MAN-RATED CHAMBER CONSIDERATIONS FOR SIMULATION TESTS OF GEMINI SPACECRAFT

by J.A. Maloney, Department Manager
Systems and Space Simulation Laboratory,
McDonnell Aircraft Corp., St. Louis, Missouri

Abstratt

The experience gained in designing and developing McDonnell's man-rated 30-foot diameter space-simulation chamber is used as a basis in discussing the man-rating of space chamber facilities. The chamber structure and associated systems necessary in providing a safe environment for both chamber observers and occupants of the spacecraft are reviewed. Various design approaches are outlined and the optimum one selected to achieve a man-rated facility with maximum safety. Structural design, material considerations, repressurizations, non-contaminant conditions, and other man-rated features are discussed in detail. Safety requirements. training and bio-medical facilities integrated with the chamber complex are reviewed in terms of the Gemini Spacecraft space-simulation tests. Proposed improvements and recommendations for design of future man-rated chambers are presented.

Introduction

The rapid evolution of simulation technology during recent years has resulted in the necessity of placing man and spacecraft under the simulated environment of space. Today, therefore, emphasis is placed on the man-rating of chambers which provides the safety features necessary for placing man under vacuum conditions.

In the past, men have performed in man-rated chambers for purposes of deep sea work, medical experimentation, and altitude work confined to aircraft environments. However, since we are now involved with extreme vacuum and temperature conditions, the man-rating of chambers is becoming increasingly complex. Emergency rescue, thorough system analyses, and adequate "fail safe" controls become critical factors during the chamber design phase.

Although the nature of man-rating has been discussed by several committees and groups, the answers to many questions are still, to some degree, undefined and unanswered. Man-rating requires the combination of a reliable chamber, associated systems, and controls which, under failure or malfunction. immediately react to produce a safe environment for chamber occupants. A detailed analysis of the various systems involved and the effects of interaction between the systems is initially necessary. It is important that man-rating of the chamber be accomplished during the design stage rather than after completion of the chamber. Therefore, if it is determined that a proposed facility will be utilized for manned testing in the future, man-rating features should be implemented in the original design. An approach utilized by McDonnell Aircraft Corporation, St. Louis. Missouri. is to review each system individually in the design stages and determine the interaction effect of the systems.

The first man-rated spacecraft chamber in the free world, located at McDonnell, is a horizontal cylinder *30* feet in diameter and **36** feet long. Attached to the chamber are two horizontal personnel locks. The primary lock, immediately adjacent to the chamber, is utilized for crewman rescue operations and repair. alteration, or modification of the spacecraft or test equipment in the main chamber. The secondary lock serves as an elevator lock for crew exchange. The entire facility, with associated Bio-Medical and instrumentation areas, is currently operational and undergoing preparation for tests to be conducted on the Gemini Spacecraft during the fall of 1964.

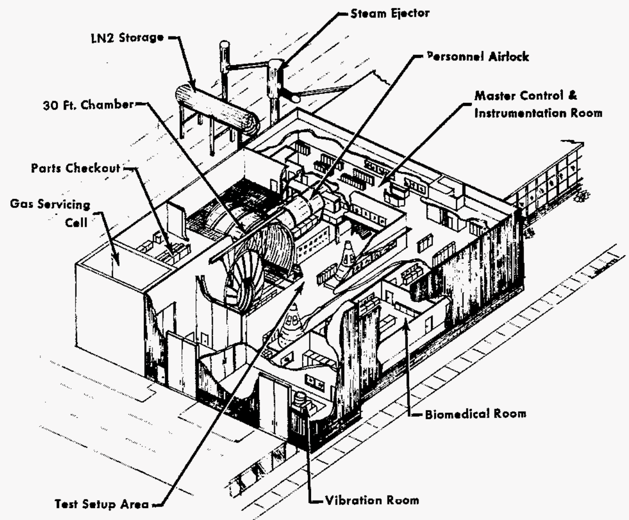

Figure 1 – McDonnell's Spacecraft Laboratory with man-rated 30-foot diameter space-simulation chamber

A review of technical features and a discussion of each system will be presented in light of the system design philosophy.

STRUCTURAL CONSIDERATIONS

Many basic geometrical design considerations have been involved in the structural conception of space chambers. Two basic geometries are usually employed in chamber construction – the sphere and the cylinder. Both of these designs should be examined in terms of cost, space, accessibility and strength; however, all should be examined principally in terms of the man-rated capabilities with prime consideration for safety.

Certain structural areas are especially prone to weaknesses such as the intersections of cylinders and attachments which break up the basic structural geometry, i.e., structural lines formed by a sphere or cylinder. These areas many times require additional stiffening or reinforcement, and consequently should be reviewed in terms of fatigue life and rapid dynamic changes caused by repressurization. At the present time no code has been established for vacuum-vessel design such as the ASME, Code section for pressure vessels. Consequently, the only means of checking the structural integrity of the vessel is to evacuate to full vacuum. Repeated evacuations can produce deformation and fatigue failures or cracks which should be clearly scrutinized during the early operation of the chamber. An example of such a failure is shown in the weld cracks of Figure 2. These weld cracks occurred after several evacuations and repressurizations to sea level. The situation was corrected by adding stiffeners and additional welding (inadvertently left out during initial shop application).

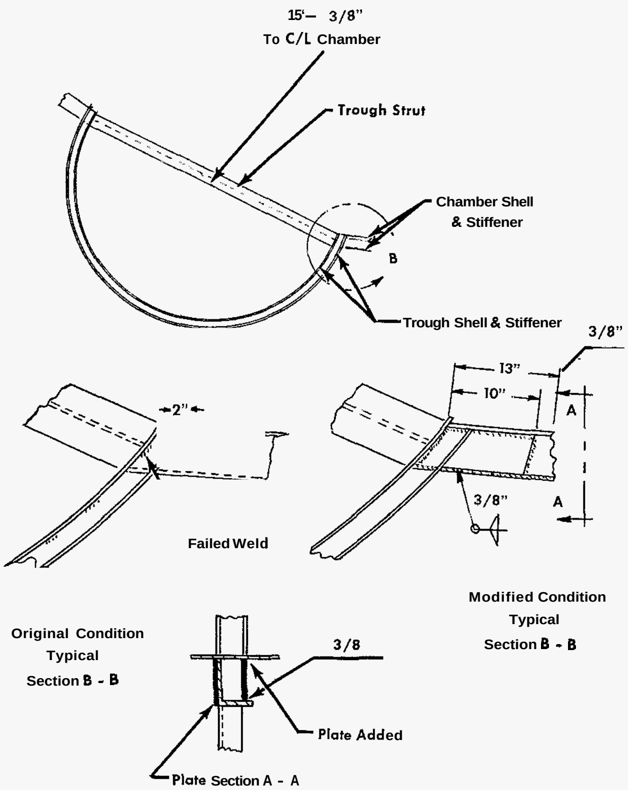

Figure 2 – Chamber weld modifications

A second example of possible structural failure is the side-moving closure door shown in Figure 3. Adjustable suspension rods, attached from the moving crane to the door structure, provide side moving of the door. Crane operation during start and stop operations caused side swaying of the door and imposed large moments on the door structural-attachment fitting. Although the door was operated several times under these conditions, analysis indicated that an additional structure was required to eliminate the swaying motion and insure a greater factor of safety.

The main chamber door, in case of failure, is designed to drop into a trough preventing it from falling forward into the work area. The trough would also serve to restrict or restrain the door during an explosion or inadvertent increase in chamber pressure. The door normally is suspended a short distance from the chamber shell and swings free when internal pressure is returned to sea level. With over-pressurization, the door could move outward and swing beyond the vertical position. To compensate for this possible condition, shock absorbers were installed which absorb the pressure energy until failure. Any remaining energy is absorbed by the trough itself.

Viewports

Viewports should provide adequate vision of all areas within the chamber and be located *so* as to avoid blind spots within the chamber. Attaining this objective requires a balance of a large number of small ports **or** a small number of large ports. It usually is better structurally and more economical to have a larger number of viewports 12 inches or less in diameter appropriately located throughout the chamber than to have a larger diameter and fewer viewports.

Viewports may be constructed from both tempered and non-tempered glass, with a safety factor of 10 being required for both the combined temperature and pressure conditions involved. There are three principal suppliers of tempered glass: Herculite, manufactured by Pittsburgh Plate, Pyrex by Corning Glass Works, and Tuflex by Libbey-Owens-Ford. The characteristics of the tempered glass will provide approximately three times the strength of the non-tempered types. However, it has the undesirable characteristic of disintegrating into small cubicle sections which can produce a hazard should a failure occur. Non-tempered glass fractures into large segments. Consequently, under failure, it will leak and normally wedge, preventing entrance into the chamber proper. Illustrations of typical tempered and non-tempered failures are shown in Figures 4 and 5. Since the non-tempered glass fails in large segments, it should be used only when a safety factor of 10 is possible. However, in larger ports (diameters of 10 and 12 inches), tempered glass is required to provide a minimum safety factor of 10.

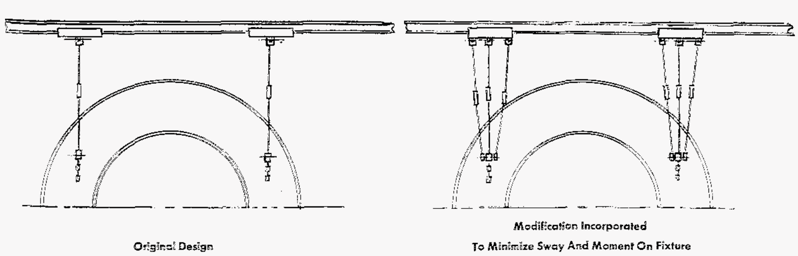

Figure 3 – Main chamber door modifications

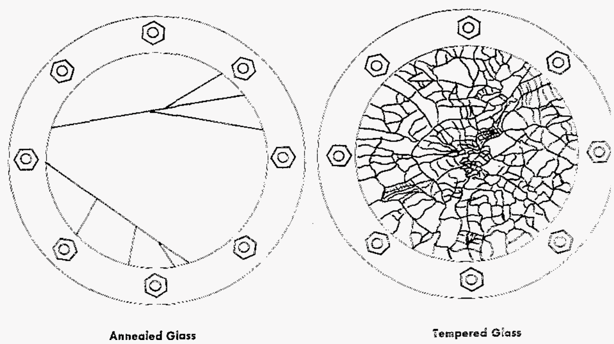

Figure 4 – Typical chamber viewport glass failure

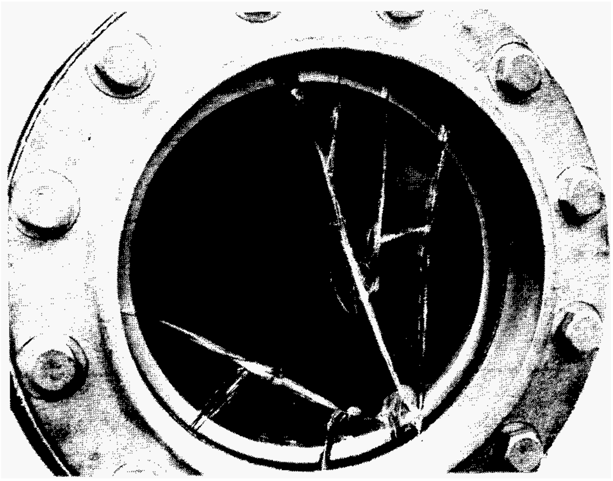

Figure 5 – Photograph of annealed glass failure in chamber viewport

To protect against inadvertent variables such as small marks and scratches from diamond rings, tools, and other objects, it is desirable to have both the inner and outer layers laminated to the center main-load carrying glass. The inner and outer laminated layers should be of sufficient thickness to provide a safety factor of two (2). From a structural standpoint, a laminated system is desirable and a necessary requirement for a man-rated design on larger ports.

Lighting Ports

Under some conditions viewports are also utilized as lighting ports. This requires an additional structural review because of the effect temperature has on the safety factor required. The amount of restraint of the viewing port is a factor in evaluating effects of thermal stress. Figure 6 illustrates graphically the effects of thermal stress on a fully restrained viewport using various makes of glass.

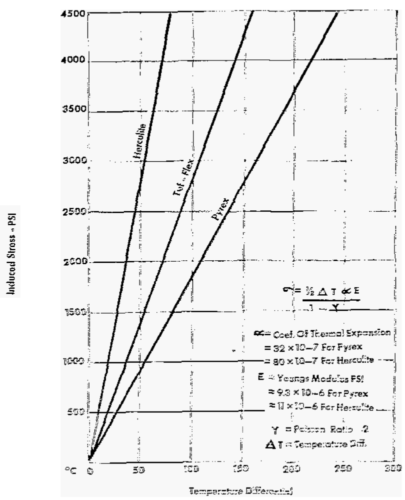

Figure 6 – Thermal stress on a fully restrained viewport

Doors

Quick opening, safe-operating doors, essential for fast access to a crewman or internal observer under altitude conditions. should be designed in terms of operation, equalization of pressure, and quick access requirements. The door hinge and location should be designed such that the internal-chamber observer is not restricted behind the door when it is fully open for the operation of valves, instruments, or other equipment. In cases of rapid pressurization or equalization of pressure between chambers, a safe-door-latching mechanism is necessary to restrain the door in a partially open condition and allow equalization of pressure between chambers. The locking mechanism should have sufficient shear strength, so that in cases of overpressurization, the door latching mechanism will not fail allowing the door to swing free injuring chamber occupants. A partial wedge action of the locking mechanism, designed for this purpose maintains control of the door when released.

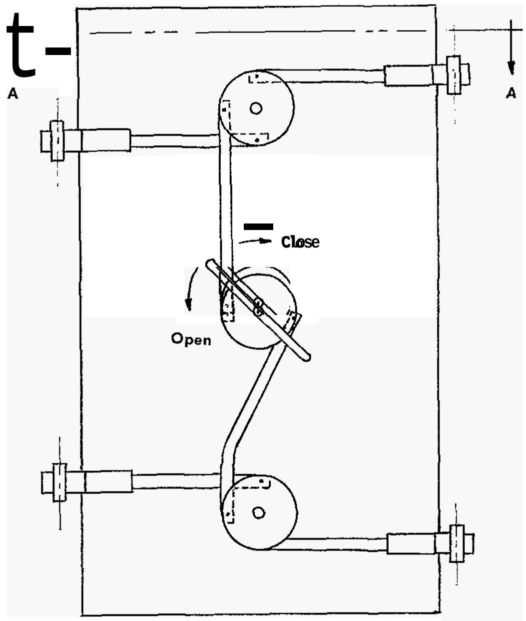

Figure 7 – Door latching mechanism

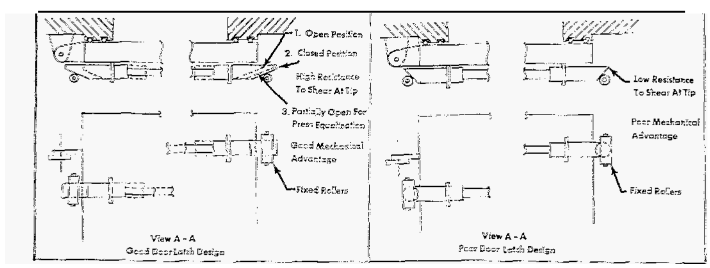

Figure 8

In some cases, pressure sealing characteristics of the door become important. When a high initial load is required to compress the seal, and the door seal and frame are not in parallel, a wedging action may occur producing large pressure differentials across the door. Should this occur, the door could open and produce an uncontrolled, rapid rate of climb or dive in the personnel lock. The pressure required to open the door and maintain a seal when closing the door should be held to a minimum to eliminate the excessive pressure change. Doors improperly installed with no equalization feature and poor shear restraints are undesirable and will not provide adequate man-rating features.

VACUUM SYSTEM

Design of the 30-foot chamber vacuum system includes man-rated features assuring proper control of the main chamber, primary lock, and secondary lock. Both automatic and manual control modes are included. The schematic of the vacuum system, shown in Figure 9, indicates an evacuation of the main chamber by means of mechanical pumps and steam ejectors. The pumping system can be operated independently or simultaneously, depending on the type of test operation conducted.

chamber as well as isolating the pumping system from the chamber in case of spacecraft system failures.

Altitude-limiting valves, restricting the secondary lock, primary lock, and main chamber to 10,000 feet, are also provided. In case of accidental or inadvertent operation of the chamber to altitude, any occupant of the chamber can limit the altitude capabilities of the system by opening these valves. Although the valving operated satisfactorily, a further man-rated safety precaution was taken by installing an electrical switch in each lock which will override and prevent operation of the vacuum pump system.

All exhausts are located on the bottom of the chambers. This provides for the removal of settled CO_2 or other heavy gases from the bottom of the chamber allowing occupants to operate without oxygen masks under low altitude or initial launch conditions. For fast repressurization through the normal system, mufflers are installed in the chambers to prevent excessive noise levels that might cause painful or damaging conditions to occupants' ears.

All control valves of the vacuum system are designed with man-rating features to maintain altitude conditions or

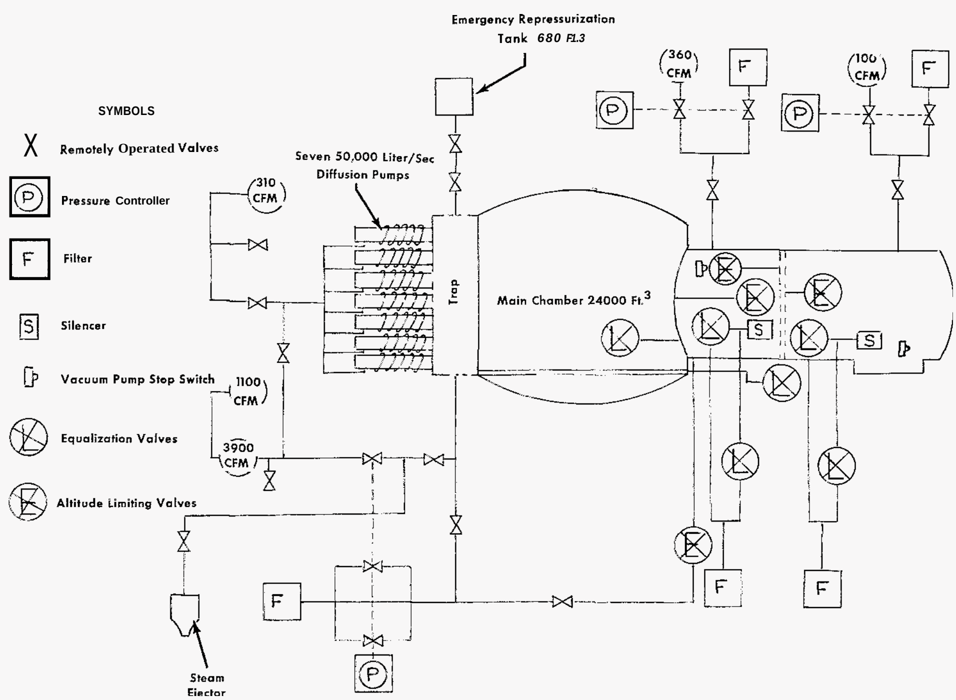

Figure 9 – 30-foot diameter chamber vacuum pumping system

The mechanical pumps, under normal conditions, operate independently of the diffusion pumps to 10^{-3} Torr at which time they are operated through the diffusion pump circuit. Under emergency procedures, diffusion pump valves are closed during repressurization to prevent oil from entering the chamber and contaminating the spacecraft or chamber occupants. Where failure of a spacecraft system could possibly cause an oxygen-rich atmosphere, valve closure prevents interaction or oxidation of diffusion pump oils. An examination of this situation, utilizing DC 704 diffusion pump fluid in a smaller chamber, indicated the development of excessive smoke; however, there were no explosions. The diffusion pump valves, therefore, serve the double function of preventing oil contamination of the

to return to sea level pressures in case of mechanical, electrical, or pneumatic failure of the control system. To prevent loss of chamber control, both a pneumatic and electrical standby supply are maintained for all pertinent systems. Systems are designed to operate mechanically, electrically, pneumatically, and wherever possible, independently so that failure of one valve or system will not cause one chamber to affect another adversely. Where the valves did not have mechanical override control and had pneumatic operators. additional manual valves were installed to control the altitude condition.

A typical performance curve of the vacuum system, shown in Figure 10, indicates the capability of obtaining a pressure of 10^{-4} Torr in slightly over one hour by operating both the mechanical and steam ejector systems. This is believed to be the fastest pumpdown rate for a chamber of this volume.

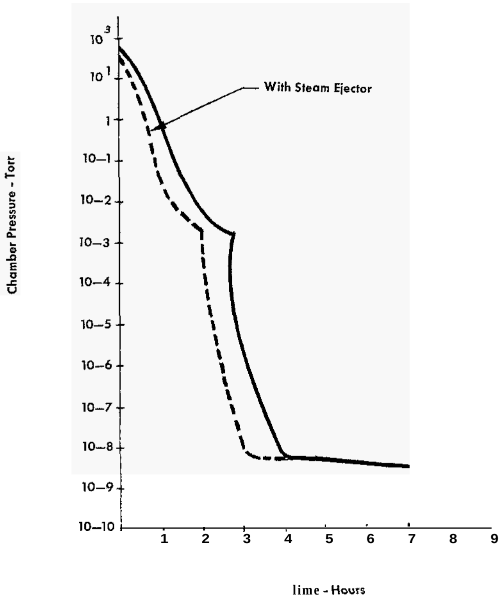

Figure 10 – Typical pumpdown curve for 30-foot diameter chamber

REPRESSURIZATION SYSTEM

A repressurization system is installed for the protection of occupants should they be suddenly exposed to the vacuum and temperature environment of the chamber. The system, incorporating a 300 psi pressure vessel, is designed to repressurize the main chamber from full vacuum to 30,000 feet in 20 seconds. Although it is desirable for man to return to safer conditions as soon as possible, the actual length of time man can endure exposure to a full vacuum is currently unknown. Hence, the 20 second repressurization period could possibly be excessive. However, from a practical standpoint, the time is reasonable considering pressure, tank size. and chamber volume. Repressurization is attained by opening two valves in series – a vacuum-type valve and a pneumatically-operated butterfly valve that allows unrestricted entry of air into the main chamber.

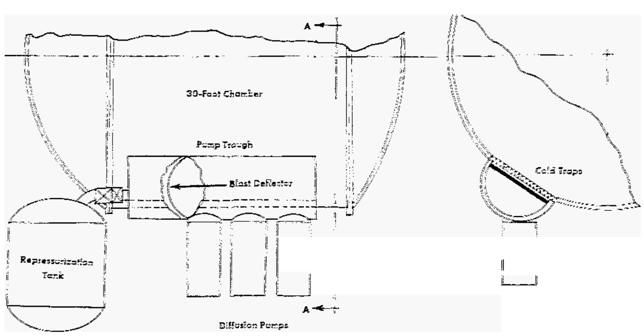

Figure 11 – 30-foot chamber repressurization system

Experiments were conducted to determine the time and temperature that would be experienced by man under these conditions. The effects of blast discharge on the spacecraft or personnel were also studied. The original concept was a design permitting full flow of gases through the entire length of the trough thus dissipating the gaseous energy all along the chamber wall. However, due to a small amount of oil present in the trough, a cloudy mist was quickly produced inside the chamber during repressurization. The mist was dissipated only after several minutes. To attain a non-contaminant, free atmosphere within the main chamber, preventing oil plating of the spacecraft and occupants, a redesign was necessary. An additional baffle, designed to eliminate the foggy and oily atmosphere, was installed and tested. The baffle was louvered to dissipate the flow through the back side of the chamber and prevent the repressurization gas from entering the trough area over the diffusion pumps and picking up oil.

Reviewing the conditions from initial repressurization to 1,000 seconds, Figure 12 graphically describes chamber wall temperature, chamber pressure, average free air temperature, and shroud temperature. The shroud temperature at the equivalent altitude of 30,000 feet, after 1,000 seconds, was found to be approximately –130°F. Therefore, technicians, crewmen, or repair mechanics are required to wear either well insulated or heated suits when entering the chamber.

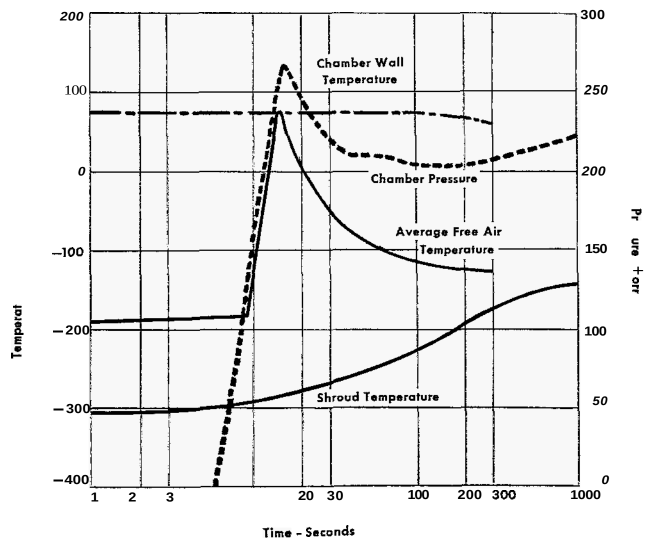

Figure 12 – Chamber conditions during initial repressurization to 1,000 seconds

The cold shroud caused a further problem of maintaining chamber pressure after the repressurization. The desired 5 psia chamber pressure could not be maintained as the repressurization gas was cooled causing the free gas pressure to approach 4 psia. To correct this condition, the repressurization valve is cycled two or three times to admit warm gas into the chamber and maintain control to R 30,000 feet, 5 psia altitude condition. Figure 13 shows a typical repressurization cycling control curve.

main chamber and both locks. Although personnel and spacecraft. in the chamber are visually monitored during all test programs, internal valve operation permits occupants to operate the system should a local fire hazard occur.

Rescue operations are practiced under blindfold conditions to simulate a dense smoke environment in which vision would be limited. Extensive practice is conducted to obtain the optimum procedure and rescue time, for each condition and particular test operation to be conducted.

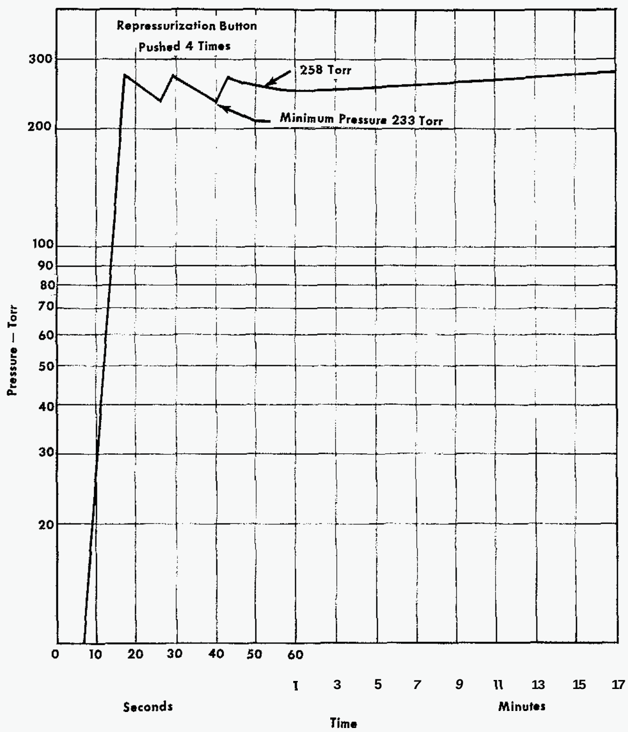

Figure 13 – Emergency repressurization cycling control curve

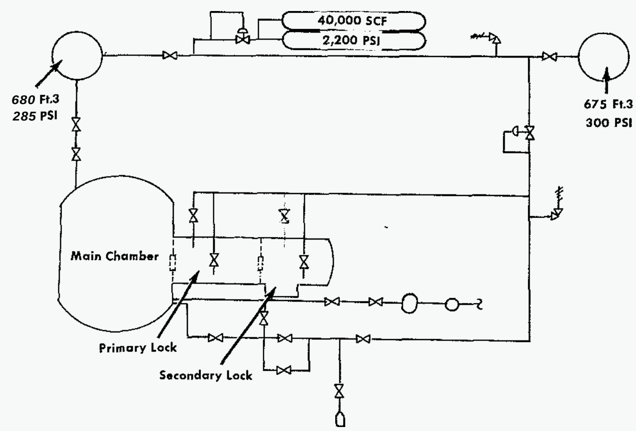

Figure 14 – Nitrogen fire protection system

FIRE PROTECTION SYSTEM

Since potential fire hazards exists, especially under sea-level 100 percent oxygen conditions and during the launch phase, an investigation was conducted to determine the selection of a fire extinguishing agent. Three extinguishing agents were viewed (nitrogen, CO_2, and Freon 1301) each having desirable characteristics for a fire protection system. In considering all aspects of the test program, it was concluded that nitrogen would be the best fire extinguishing agent for manned tests.

Utilizing CO_2 as an agent during sea level conditions makes it almost impossible for rescue teams to enter the chamber. Chamber visibility was reduced almost to zero due to CO_2 solidification causing a dense white fogging atmosphere.

The high density of CO_2 and Freon, as compared to air, further complicates rescue procedures. In situations where the chamber door would require opening, large quantities of either gas drench the test preparation area. CO_2 and Freon also have a tendency to fill the chamber from the bottom while nitrogen will disperse equally throughout the rhamber area when discharged under atmospheric or vacuum conditions. Freon and CO_2 will solidify or liquify on the cold wall in the main chamber; nitrogen, in this condition, remains in the gaseous state and consequently will be capable of diluting the oxygen from the testing apparatus or the spacecraft.

The fire extinguishing system is designed with internal and external manual controls for operation in the

910-MEDICAL FACILITIES

A complete bio-medical facility is located immediately adjacent to the chamber area. FAA Class 2 physicals are given to all personnel who will enter the chamber for testing, observation, or emergency rescue, and provisions for medical attention are readily available for personnel exposed to vacuum conditions.

Throughout all testing operations, chamber occupants are visually monitored externally, and closed circuit television utilized when required by physicians specialized in life support. A medical monitoring system is also available for recording and monitoring physiological parameters during testing. The system is composed of an electrocardiograph, electroencephalograph, impedance pneumograph (respiration rate, depth, and volume), cardiotrachometer (heart rate), cardiac microphone (heart sound), pneumotachometer (respiration ratel, and channels for blood pressure (systolic and diastolic). and body temperature (4 channels).

By monitoring, the physician is able to determine, and in many cases, anticipate necessary repressurization requirements or the return to sea level conditions. His instructions are directed to the Test Conductor who returns the Chamber occupants to a safe environmental condition. Rescue teams (at a 30.000 foot altitude or at a sea level condition)mill. upon instructions from the medical director. either apply immediate medical attention or transfer the occupants to the bio-medical area. All chamber observers and chamber operators are trained by both medical and engineering personnel to understand the dangers of altitude and space operations and chamber operations. They are also required to complete a minimum of 10 hours flight time in the chamber. Special rescue teams are formed for every test, and practice rescues are conducted until a minimum time is established.

Although hyperbaric chambers are not normally associated with the space simulation chambers, recent studies indicated a need for such facilities in the close proximity of the chamber area. In cases where chamber occupants or observers would be inadvertently exposed to full vacuum, repressurization above sea level pressure may be required. Plans have been formulated to add such a facility to the present laboratory.

In addition to numerous items in the bio-medical facility, other safety equipment such as portable CO_2 and dry chemical fire extinguishers, portable breathing oxygen bottles, masks and regulators, fire blankets, flameproof coveralls, and emergency lights are available in the immediate area of the chamber for utilization by the rescue team during emergency conditions. It is desirable that members of the rescue team have oxygen masks, with protection for the eyes from dense smoke or noxious gas, portable lights, and fire extinguishing equipment capable of subduing local fires. Deletion of any of these items may cause a loss of time and increase the hazards to, not only the personnel in the chamber, but also to the rescue teams.

GEMINI SPACECRAFT INTEGRATION

A Gemini Spacecraft will be installed in the 30-foot chamber with heat, simulating solar radiation and earth radiation, applied by means of infrared lamps which will be programmed around the spacecraft simulating orbiting conditions. Each spacecraft will be monitored by specialists from the control room which is equipped with extensive instrumentation and ground support equipment allowing complete monitoring from launch to orbiting condition. Approximately 200-300 parameters (temperatures, pressures, voltage, etc.) are constantly plotted to provide quick-look data of pertinent spacecraft and chamber parameters. The data is simultaneously transmitted to a central acquisition system and later plotted and evaluated.

Tests will be normally conducted utilizing a simulated man which will provide proper CO_2, oxygen, humidity, and heat functions as required to evaluate the spacecraft system. In future manned operations, chamber observers will be stationed in the primary lock at an altitude of 30,000 feet. They will function as a rescue team and also be equipped to correct any deficiency in the test setup or small modifications to the spacecraft required at the 30,000 foot level. Utilizing this procedure, the chamber is repressurized to the 30,000 foot level for repair and alteration, then returned to full orbiting condition without terminating the complete mission. This would only require purging of the LN_2 shroud system for the 10 minutes necessary to complete minor modifications to the spacecraft or minor modifications to the spacecraft or test setup. However, when extensive damage or deficiencies are encountered during orbit operations, modifications would require return to sea level. A setup of the Gemini Spacecraft inside the space chamber is shown in Figure 15 with the rescue and work platform, required to service the vehicle or the occupants, extending from the primary lock.

FUTURE CONSIDERATIONS

Van-rating considerations should include comprehensive reviews of the chamber electrical system, communications system, and oxygen system with emphasis on safety, reliability, and emergency requirements for possible system failures. These areas, considered in the design of McDonnell's 30-foot diameter chamber, are not discussed here as their design is necessarily unique to each particular chamber.

Future Design Considerations

Future man-rated chambers will include improved system designs, providing even greater safety, reliability, and emergency requirements. Experience gained during the design and construction of McDonnell's 30-foot diameter chamber has resulted in such design improvements, some of which are briefly discussed below.

Addition of Diffusion Ejector Pumps to the Pumping System – Diffusion ejector pumps, initially operated at a much lower vacuum range, would more readily attain lower vacuum conditions in the 10^{-4} range. and consequently, minimize any oil contamination in the chambers. The blowers presently used have difficulty in attaining the lower vacuum range and pumpdown time becomes excessive for efficient operation.

Modification of Diffusion Pump Valves – Diffusion pump valves should be modified to operate simultaneously with other necessary repressurization operations. This would prevent the present five (5) second delay for operation of the valves and pressurization ot the chamber. The initial operation of the emergency repressurization system should permit air or gas to enter the chamber immediately with no delay.

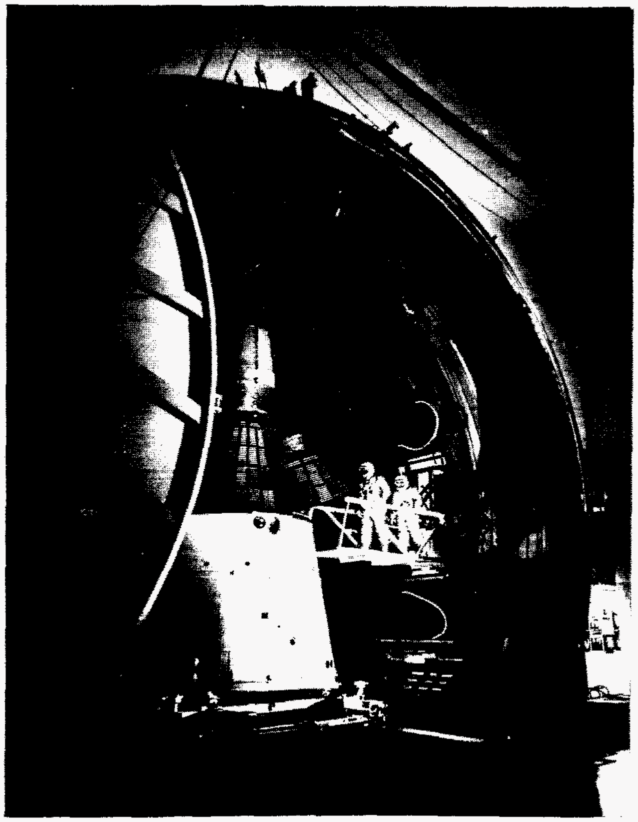

Figure 15 – **The 30-foot diameter chamber enables the Gemini Spacecraft and adapter section to be tested, with occupants, under simulated conditions of space**

Modification of Repressurization Flow – The repressurization system should enter the chamber above the cold traps preventing cooling of the gas. Gas distribution should flow evenly throughout the test area eliminating turbulence and acoustic noise in the chamber and decreasing repressurization time by increasing the flow rate.

Improvement of External Lighting – All external lighting through viewports should be placed at a sufficient distance to minimize radiation heat effect on the glass. The glass area should be cooled, if necessary, to minimize thermal stress gradients and supported to minimize structural restraints.

Addition of Repressurization Tank Drains – The repressurization tank should have drains for removal of moisture which could inadvertently enter the tank proper, and in time, condense on the tank walls.

Improvement of Repressurization Valves – All repressurization valves should be of a normally closed design and initiated only when electric or pneumatic power operation is required. In addition these valves should have mechanical overrides, providing a further safety factor in case of failure of the emergency operating systems.

Addition of Emergency Systems – Standby emergency water cooling systems for the diffusion and mechanical pumps and an emergency electrical system should be available to operate the prime controlling valves and monitoring systems.

Improvement of Chamber Doors – Chamber doors should be lightweight, equipped with anti-friction hearings, and be capable of full opening within three (3) seconds of initial operations. All internal chamber operations should be located such that they will remain accessible when doors are open.

Improvement of Chamber Control Valves – Control valves for all chambers should be available in the immediate area of the chamber operator, and all internal valves should be grouped so the internal observer can control his section of the chamber from one location (employing the work station concept in the initial design). These valves, oxygen regulators, communications systems, viewports, etc.. should be grouped together within arm's length for operation by the internal chamber observer.

ACKNOWLEDGEMENT

Prime contractor for McDonnell's 30-foot diameter, space-simulation chamber was Chicago Bridge and Iron Company. Cryogenic systems were designed and constructed by Air Reduction Company. All chamber systems operate satisfactorily according to McDonnell specifications.

Technical assistance for this paper was contributed by Emile S. J. Wang, B.S. Chemistry. M.S. Chemical Engineering, engineers and technicians of McDonnell's Systems and Space Simulation Laboratory, and Mrs. Katherine Meissner, B.S. Technical Journalism.

BIBLIOGRAPHY

1 Albright, G.A., Helvey, W.M. Rind, H., and Beck, A.I., Republic Aviation Corporation, Report #2645–62 presented at American Rocket Society 17th Annual Meeting and Space Flight Exposition.
2 "Chicago Bridge and Iron Company Proposal" to McDonnell Aircraft Corporation Specification #115200.
3. "Compatibility of Vacuum Pump Fluids with Oxygen", McDonnell Aircraft Corporation Report WR5511.
4. "Conditions Leading to Initiation of Fire in Electrical Cabling", McDonnell Systems and Space Simulation Laboratory Report WR5543.
5. "Fire Protection Handbook", twelfth edition, National Fire Protection Association, Boston 10, Mass., 1962.
6. "Flexure Testing of Pittsburgh Plate Glass Company's Chemically Strengthened Glass", Report #12K–053, 21 October 1963.
7. "Fourteen Day – Five PSIA Test", Accident Report ACEL, Naval Ship Yards, Philadelphia, Pa.
8. Furlong, David, Goerz, David J. Jr., and Mayer, Franklin R. of Bechtel Corporation, "Man Rating Features of the Space Environmental Simulation Chambers at National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas", presented at 5th Annual Symposium, Space Environmental Simulation, AEDC, Technical Report No. SDD–92–5.
9. "Investigation of Effects of Chemicals on Vacuum Pump Fluids", McDonnell Aircraft Corporation Report WR 4533, 18 December 1962.
10. "Manned Systems Experimental Programming", PIBA–18, General Electric Missile and Space Division, Valley Forge Space Technology Center, Philadelphia, Pa.
11 Milligan, Lowell H., Ph.D., "The Strength of Glass Containing Cracks."
12. "Progress Report on Wet-Wire Fires," Lockheed California, 1 May 1963.
13. "Properties of Selected Commercial Glasses", Coming Glass Works, B–83, 1963.
14. "Unfired Pressure Vessel Code", ASME, Section VIII.
15. "Safety Provisions and Procedures for Manned Environmental Control System Evaluation", McDonnell Aircraft Corporation Report 9683.
16. "Satisfactory Standards for Low Pressure Chambers Under Variable Temperature Conditions", ARTC–1 1963.
17. Shand, Errol B., "Correlation of Strength of Glass with Fracture Flaws of Measured Size", Corning, New York.
18. "Space Cabin Simulator", USAF Accident Report, Brooks Air Force Base, Texas.
19. "Space Chamber Study Contract", AF 40(600)–952 for XEDC, Bechtcl Corporation, 15 December 1961.