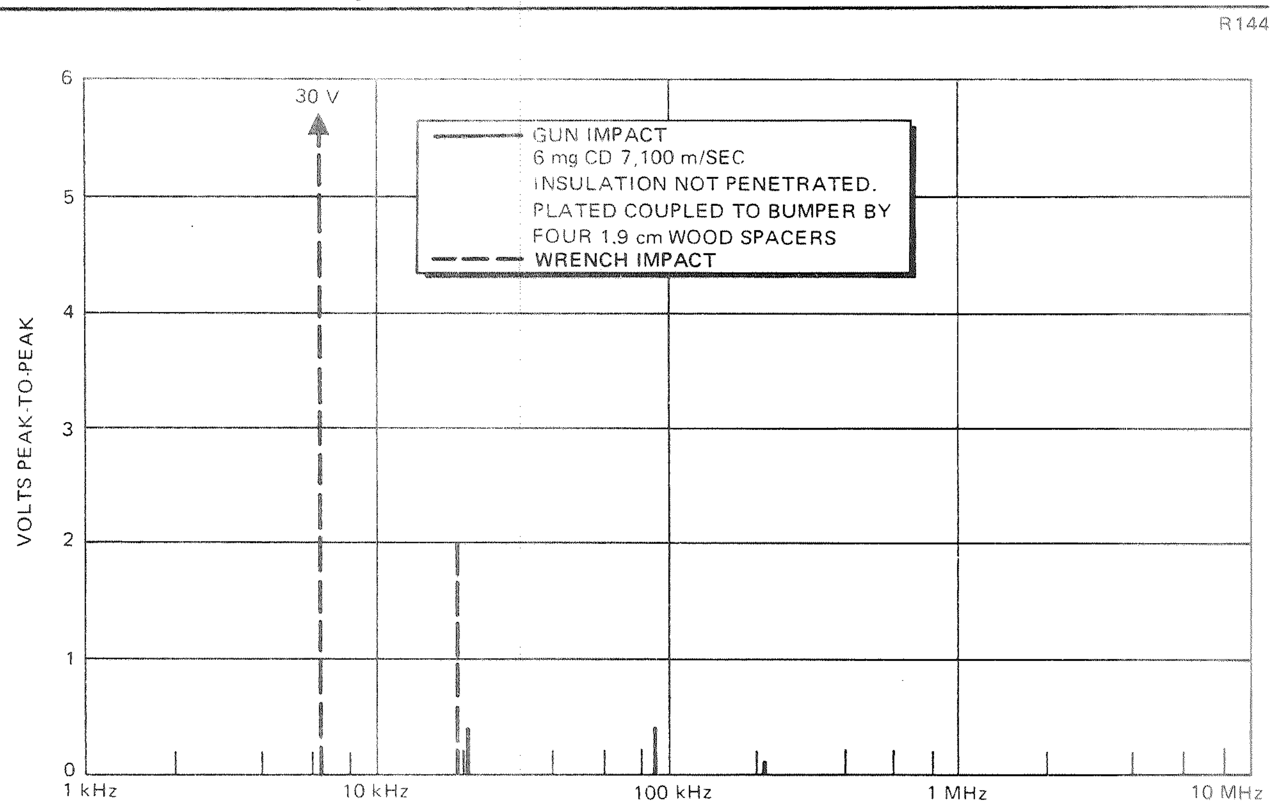


Figure B-8. Shot B48-54 Impact Signature

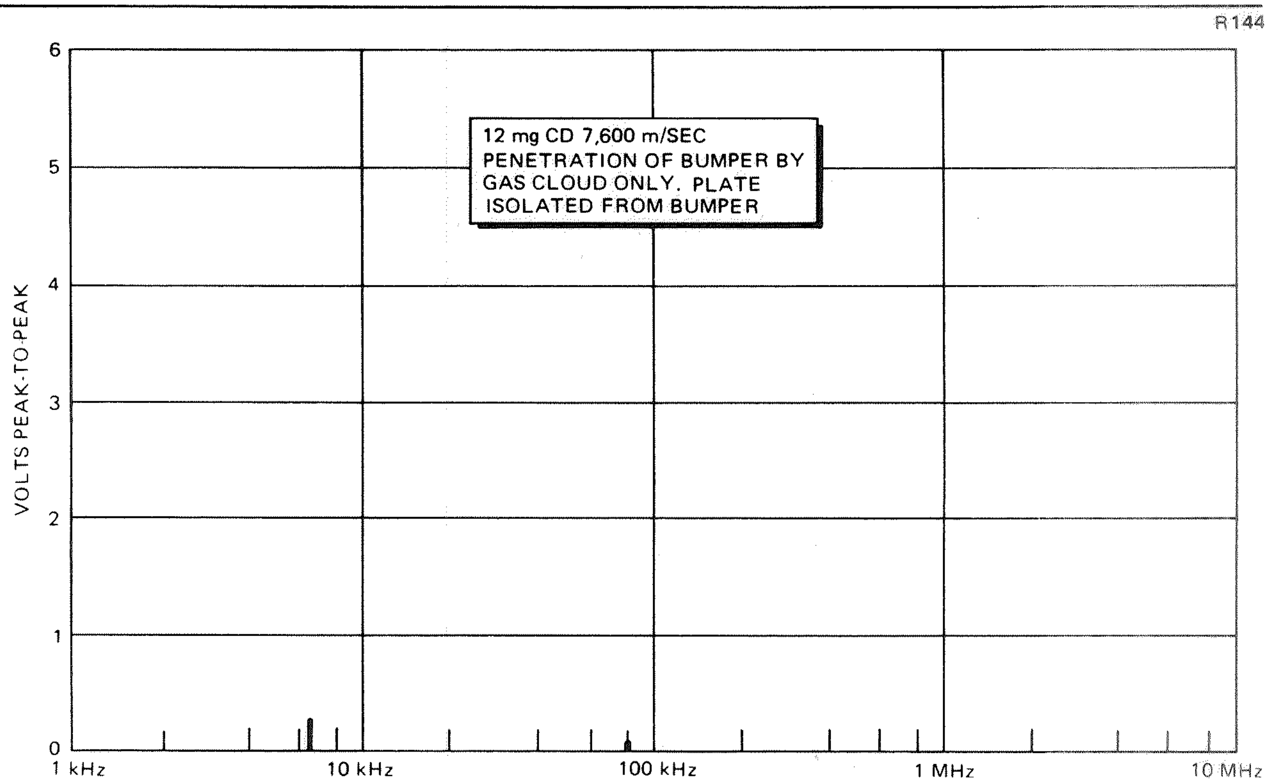


Figure B-9. Shot B48-55 Impact Signature

as the initial signal. A time-frequency history in a typical and the exceptional case is illustrated in Figure B-10. Figures B-11 and B-12 are representative recorded data. High-frequency oscillations are absent in the first 20 μsec after projectile impact of Figure B-12 followed by 3-kHz burst for 20 μsec. Even in this case, the fast rise time of the signal represents an initial high-frequency component.*

The highest frequency of large amplitude which can be excited in a structure by an impact is related to the duration of the impact; the shorter the duration, the higher the frequency. The duration is a function of the time required for the pulse to travel through one of the contacting parts and reflect to the interface. For example, a 0.16 cm diameter (1/16-inch) steel ball will excite a frequency of about 1 MHz. Larger objects will produce lower

*M. Garjup. Calibration of a Micrometeoroid Impact Gauge. University of Toronto Institute for Aerospace Studies. Technical No. 97. March 1967.

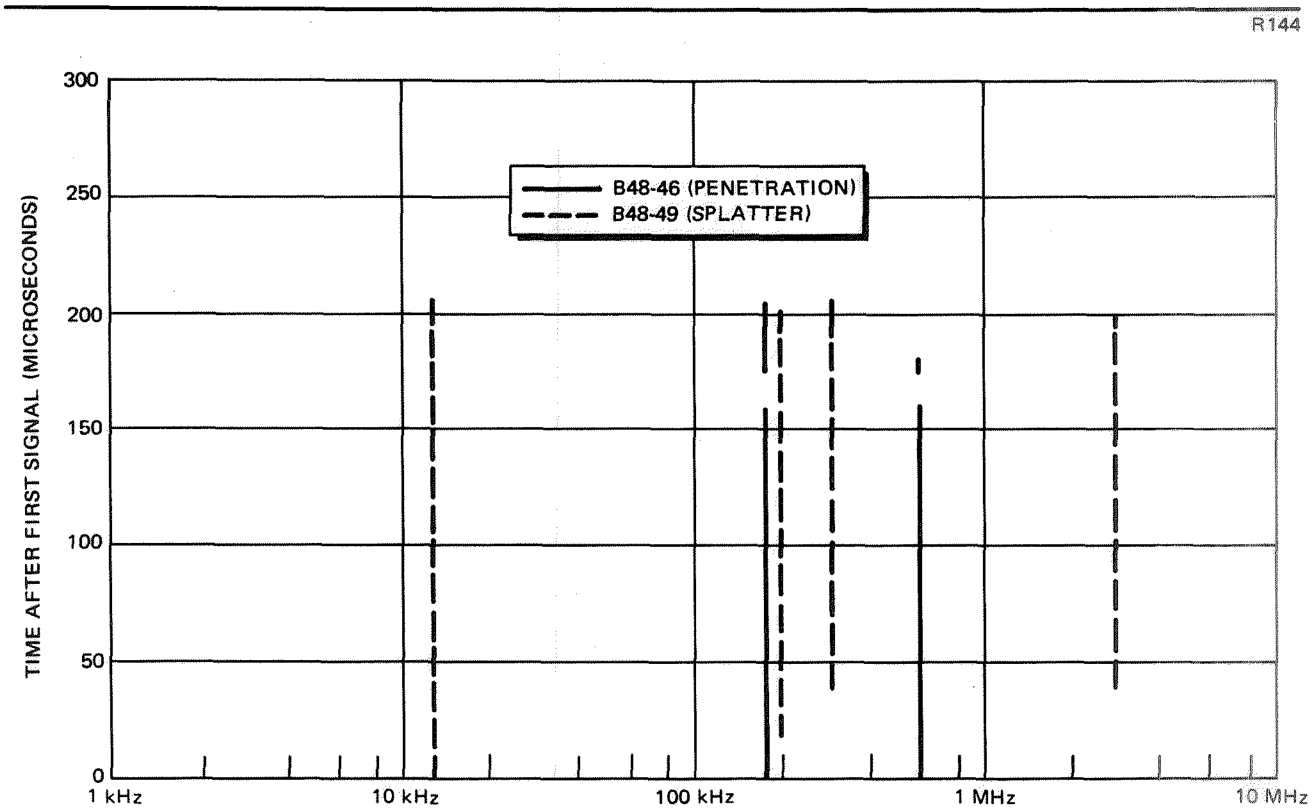
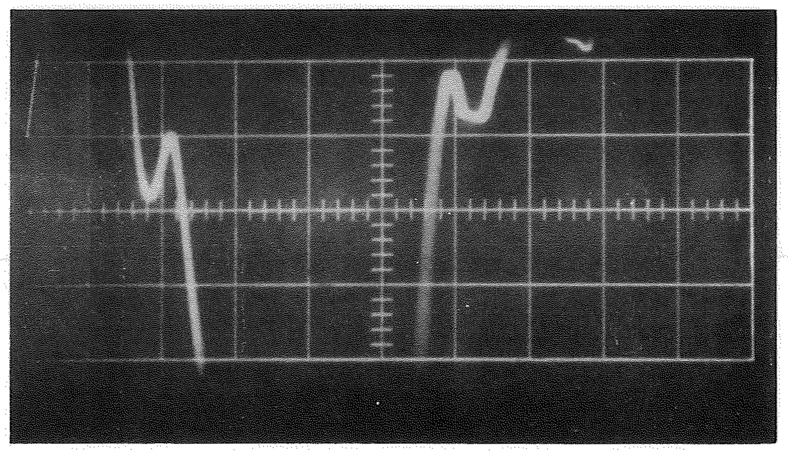


Figure B-10. Time/Frequency History of Impacts

frequencies because of the longer pulse durations generated. It has been found that the output of a piezogage is proportional to the momentum transferred by an impact. Thus, although small objects hitting a cabin wall at low velocities can generate high frequencies, the amplitudes will be low. Large low-velocity objects, while producing high amplitudes, will not generate high frequencies. The only obvious mechanism for generating high-frequency, high-amplitude acoustic waves is the direct impact of a meteoroid or the spray from meteoroid/bumper debris impinging on the cabin wall.

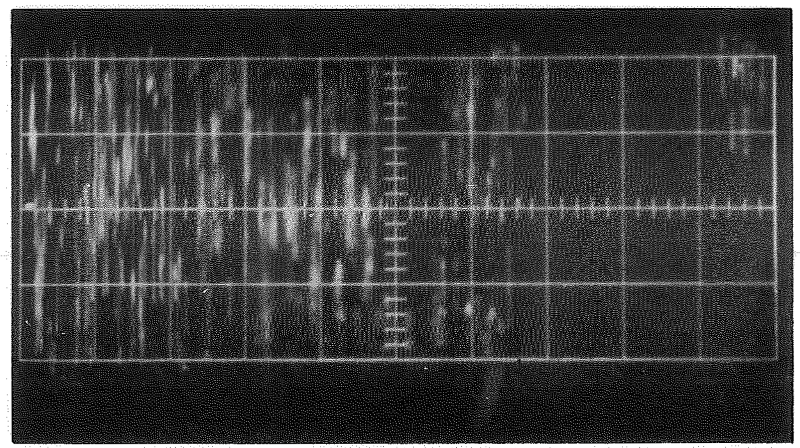
A second series of experiment were designed to evaluate the impact-generated signals after they have traveled some distance through a structure and assess the potential of a three-unit omnidirectional sensor system.

A sheet of 7075 T6 aluminum 122 x 58 x 0.32 cm was placed in the range tank of a light gas gun. The desired impact area was bolted to the connector tube between the range tank and blast receiver with a gasket so the blast



B48-53

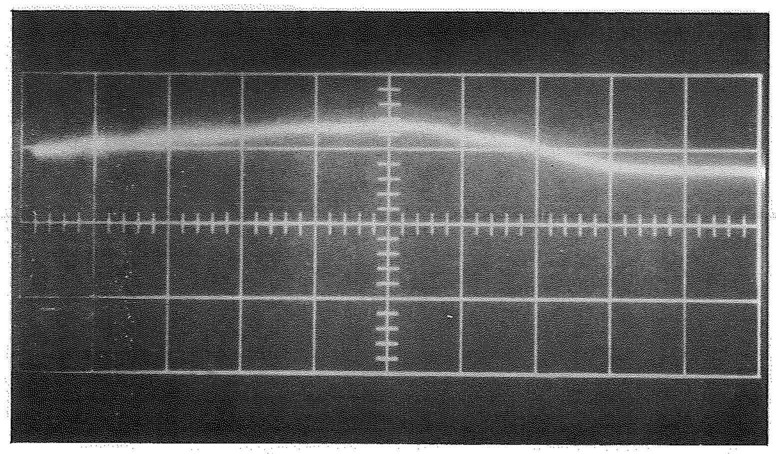
STEEL ROD IMPACT
1 V/cm 20 μSEC/cm



B48-53

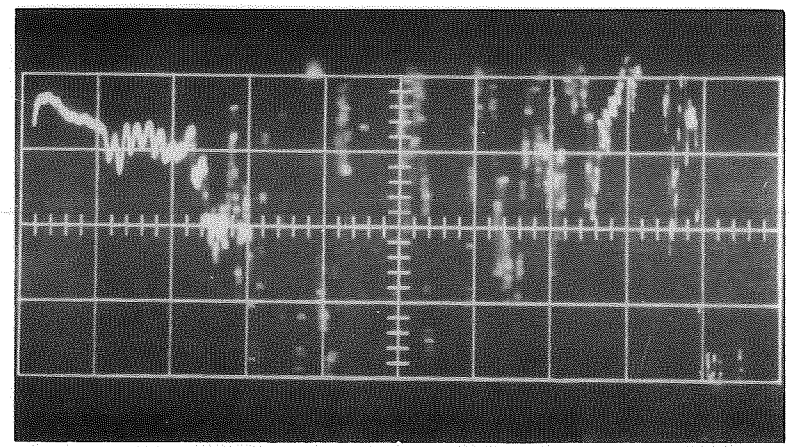
PROJECTILE IMPACT
1 V/cm 20 μSEC/cm

Figure B-11. Shot B48-53 Rod and Projectile Impact Traces



B48-49

STEEL ROD IMPACT 5 V/cm 50 μSEC/cm



B48-49

PROJECTILE IMPACT 1 V/cm 20 μSEC/cm

Figure B-12. Shot B48-49 Rod and Projectile Impact Traces receiver could be evacuated (Figure B-13). The clamping action prevented flexure waves generated by impact from propagating beyond the gasket, but little attenuation to the longitudinal wave resulted. The range tank was maintained at 1-atm pressure. Three of the special transducers were mounted on the rear surface of the target sheet and connected to separate oscilloscope channels. All traces were triggered together, preserving the time relationship.

A total of three shots were made on this sheet (Figures B-14, B-15 and B-16). The longitudinal wave velocity in the sheet was calculated from the difference in arrival times of the first signal appearing at two transducers using the impact location to establish path lengths. Using this velocity constant, the arrival time differences at the three transducer pairs was converted into path length differences. These path length differences were used to generate the sets of hyperbolas locating the impact point. (The hyperbola generated from transducers 1 and 2 of Figure B-14 is not shown because the curvature is too steep for accurate plotting.)

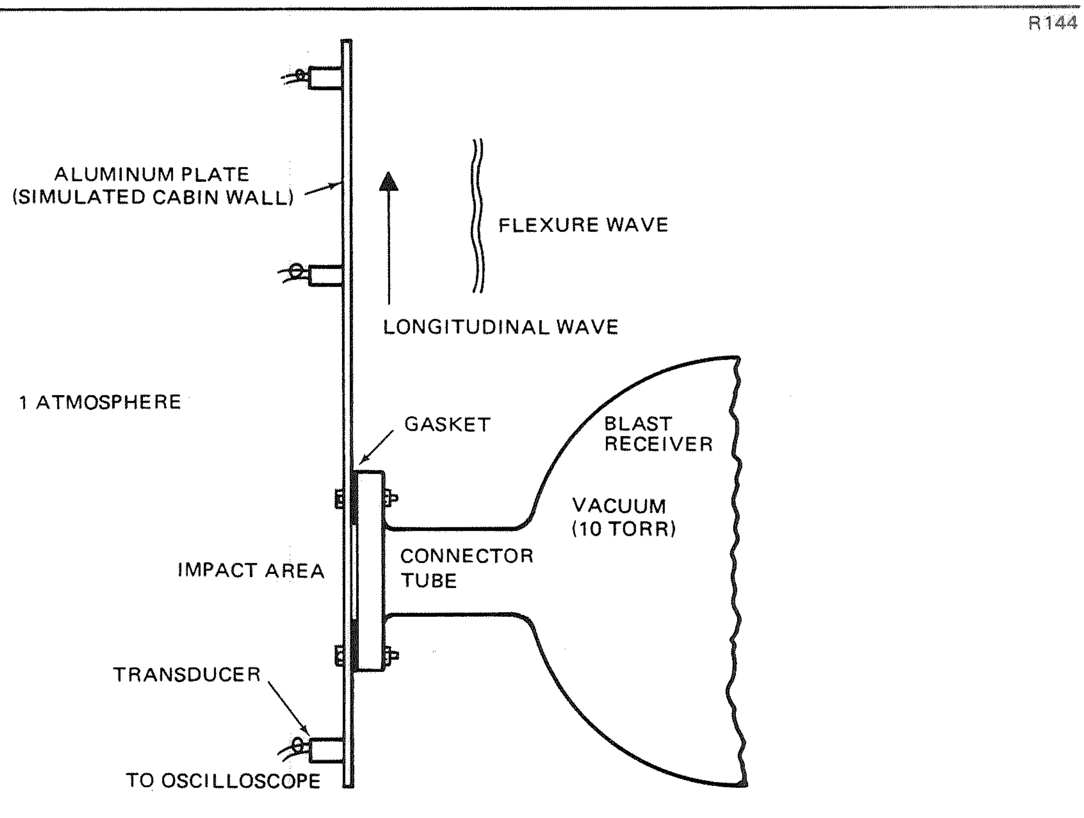


Figure B-13. Test Set-Up

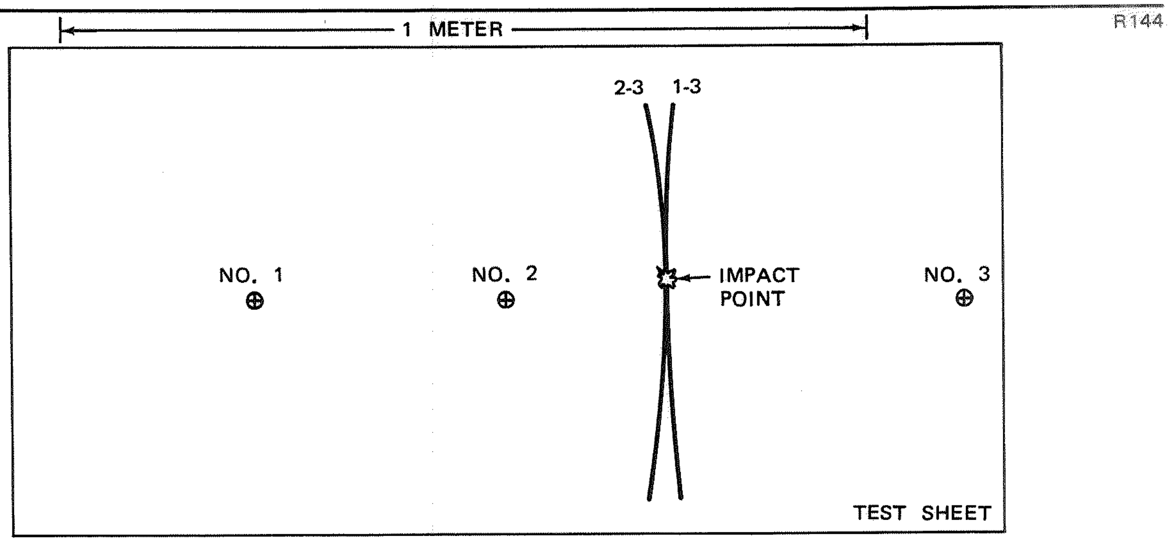


Figure B-14. Shot B56-1 Test Sheet

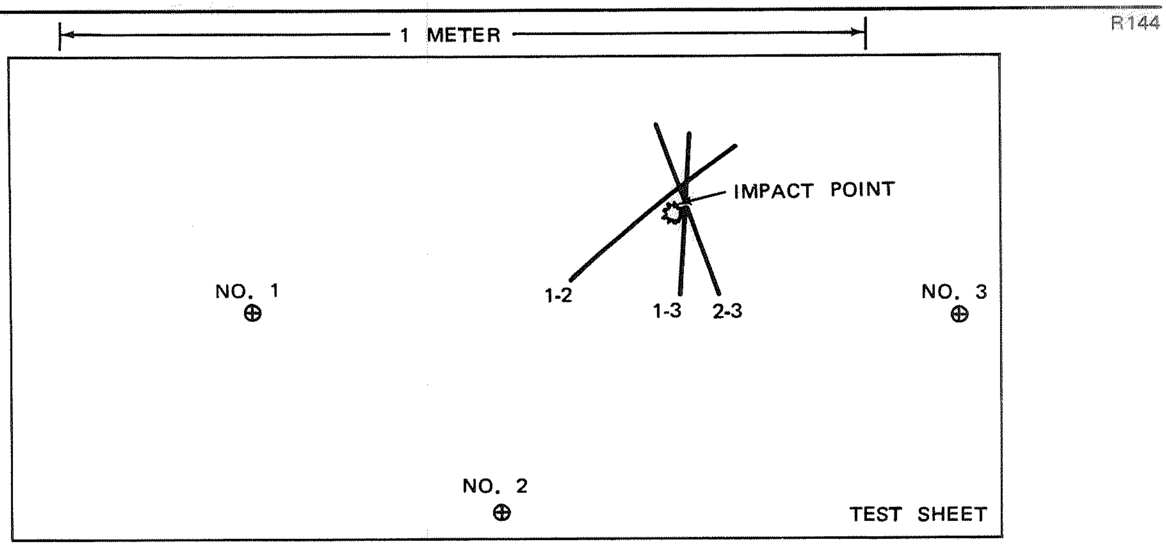


Figure B-15. Shot B-56-2 Test Sheet

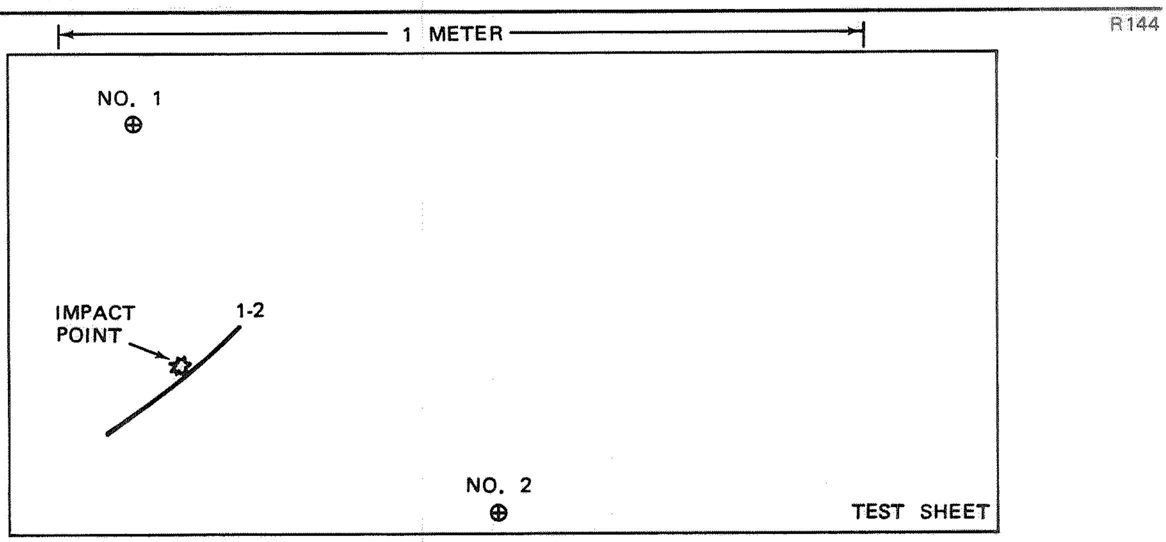


Figure B-16. Shot B56-3 Test Sheet

A second sheet of 7075 T6 aluminum 122 x 61 x 0.254 cm was reinforced with stiffeners of 2024 T3 aluminum as shown in Figures B-17 through B-20. Three shots were made on this plate and the calculations performed as before. The decreased plate thickness resulted in a 10-percent reduction in shock velocity. Except for an apparent error in shock arrival time at transducer 2 of Shot B56-6, the stiffeners had no apparent effect on the measurements. This is rather surprising in view of the effect of thickness upon velocity. Figure B-21 shows typical impact signatures for this configuration.

A fourth impact was made on the second sheet which was protected by a 0.04 cm (0.025 inch) thick 7075 T6 bumper with a 5.1-cm standoff distance (Figure B-22). Although the bumper caused a large spray to impinge on the plate, the projectile retained enough integrity to penetrate the target plate.

The test conditions are summarized in Table B-2. Two tests (B56-3 and B56-4) are lacking data as a result of a defective film in the oscilloscope

Table B-2

TRIANGULATION LOCATION TEST CONDITIONS

Shot	Velocity (km/sec)	Transducer 1	Transducer 2	Transducer 3
B56-1	6.18	55 μsec	0 Ref	29 μsec
-2	6.18	32	13	0
-3	6.35	0	19	-
-4	6.5	0	-	101
-5	6.4	104	0	0
-6	6.6	0	20	37
-7	6.45	46	0	5

All projectiles 0.975 cm diameter by 0.507 cm long (0.360-g polyethylene)

Longitudinal velocity on B56-1, 2, and 3 - 0.56 cm/μsec

Longitudinal velocity on B56-4 through 7 - 0.507 cm/μsec

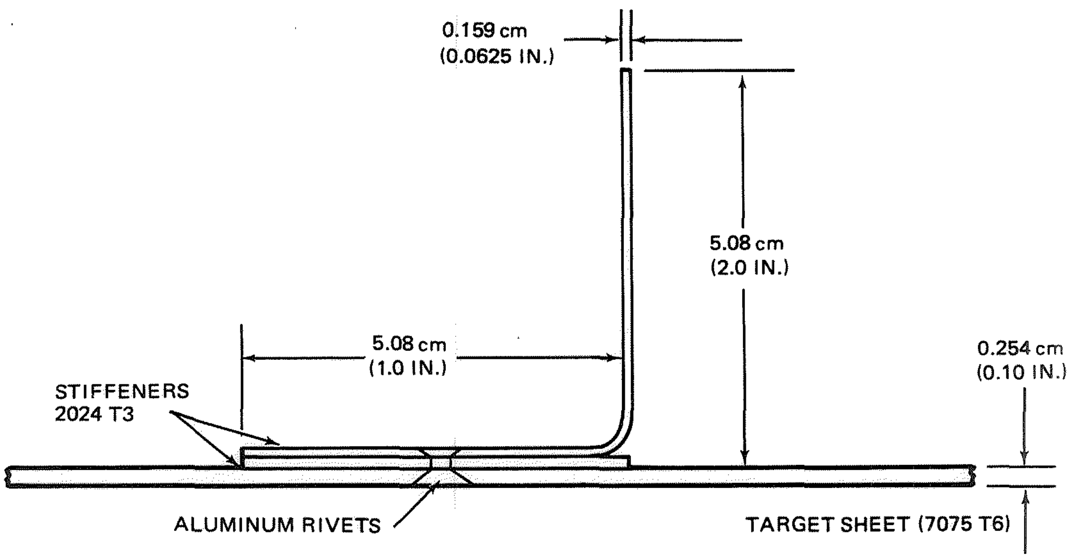


Figure B-17. Stiffener Detail

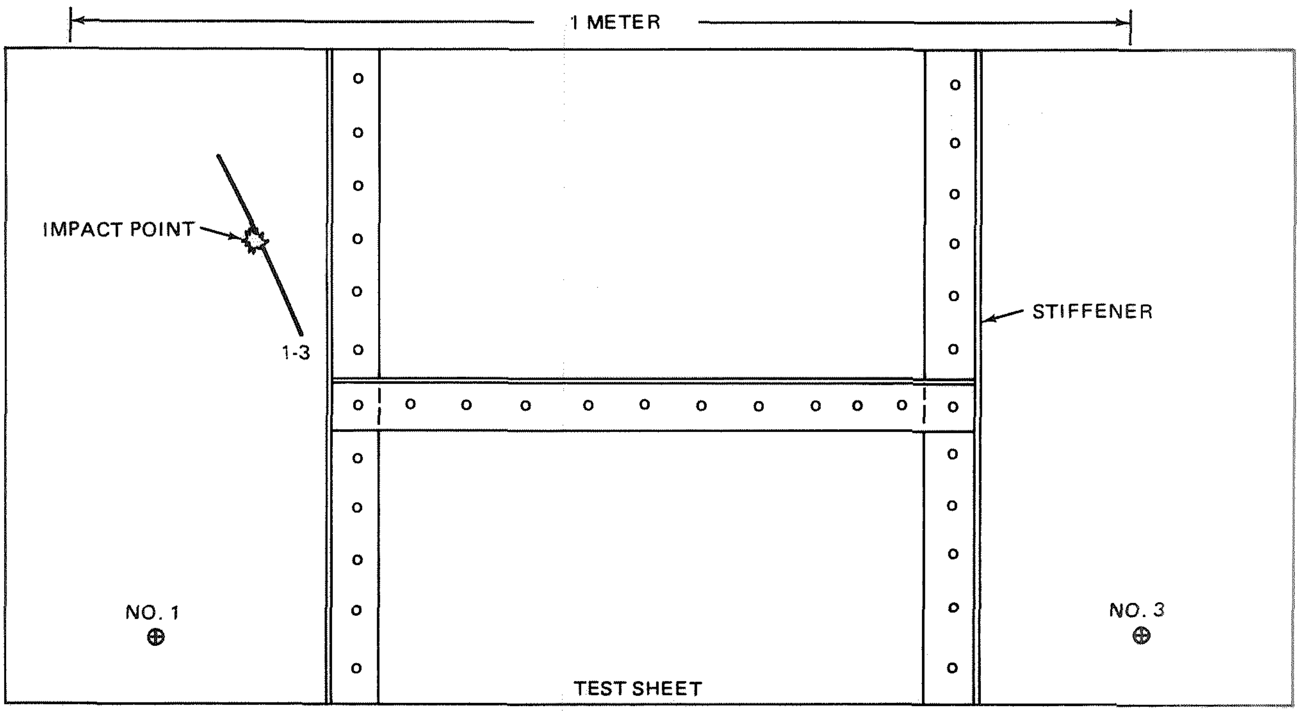


Figure B-18. Shot B56-4 Test Sheet

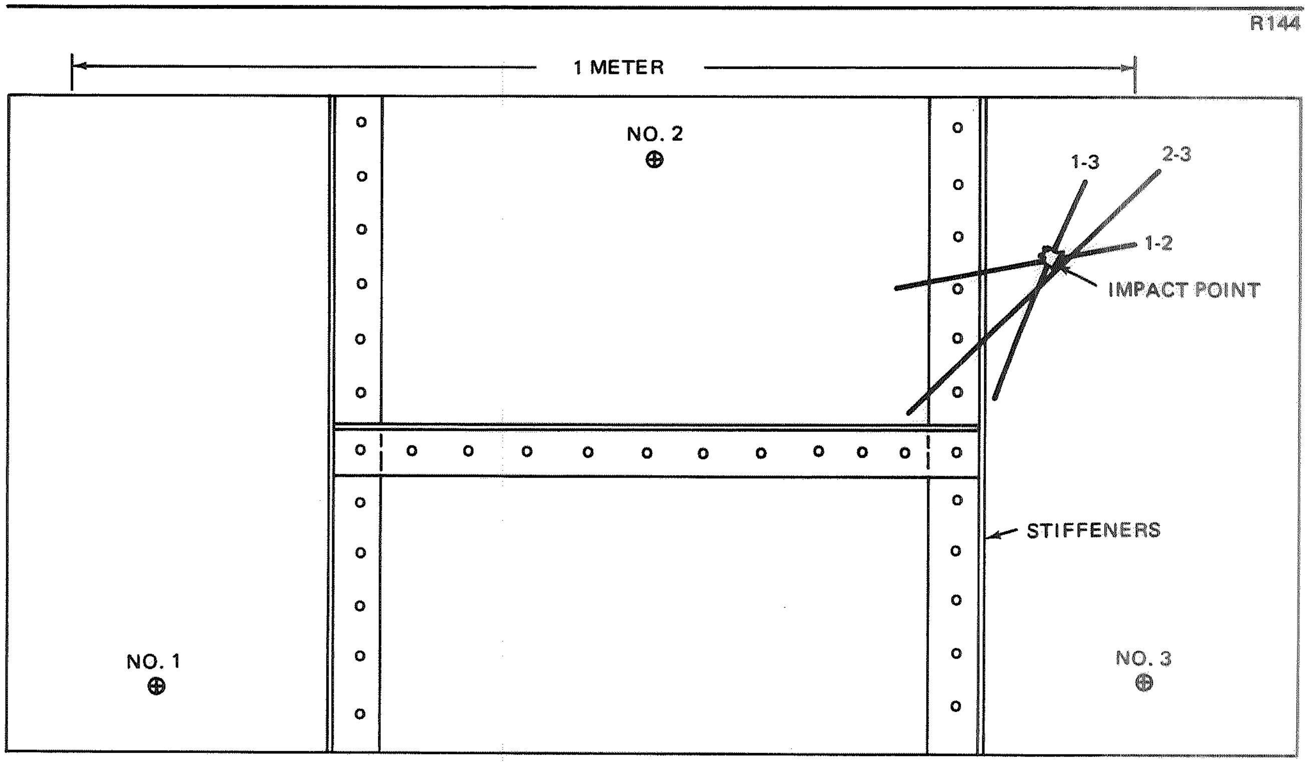


Figure B-19. Shot B56-5 Test Sheet

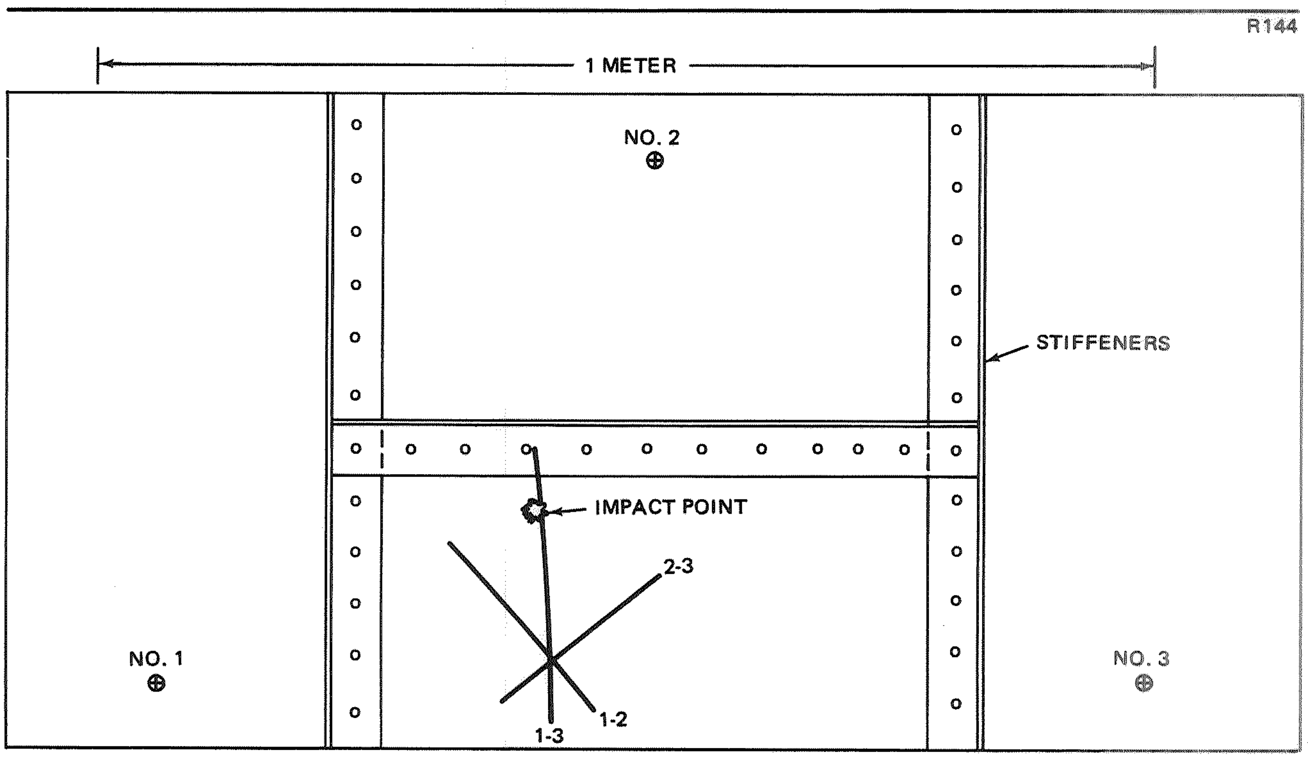
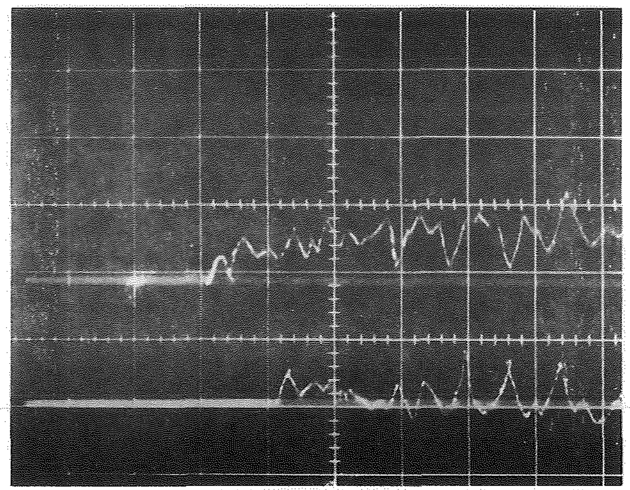


Figure B-20. Shot B56-6 Test Sheet



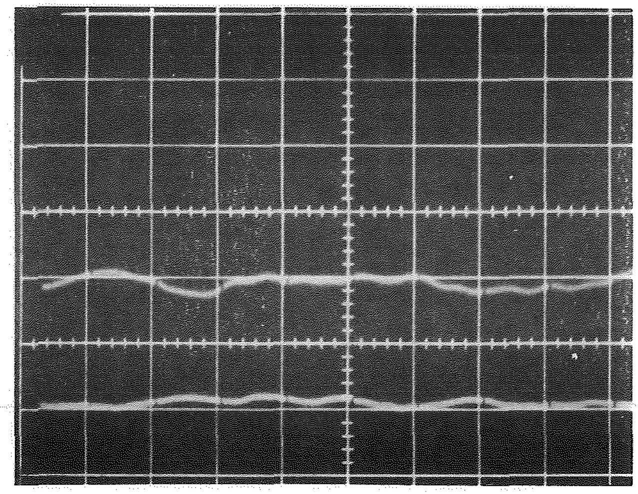
B56-6 IMPACT

UPPER TRACE – TRANSDUCER NO. 1

20 SEC/cm
20 VOLTS/cm

LOWER TRACE – TRANSDUCER NO. 2

20 SEC/cm
20 VOLTS/cm



IMPACT BY 1/2 X 3 INCH BOLT

UPPER TRACE – TRANSDUCER NO. 1

20 SEC/cm
2 VOLTS/cm

LOWER TRACE – TRANSDUCER NO. 2

20 SEC/cm
2 VOLTS/cm

Figure B-21. Impact Signatures

R144

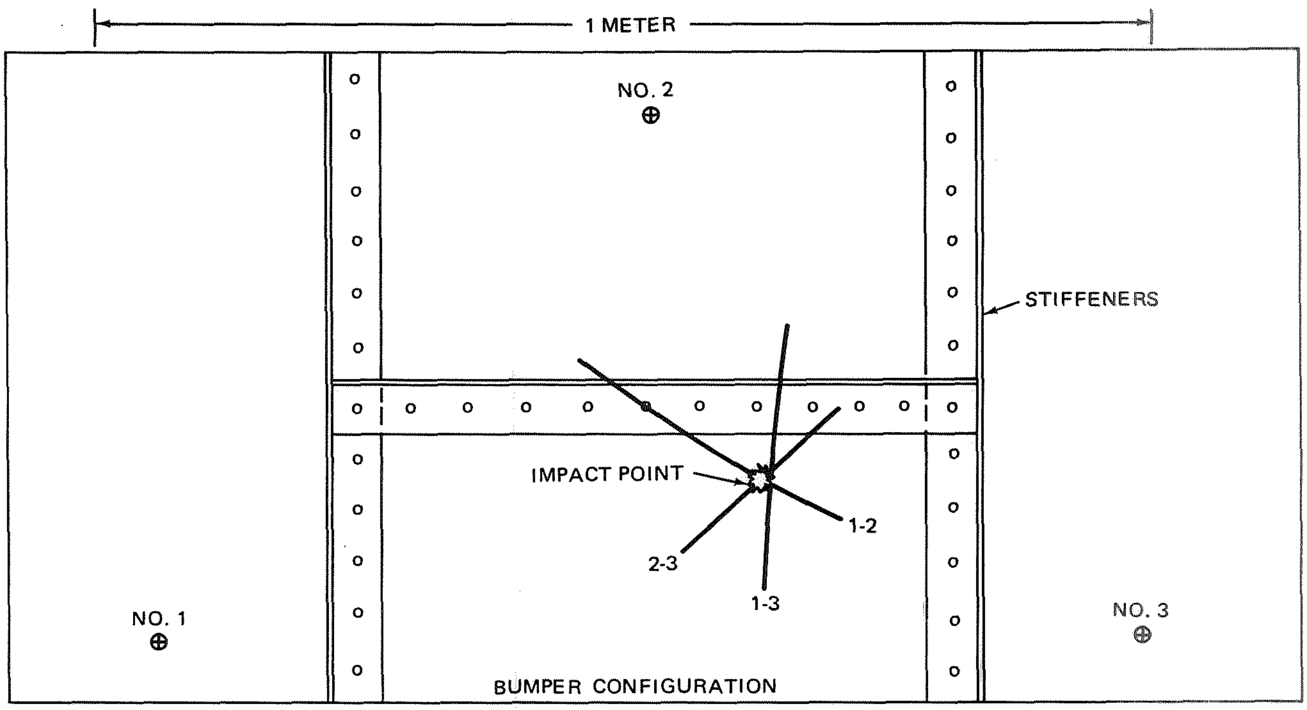


Figure B-22. Shot B56-7 Test Sheet—Bumper Configuration (Double Wall)

camera. It is observed that the high-frequency oscillations seen in the first series of tests are absent although fast rise times are still present. (The high sensitivity used in the first series makes a direct comparison of rise times difficult.)

Conclusions

The following conclusions were reached:

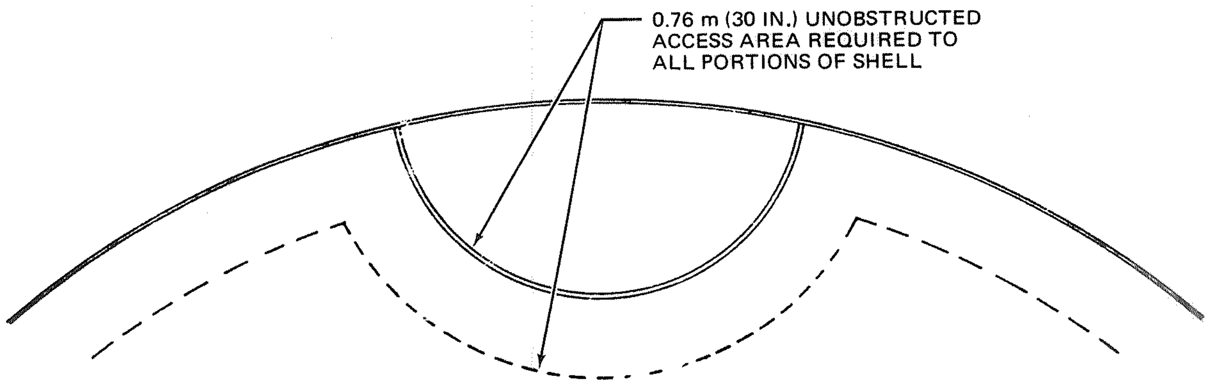
A. Impact location by a wave arrival time technique has been proven on a limited scale test and appears less sensitive to structural irregularities than was predicted.

B. The signature of a meteoroid impact contains high-frequency components of high amplitude. These components can be used as the basis for activating a detection system.

Appendix C
ACCESS METHODS

This appendix presents a pictorial review of access methods that can be used for leak repairs on the pressure shell or to the installed vehicle system. Each figure presents the condition obstructing access, identifies the access method, and has a brief comment on the method. For additional information on how each access method was evaluated and identified, refer to Section 6 of this report.

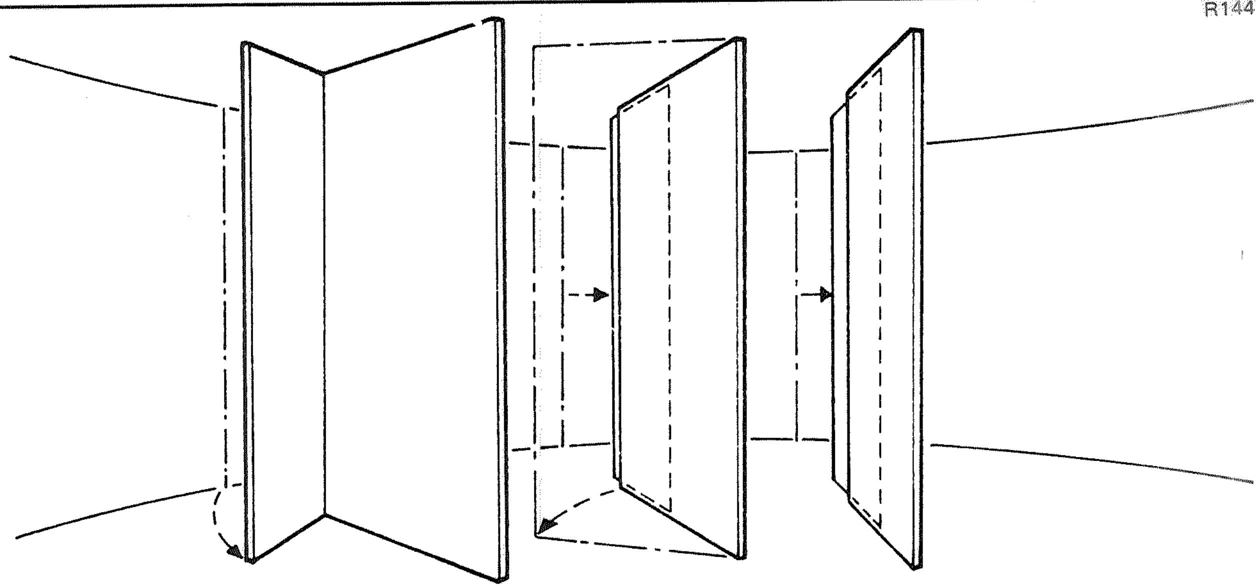
R144



ACCESS METHOD
INHERENT IN DESIGN
COMMENT
INHERENT-IN-DESIGN IS THE FIRST METHOD TO BE CONSIDERED IN ACCESS SELECTION PROCESS. WHERE APPLICABLE, IT IS TO BE UTILIZED (AS IN ABOVE-ILLUSTRATED CONDITION).

Figure C-1. Airlock Equipment Protruding into Access Area

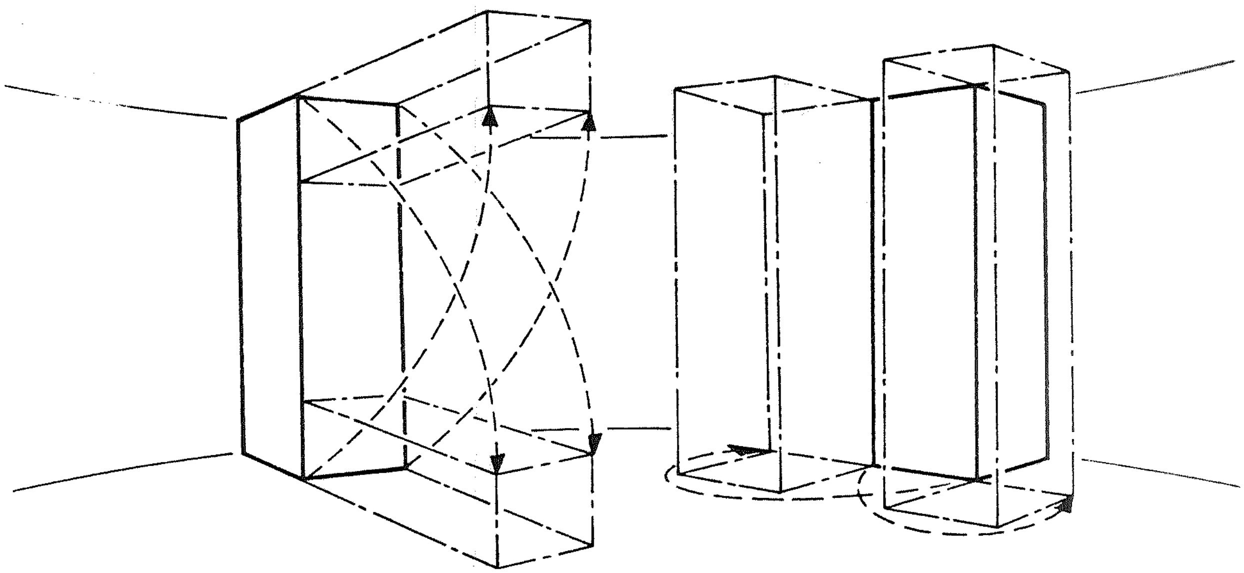
R144



ACCESS METHOD
PIVOT, SLIDE, SLIDE/PIVOT
COMMENT
PIVOT ACCESS IS MOST DESIRABLE; SLIDE, SLIDE/PIVOT, AND UNIT REMOVAL ARE SECOND, THIRD, AND FOURTH IN ORDER OF DESIRABLE ACCESS METHODS

Figure C-2. Partition Butting Against Shell

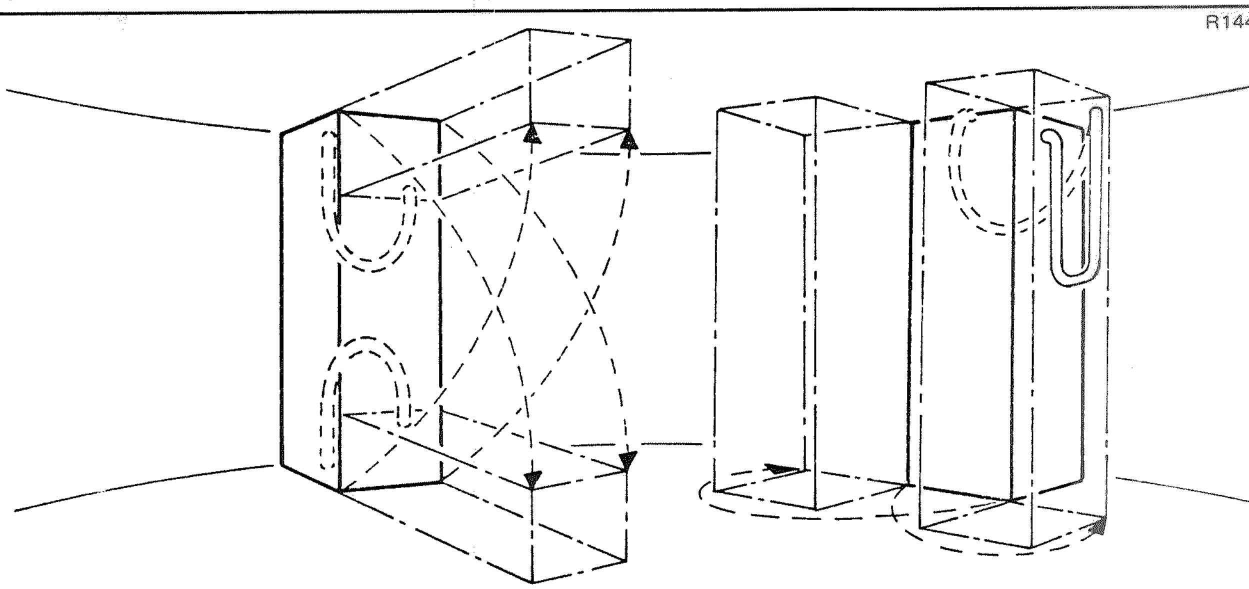
R144



ACCESS METHOD
PIVOT
COMMENT
PIVOT ACCESS IS THE MOST DESIRABLE METHOD. UNIT REMOVAL, SLIDE, AND SLIDE/PIVOT ARE SECOND, THIRD, AND FOURTH METHODS, RESPECTIVELY.

Figure C-3. Storage Cabinet Butting Against Shell

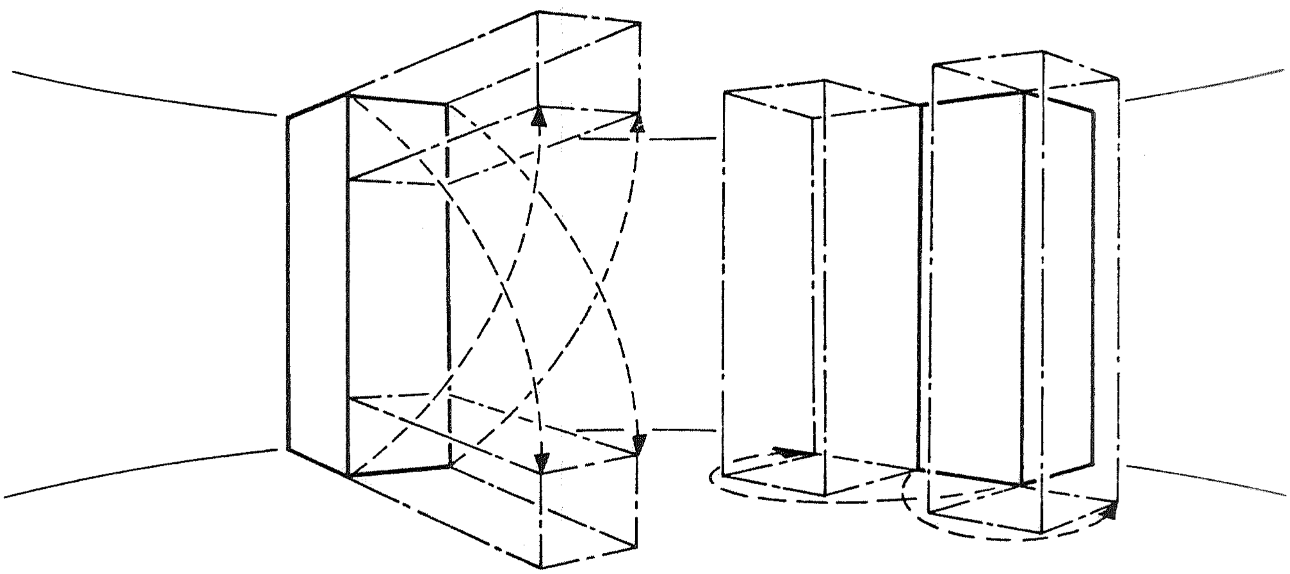
R144



ACCESS METHOD
PIVOT
COMMENT
PIVOT ACCESS IS THE FIRST CHOICE; SLIDE, UNIT REMOVAL, AND SLIDE/PIVOT ARE SECOND, THIRD, AND FOURTH METHODS, RESPECTIVELY.
NOTE
FLEX LINES TO BE AS SHORT AS POSSIBLE AND AS CLOSE TO THE LINE OF PIVOT AS FEASIBLE.

Figure C-4. Equipment Butting Against Shell (Flex Lines)

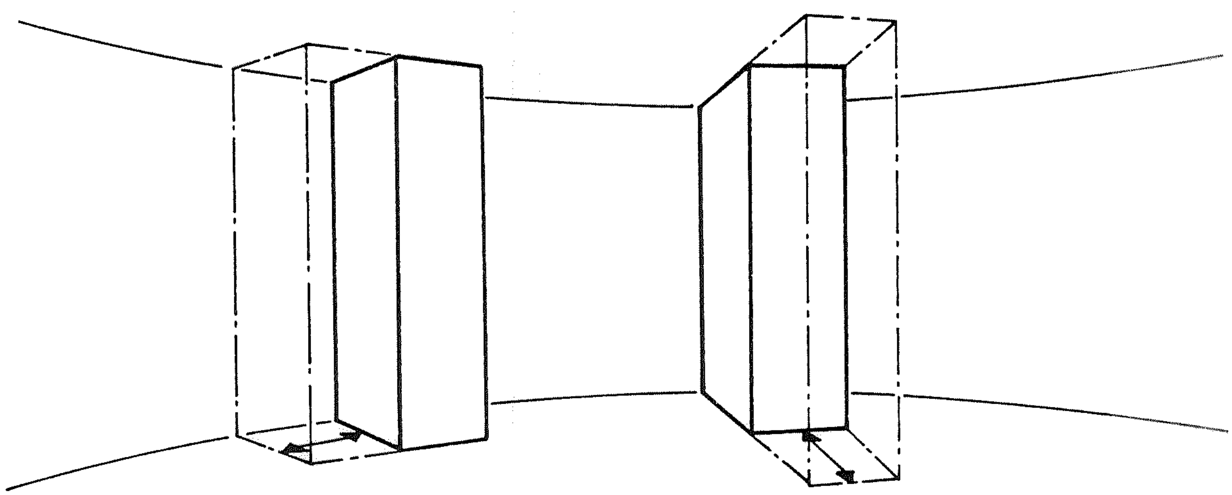
R144



ACCESS METHOD
PIVOT
COMMENT
PIVOT ACCESS METHOD IS THE FIRST CHOICE FOR BOTH OF THE ILLUSTRATED ACCESS CONDITIONS, FOLLOWED BY UNIT REMOVAL, SLIDE, AND SLIDE/PIVOT, RESPECTIVELY.

Figure C-5. Equipment Butting Against Shell (Disconnect Lines)

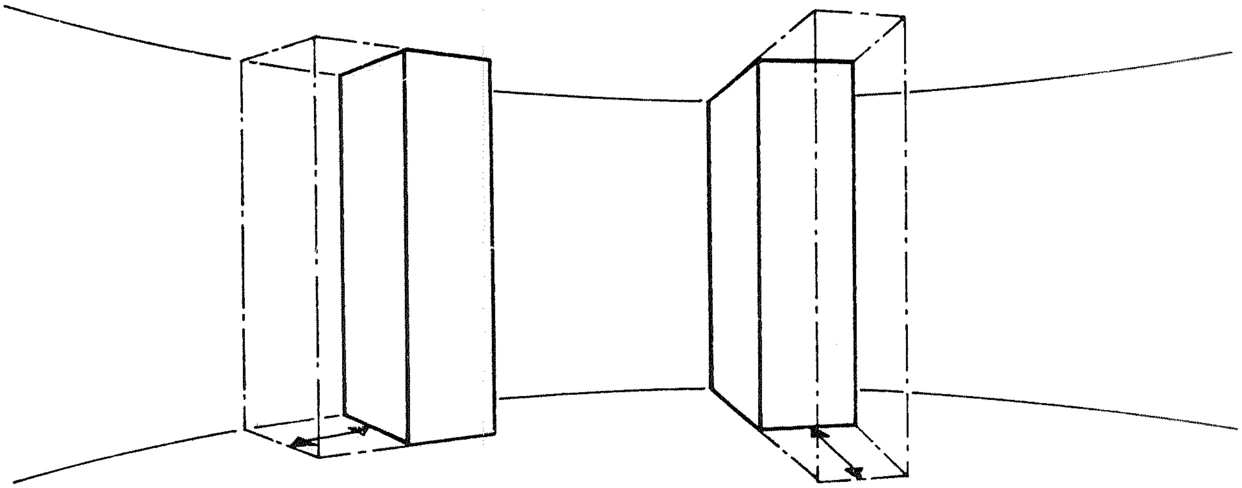
R144



ACCESS METHOD
SLIDE
COMMENT
SLIDE ACCESS TO BE UTILIZED WHEN PIVOT AND UNIT REMOVAL ACCESS ARE NOT FEASIBLE.

Figure C-6. Storage Cabinets Butting Against Shell

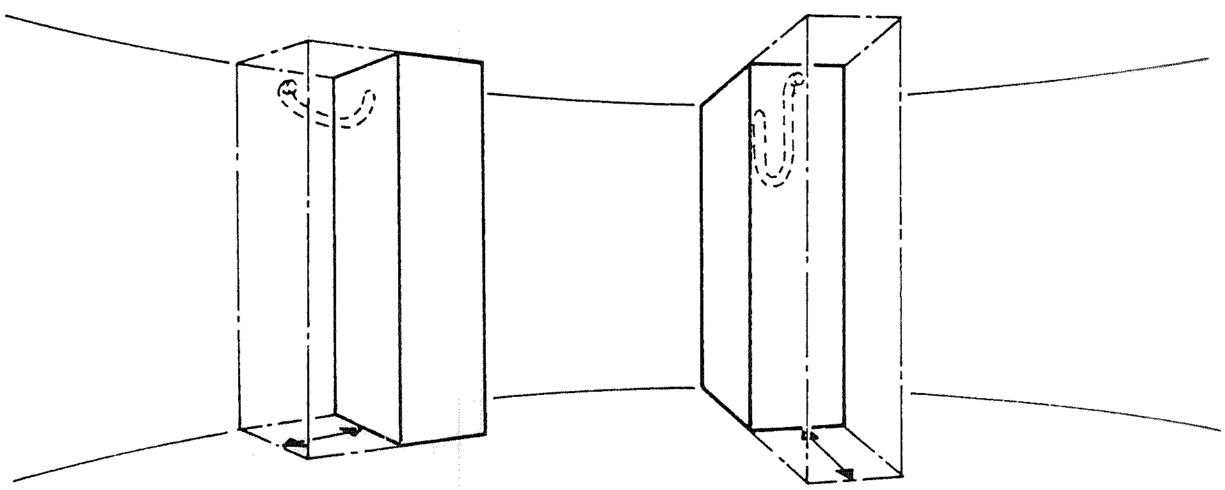
R144



ACCESS METHOD
SLIDE
COMMENT
SLIDE ACCESS IS THE THIRD CHOICE OF ACCESS METHODS. PIVOT AND UNIT REMOVAL RANK FIRST AND SECOND, RESPECTIVELY, AS ACCESS METHODS.

Figure C-7. Equipment Butting Against Shell (Disconnect Lines)

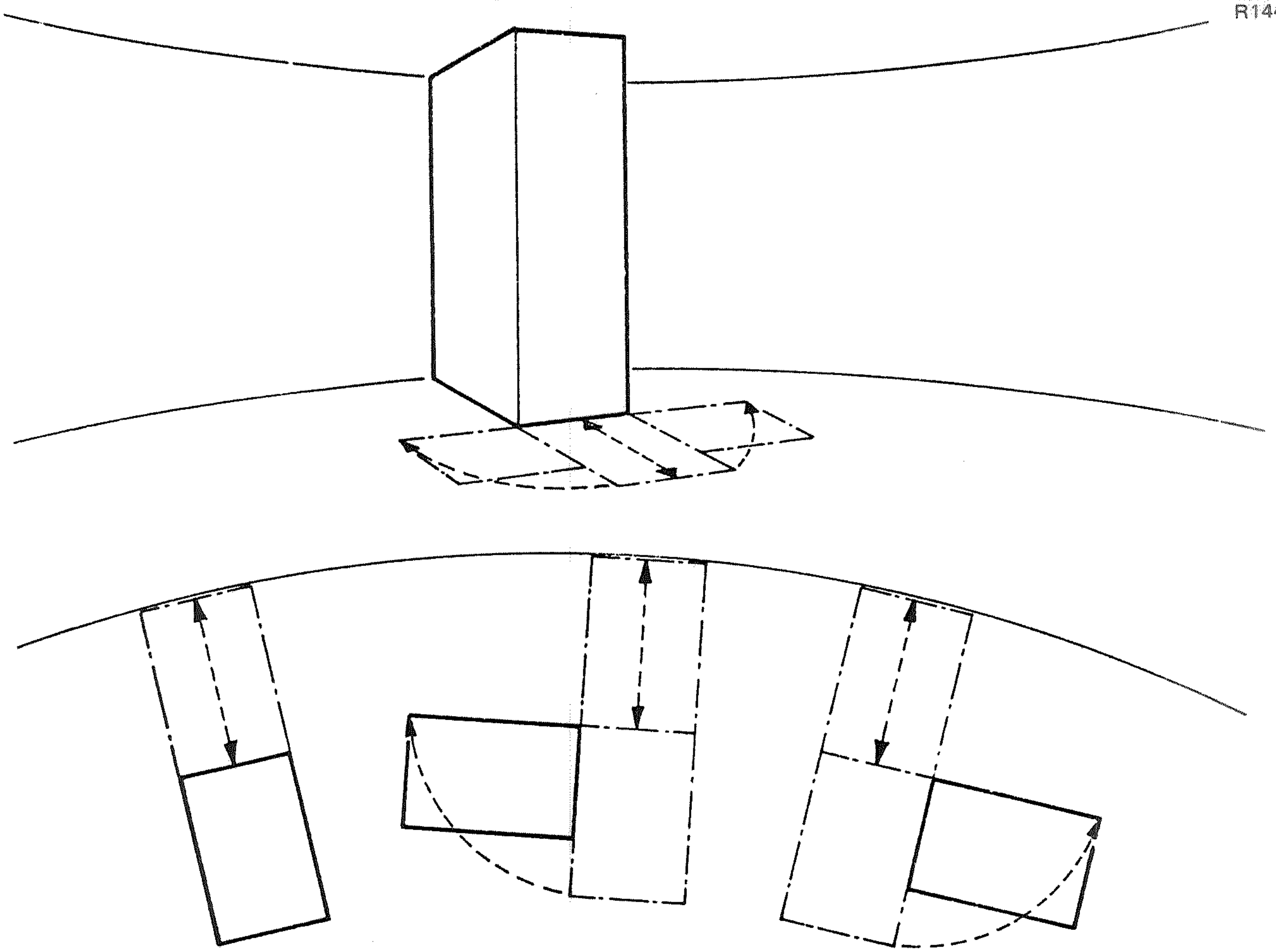
R144



ACCESS METHOD
SLIDE
COMMENT
SLIDE ACCESS IS THE SECOND-CHOICE METHOD; PIVOT ACCESS AND UNIT REMOVAL THE FIRST AND THIRD CHOICES, RESPECTIVELY.

Figure C-8. Equipment Butting Against Shell (Flex Lines)

R144

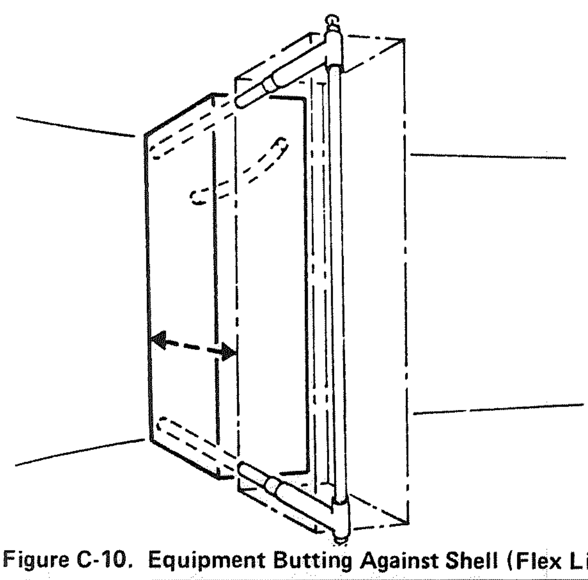


ACCESS METHOD
SLIDE/PIVOT

COMMENT
SLIDE/PIVOT ACCESS IS THE LEAST DESIRABLE METHOD AND IS UTILIZED ONLY IF PIVOT, UNIT REMOVAL, AND SLIDE ACCESS CANNOT BE INCORPORATED'

Figure C-9. Storage Cabinets Butting Against Shell

R144

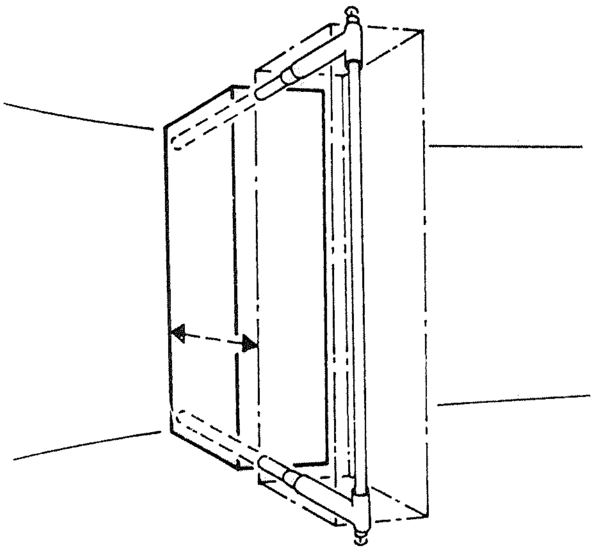


ACCESS METHOD
UNIT REMOVAL

COMMENT
UNIT REMOVAL IS THE THIRD CHOICE ACCESS METHOD. PIVOT ACCESS AND SLIDE ACCESS ARE FIRST AND SECOND CHOICE, RESPECTIVELY.

Figure C-10. Equipment Butting Against Shell (Flex Lines)

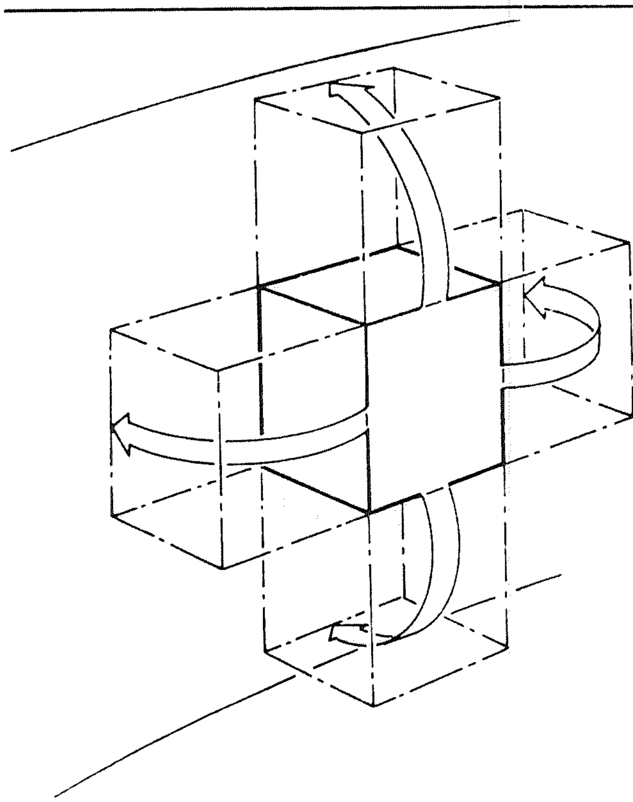
R144



ACCESS METHOD
UNIT REMOVAL
COMMENT
UNIT REMOVAL IS THE SECOND CHOICE ACCESS METHOD. PIVOT, SLIDE, AND SLIDE/PIVOT ARE FIRST, THIRD, AND FOURTH CHOICES, RESPECTIVELY.

Figure C-11. Equipment Butting Against Shell (Disconnect Lines)

R144



ACCESS METHOD
PIVOT
COMMENT
PIVOT IS THE FIRST CHOICE ACCESS METHOD. UNIT REMOVAL, SLIDE, AND SLIDE/PIVOT ARE SECOND, THIRD, AND FOURTH METHODS, RESPECTIVELY.
NOTE
A SINGLE PIVOT POINT MAY BE EMPLOYED IF UNIT MASS IS LOW AND A FRACTION PIVOT IS UTILIZED.

Figure C-12. Shell-Mounted Storage Cabinets

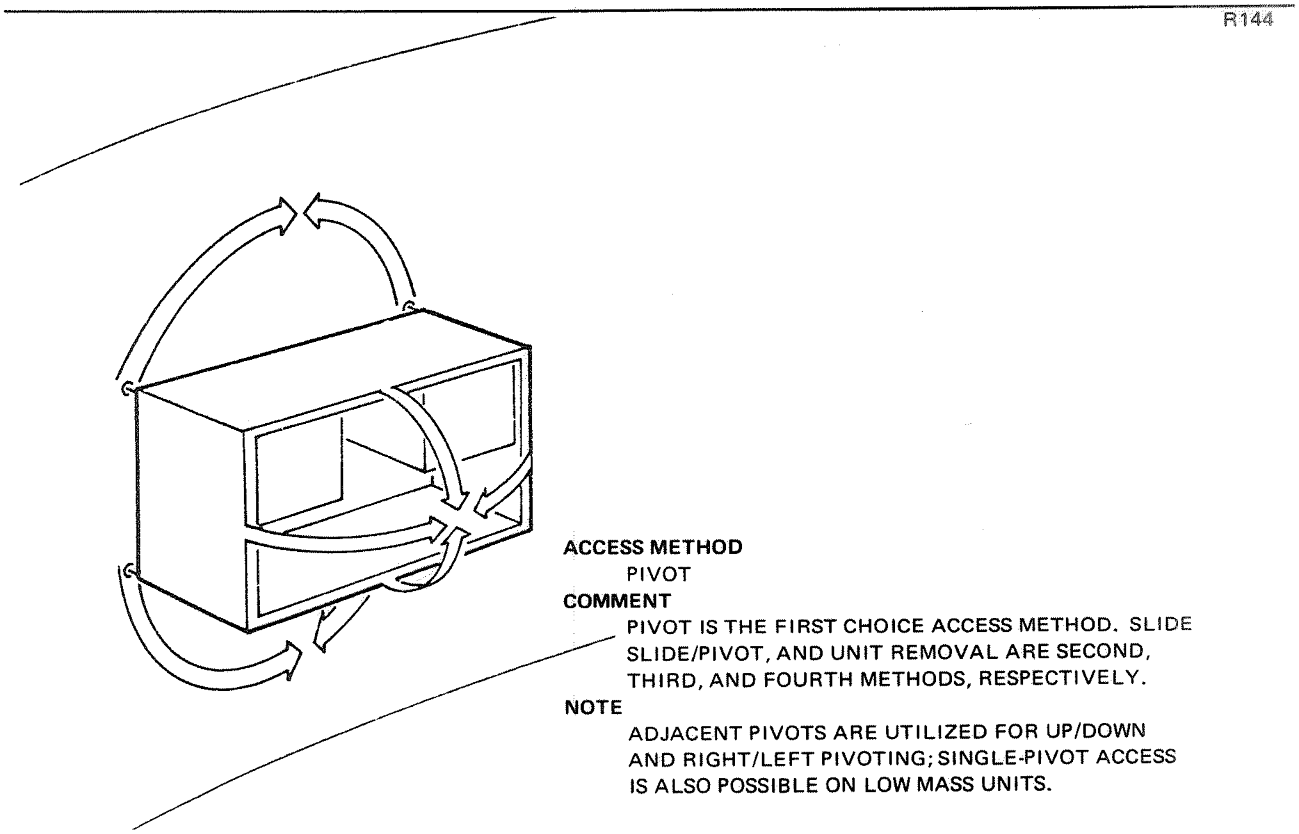


Figure C-13. Shell-Mounted Crew Furniture

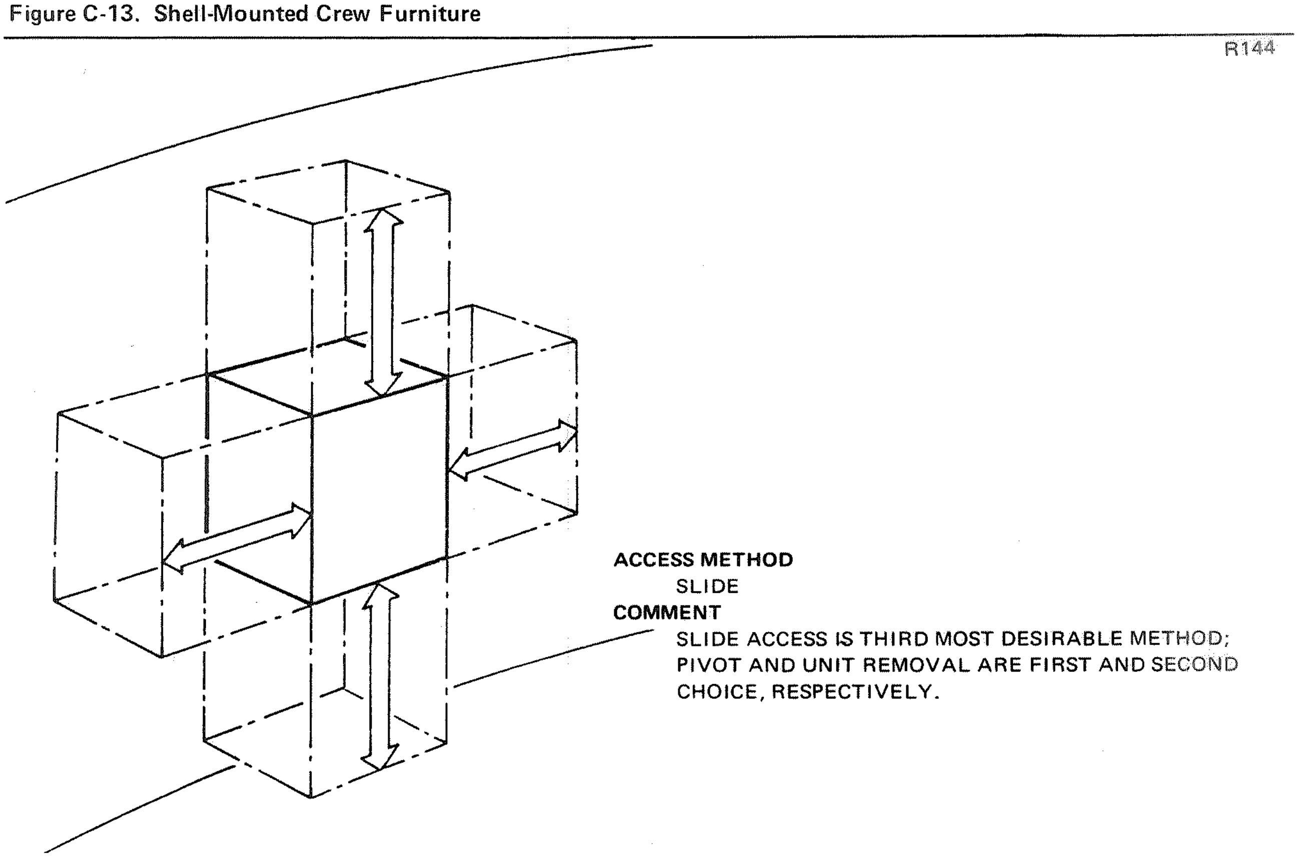
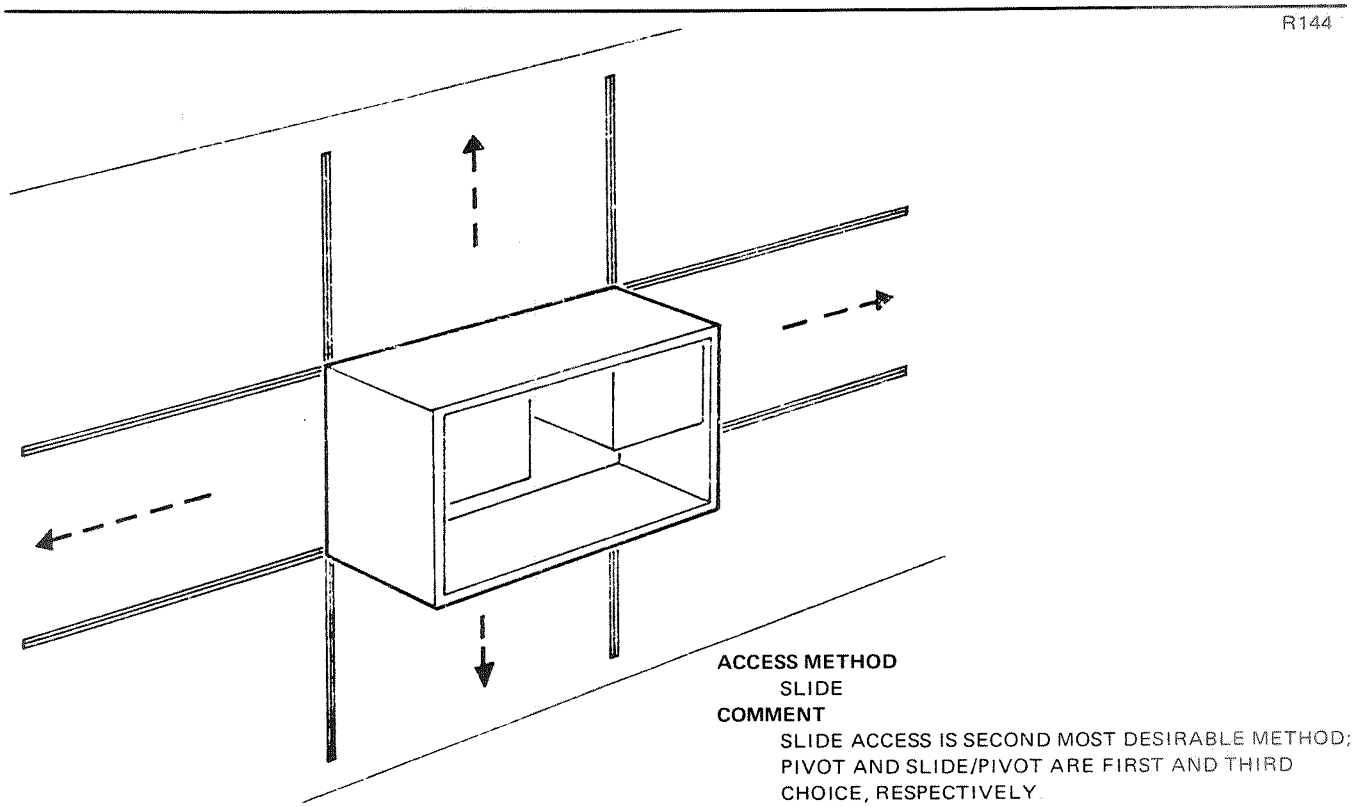
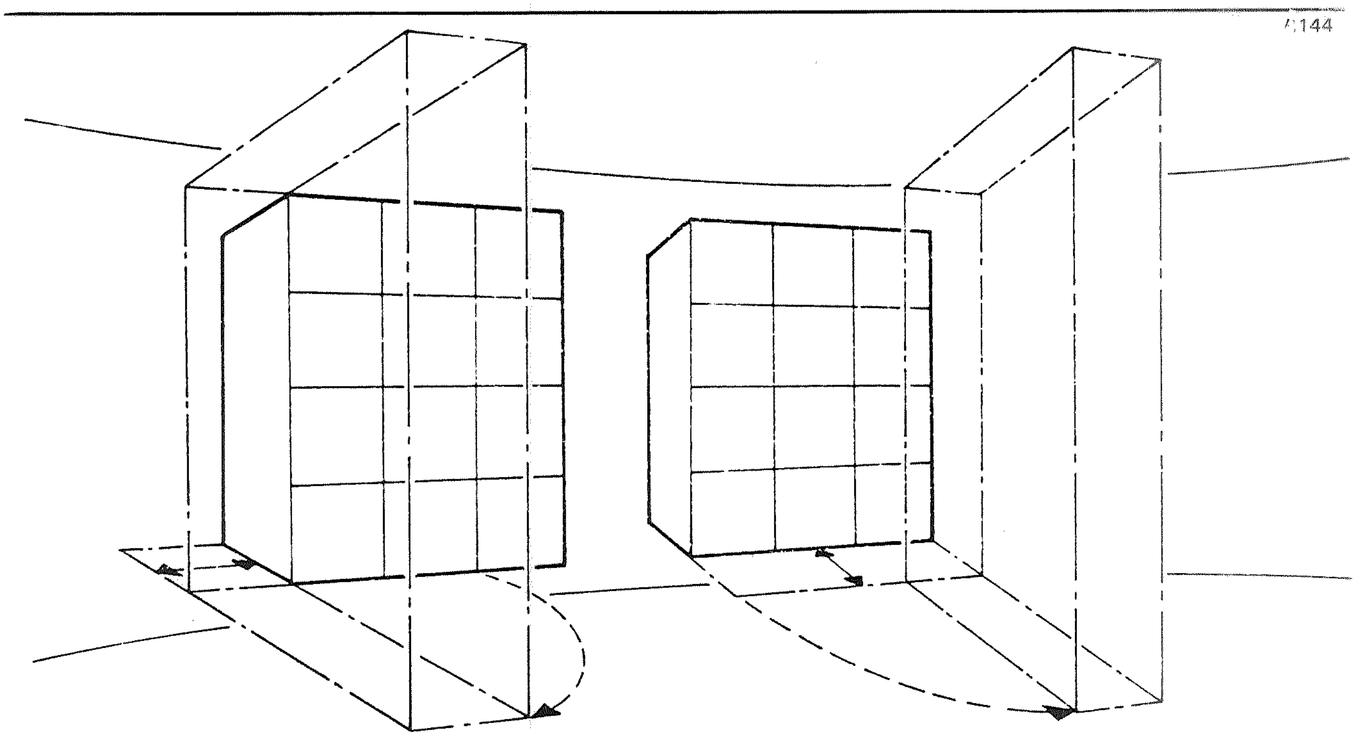


Figure C-14. Shell-Mounted Storage Cabinets



ACCESS METHOD
SLIDE
COMMENT
SLIDE ACCESS IS SECOND MOST DESIRABLE METHOD; PIVOT AND SLIDE/PIVOT ARE FIRST AND THIRD CHOICE, RESPECTIVELY.

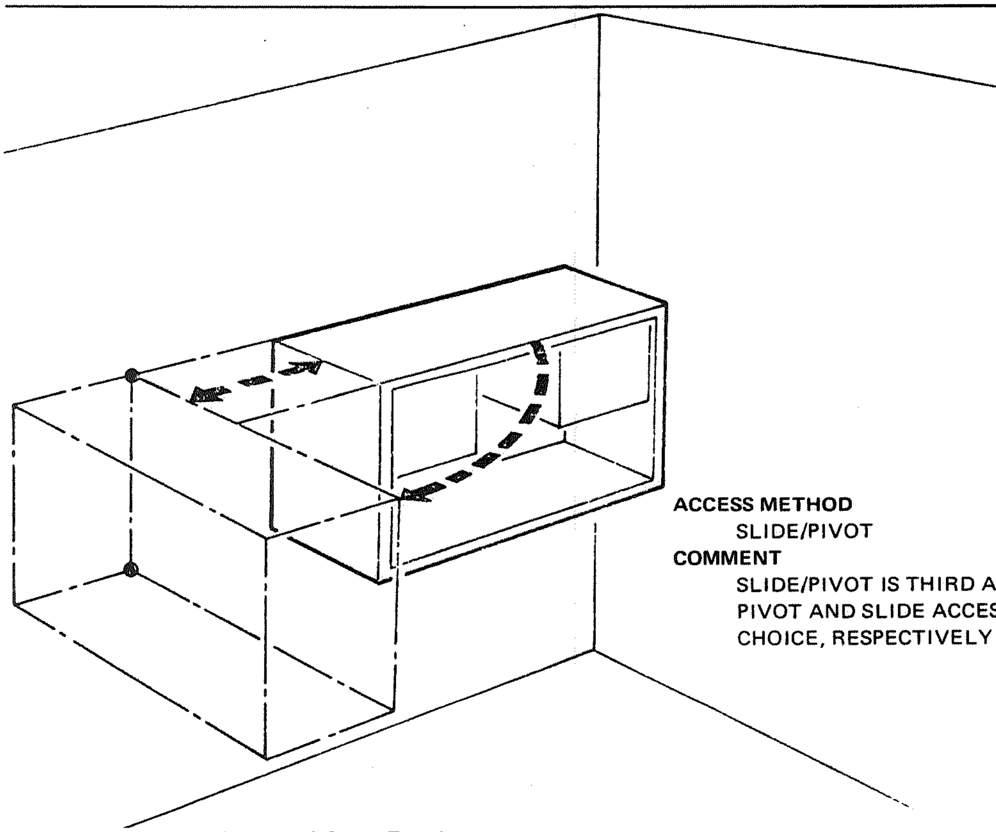
Figure C-15. Shell-Mounted Crew Furniture



ACCESS METHOD
SLIDE/PIVOT

COMMENT
SLIDE/PIVOT ACCESS IS FOURTH CHOICE. PIVOT, UNIT REMOVAL, AND SLIDE ACCESS ARE FIRST, SECOND, AND THIRD CHOICE, RESPECTIVELY.

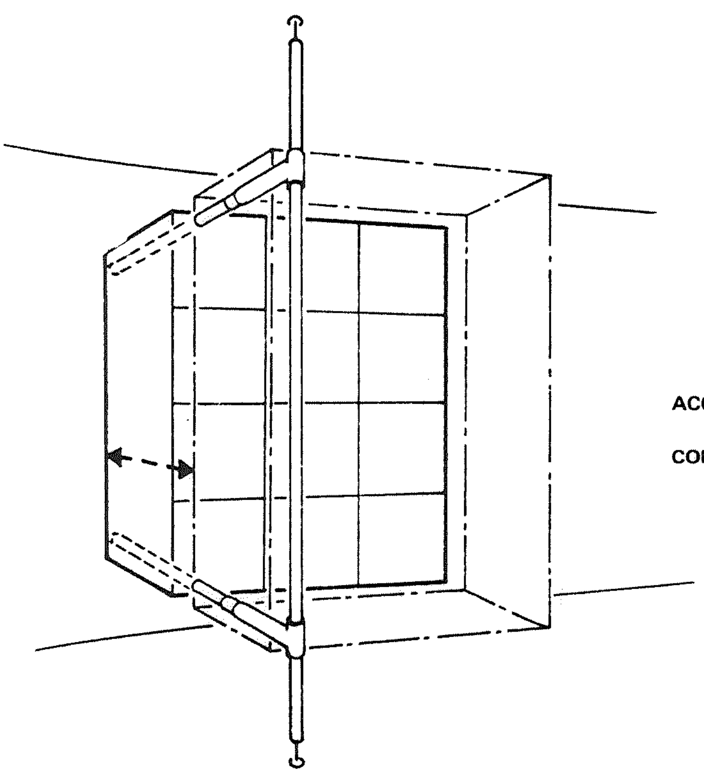
Figure C-16. Shell-Mounted Storage Cabinets



ACCESS METHOD
SLIDE/PIVOT
COMMENT
SLIDE/PIVOT IS THIRD ACCESS METHOD CHOICE. PIVOT AND SLIDE ACCESS ARE FIRST AND SECOND CHOICE, RESPECTIVELY

Figure C-17. Shell-Mounted Crew Furniture

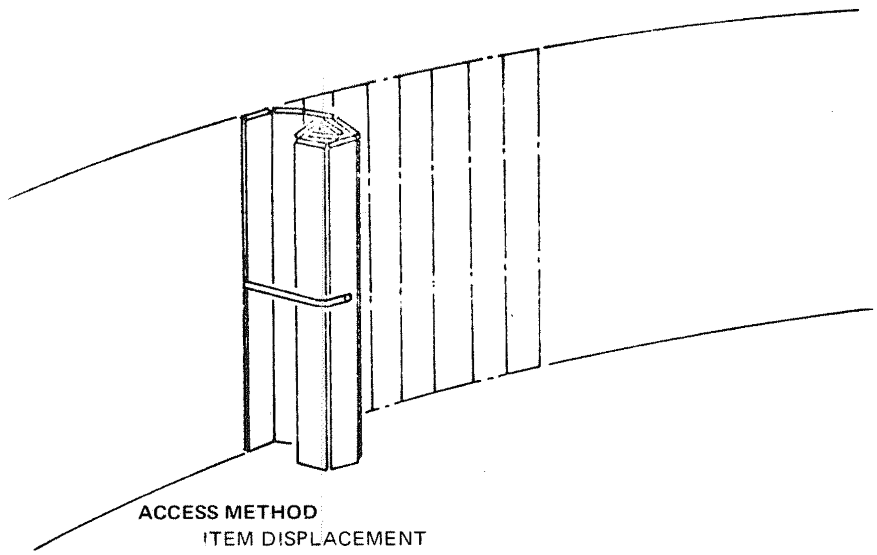
R144



ACCESS METHOD
UNIT REMOVAL
COMMENT
UNIT REMOVAL IS SECOND CHOICE OF ACCESS METHODS. PIVOT AND SLIDE ACCESS METHODS ARE FIRST AND THIRD CHOICES, RESPECTIVELY.

Figure C-18. Shell-Mounted Storage Cabinets

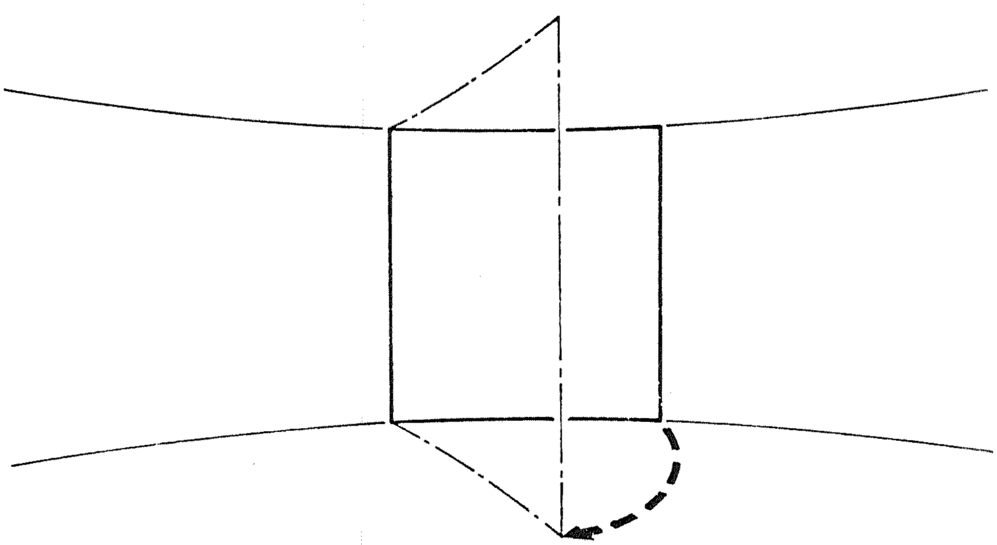
R144



ACCESS METHOD
ITEM DISPLACEMENT
COMMENT
ITEM DISPLACEMENT IS THE PREFERRED ACCESS METHOD FOR FLEXIBLE DECOR AND PADDING.

Figure C-19. Shell-Mounted Decor and Crew Protective Padding

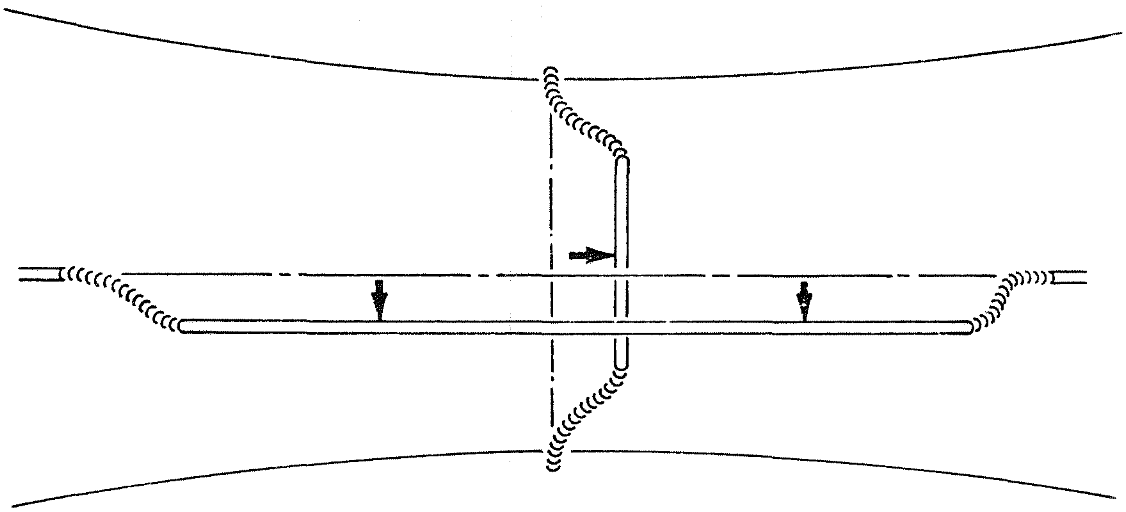
R144



ACCESS METHOD
PIVOT
COMMENT
PIVOT ACCESS IS THE PREFERRED METHOD FOR RIGID DECOR AND PADDING.

Figure C-20. Shell-Mounted Decor and Crew Protective Padding

R144



ACCESS METHOD

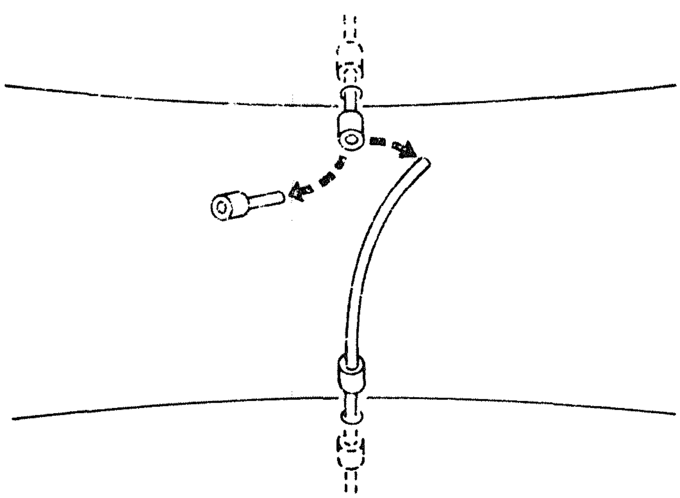
ITEM DISPLACEMENT

COMMENT

ITEM DISPLACEMENT IS THE PREFERRED ACCESS METHOD. PARTIAL DISASSEMBLY, AND DISASSEMBLY ARE SECOND AND THIRD CHOICES, RESPECTIVELY.

Figure C-21. Liquid and Gas Transfer Lines and Ducting; Conduit and Electrical Cable

R144



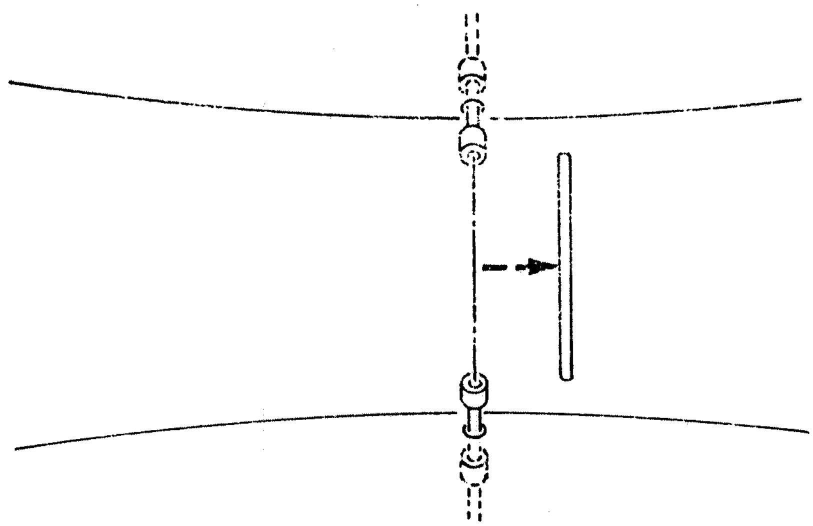
ACCESS METHOD

PARTIAL DISASSEMBLY

COMMENT

PARTIAL DISASSEMBLY OF THE ITEM IS THE SECOND CHOICE ACCESS METHOD. ITEM DISPLACEMENT AND DISASSEMBLY ARE FIRST AND THIRD CHOICES, RESPECTIVELY.

Figure C-22. Liquid and Gas Transfer Lines and Ducting; Conduit and Electrical Cable



ACCESS METHOD
DISASSEMBLY
COMMENT
DISASSEMBLY IS THE LEAST DESIRABLE ACCESS METHOD. ITEM DISPLACEMENT AND PARTIAL DISASSEMBLY ARE FIRST AND SECOND CHOICES, RESPECTIVELY.

Figure C-23. Liquid and Gas Transfer Lines and Ducting; Conduit and Electrical Cable

Appendix D
DETAILED CREW LEAK REPAIR PROCEDURES

This appendix presents examples of the procedures developed to provide the basis for calculations of $D_{(P)}$ in Table 7-6. Evaluations were performed on each of the procedures as applicable to the fluid-container leak conditions.

The ground rules were:

A. All durations are presented in units of minutes.

B. All durations are gross estimations of time requirements to accomplish each step of a procedural sequence. While they may not be sufficiently accurate for other purposes, their standardized use across all applicable procedures permits consistent study conclusions to be drawn based upon procedural time requirements.

C. Where necessary, sufficient information is presented to explain apparent inconsistencies in seemingly identical procedures.

PROCEDURE

CONTAINER TYPE & MATERIAL Stainless condenser NO. 10-1

FLUID H_2O R/R TECHNIQUE Weld

NO. CREWMEN 1

SPECIAL SKILLS Arc welding

PROTECTIVE EQUIPMENT Eye and skin protection

SPECIAL PREPARATIONS None

SPECIAL TEST REQUIREMENTS None

WASTE MATERIAL GENERATED None

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (wipe with absorbent cloth)	2.00
7. Assure no residual flammable fluids in area (hazard)	1.00
8. Apply weld to defective surface	2.00
9. Verify acceptability of R/R	.50
10. Activate controls to initiate fluid flow	.50
11. Verify no leak	.25
12. Stow and secure R/R materiel	5.00
	TOTAL: 19.5

PROCEDURE

CONTAINER TYPE & MATERIAL Aluminum tubing NO. 23-1
FLUID) O_2 R/R TECHNIQUE Weld

NO. CREWMEN 1
SPECIAL SKILLS Arc welding

PROTECTIVE EQUIPMENT Eye, skid protection
SPECIAL PREPARATIONS None

SPECIAL TEST REQUIREMENTS Pressure test
WASTE MATERIAL GENERATED None

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow distontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (wipe with absorbent cloth)	2.00
7. Assure no residual flammable fluids in area (hazard)	1.00
8. Apply weld to defective surface	2.00
9. Verify acceptability of R/R	.50
10. Activate controls to initiate fluid flow	.50
11. Verify no leak (pressure test—non operational)	2.25
12. Stow and secure R/R materiel	5.00
	TOTAL: 21.5

PROCEDURE

CONTAINER TYPE & MATERIAL Stainless tubing NO. 42-1
FLUID H_2 R/R TECHNIQUE Weld

NO. CREWMEN 1
SPECIAL SKILLS Arc welding
PROTECTIVE EQUIPMENT Eye, skin protection
SPECIAL PREPARATIONS Test for residual H_2
SPECIAL TEST REQUIREMENTS Pressure test
WASTE MATERIAL GENERATED None

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance (test for residual H_2)	2.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (wipe with absorbent cloth)	2.00
7. Assure no residual flammable fluids in area (hazard)	1.00
8. Apply weld to defective surface	2.00
9. Verify acceptability of R/R	.50
10. Activate controls to initiate fluid flow (non-system)	.50
11. Verify no leak (pressure test—non operational)	2.25
12. Stow and secure R/R materiel	5.00
	TOTAL: 23.5

PROCEDURE

CONTAINER TYPE & MATERIAL Stainless tubing NO. 3-2

FLUID H_2O R/R TECHNIQUE Elastomer Sealant

NO. CREWMEN 1

SPECIAL SKILLS None

PROTECTIVE EQUIPMENT None

SPECIAL PREPARATIONS L

SPECIAL TEST REQUIREMENTS None

WASTE MATERIAL GENERATED L

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (Wipe with absorbent cloth)	2.00
7. Apply sealant	.25
8. Wait for sealant to cure	1,440.00
9. Stow and secure R/R materiel	5.00
10. Verify acceptability of R/R	.50
11. Activate controls to initiate fluid flow	.50
12. Verify no leak	.25
Excludes wait for cure	TOTAL: 16.75

PROCEDURE

CONTAINER TYPE & MATERIAL Aluminum valve NO. 26-3

FLUID O_2 R/R TECHNIQUE Replace

NO. CREWMEN 1

SPECIAL SKILLS None

PROTECTIVE EQUIPMENT None

SPECIAL PREPARATIONS None

SPECIAL TEST REQUIREMENTS Pressure test

WASTE MATERIAL GENERATED Valve

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Engage tool and loosen fitting	1.50
7. Disconnect and remove component	.50
8. Deploy replacement component	.25
9. Install replacement component	1.50
10. Verify acceptability of replacement	.50
11. Activate controls to initiate fluid	.50
12. Verify no leak (pressure test—non operational)	2.25
13. Stow and secure R/R materiel	5.00
	TOTAL: 20.

PROCEDURE

CONTAINER TYPE & MATERIAL Teflon Seals—Walls NO. 38-3

FLUID O_2 R/R TECHNIQUE Replace

NO. CREWMEN 1

SPECIAL SKILLS None

PROTECTIVE EQUIPMENT (O_2 Supply)

SPECIAL PREPARATIONS Particle face cleaning

SPECIAL TEST REQUIREMENTS None

WASTE MATERIAL GENERATED Excess seal

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Engage tool and loosen fitting	1.50
7. Disconnect and remove component	.50
8. Deploy replacement component	.25
9. Install replacement component	1.50
10. Verify acceptability of replacement	.50
11. Activate controls to initiate fluid	.50
12. Verify no leak	.25
13. Stow and secure R/R materiel	5.00
	TOTAL: 18.25

PROCEDURE

CONTAINER TYPE & MATERIAL Stainless tank NO. 6-4
FLUID H_2O R/R TECHNIQUE Bolt and seal

NO. CREWMEN 2
SPECIAL SKILLS Metal drilling

PROTECTIVE EQUIPMENT Eye protection, particle collector
SPECIAL PREPARATIONS Hole drilling, surface smoothing

SPECIAL TEST REQUIREMENTS None
WASTE MATERIAL GENERATED Metal particles

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (drill hole to size, smooth edges)	4.00
7. Apply sealant	.25
8. Insert and secure bolt	.25
9. Verify acceptability of R/R	.50
10. Activate controls to initiate fluid flow	.50
11. Verify no leak	.25
12. Stow and secure R/R materiel	5.00
	TOTAL: 19.0

PROCEDURE

CONTAINER TYPE & MATERIAL Stainless tank NO. 46-4
FLUID H_2 R/R TECHNIQUE Bolt and seal

NO. CREWMEN 2
SPECIAL SKILLS Metal drilling
PROTECTIVE EQUIPMENT Eye, particle collector
SPECIAL PREPARATIONS Test for residual H_2
SPECIAL TEST REQUIREMENTS Pressure test
WASTE MATERIAL GENERATED None

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (test for residual H_2)	4.00
7. Apply sealant	.25
8. Insert and secure bolt	.25
9. Verify acceptability of R/R	.50
10. Activate controls to initiate fluid flow (non-system)	.50
11. Verify no leak (pressure test—non operational)	2.25
12. Stow and secure R/R materiel	5.00
	TOTAL: 21.0

PROCEDURE

CONTAINER TYPE & MATERIAL Polyethylene tubing NO. 34-5
FLUID O_2 R/R TECHNIQUE Epoxy adhesive

NO. CREWMEN 1
SPECIAL SKILLS None
PROTECTIVE EQUIPMENT Eye and skin
SPECIAL PREPARATIONS None
SPECIAL TEST REQUIREMENTS Pressure test
WASTE MATERIAL GENERATED Excess adhesive

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (wipe with absorbent cloth)	2.00
7. Apply sealant	.25
8. Wait for sealant to cure	240.00
9. Stow and secure R/R materiel	5.00
10. Verify acceptability of R/R	.50
11. Activate controls to initiate fluid flow (test system)	.50
12. Verify no leak	2.25
Excludes wait for cure	TOTAL: 18.75

PROCEDURE

CONTAINER TYPE & MATERIAL Aluminum walls NO. 30-6

FLUID O_2 R/R TECHNIQUE Epoxy adhesive patch

NO. CREWMEN 1

SPECIAL SKILLS None

PROTECTIVE EQUIPMENT (O_2 supply) particle collector

SPECIAL PREPARATIONS Smooth surface, shape patch

SPECIAL TEST REQUIREMENTS None

WASTE MATERIAL GENERATED Excess patch, metal particles

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (wipe with absorbent cloth)	2.00
7. Cut patch to shape	2.00
8. Apply sealant	.25
9. Wait for sealant to cure	60.00
10. Stow and secure R/R materiel	5.00
11. Verify acceptability of R/R	.50
12. Activate controls to initiate fluid flow	.50
13. Verify no leak	.25
Excludes wait for cure	TOTAL: 18.75

PROCEDURE

CONTAINER TYPE & MATERIAL Fiberglass ducts NO. 41-7

FLUID O_2 R/R TECHNIQUE

NO. CREWMEN 1

SPECIAL SKILLS None

PROTECTIVE EQUIPMENT None

SPECIAL PREPARATIONS None

SPECIAL TEST REQUIREMENTS None

WASTE MATERIAL GENERATED None

DESCRIPTION	DURATION
1. Inspect failure	.50
2. Activate control to passivate leak	.50
3. Verify flow discontinuance	.25
4. Obtain appropriate materiel for replace or repair (R/R)	5.00
5. Deploy R/R materiel to work location	2.00
6. Prepare surface for R/R (wipe with absorbent cloth)	2.00
7. Apply sealant	.25
8. Wait for sealant to cure	60.00
9. Stow and secure R/R materiel	5.00
10. Verify acceptability of R/R	.50
11. Activate controls to initiate fluid flow	.50
12. Verify no leak	.25
Excludes wait for cure	TOTAL: 16.75