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DEVELOPMENT OF A LARGE METAL ULTRAHIGH
VACUUM SIMULATION CHAMBER

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

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DEVELOPMENT OF A LARGE METAL ULTRAHIGH
VACUUM SIMULATION CHAMBER

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ABSTRACT

A large ultrahigh vacuum chamber has been built for environmental testing of components for the SNAP (Systems for Nuclear Auxiliary Power) program at temperatures as high as 1000°F. The chamber employs diffusion, electronic, and cryogenic pumping to handle high gas loads at high temperature and ultrahigh vacuum. A unique internal heating system, connections, assemblies, flanges, and test set-up jigs are described in detail.

I. INTRODUCTION

At extreme altitudes of 300 mi (atmospheric pressure = 10^{-9} mm Hg) the effects upon materials, mechanisms, and devices are quite different from those at 50 mi (10^{-3} mm Hg). Because SNAP (Systems for Nuclear Auxiliary Power) devices will be operating at these higher altitudes, these devices must be tested for reliability under simulated environmental conditions.

Data obtained on dielectric strength, fatigue, creep, and heat transfer at 10^{-6} mm Hg are sufficiently accurate to be used for design of components for outer space operation. Commercial equipment is available for testing in this range.

Testing has shown however, that friction data obtained from studies of mechanical motion at 10^{-6} mm Hg cannot be considered sufficiently accurate for application to outer space operation.

Two significant effects of outer space on friction are: 1) greases and lubricants volatilize, and 2) dry sliding friction is greatly increased and galling often occurs. At atmospheric conditions a thin layer of oxides and nitrides covers the surface. The formation of this layer is dependent upon the molecules in the atmosphere; at ultrahigh vacuum the gas density is so low that very few molecules strike the surface per unit time.

Theoretical calculations show that a monomolecular layer is formed on a clean surface at 10^{-6} mm Hg in 1.6 sec and at 10^{-9} mm Hg in 1600 sec¹. In outer space, molecules leaving the surface have negligible chance of returning to the surface, and therefore the eventual equilibrium is when the surface is essentially "perfectly clean". The effect of two "perfectly clean" surfaces in contact is not well known. There is a strong tendency for such surfaces to cold-weld together with possible fusion of atoms of one to the other. Because this phenomenon is not well understood, simulation testing must be performed to develop components with high reliability.

One of the major components requiring high reliability in outer space is bearings, particularly those with slow or intermittent movement. In simulated space environment tests, insufficiently high vacuum may give misleading data due to the reformation of the monomolecular layer during the test. To insure reliability of data applicable to those higher altitudes, testing must be carried out

under simulated pressures of 10^{-9} mm Hg or better. Hence, the objective of the equipment described in this report is to provide a suitable chamber for testing components at ultrahigh vacuum.

The SNAP components to be tested in the chamber described in this report are to operate at 1000°F ; thus the chamber will have the additional requirement of maintaining ultrahigh vacuum at this design temperature. At such extreme temperatures and accompanying vacuum conditions, outgassing loads will be high. Consequently, further requirements include high pumping capacity at the required pressure range.

The ultimate in design and advanced vacuum technology has been used in providing equipment for such stringent requirements. Conventional vacuum equipment as well as custom designed liquid hydrogen cryogenic pumping has been incorporated into one system to provide the ability to meet all requirements of flexibility, high pumping capacity, and 1000°F test temperature at ultrahigh vacuum.

II. SELECTION OF AN ULTRAHIGH VACUUM SYSTEM

A. OPERATING REQUIREMENTS

Methods for producing a vacuum are selected on the basis of the characteristics of the vacuum required. Factors which govern the selection of chamber pumps and controls are the size of the chamber, temperature of environment, pressure range, outgassing gas load of the chamber walls, fixtures within the chamber, and the functions to be performed under the environment produced. The size of the chamber should be kept to a minimum capable of producing the functions required in order to reduce chamber wall surface and outgassing loads. Therefore, the size of the part to be tested and mechanisms for performing the test govern the chamber size. The objective of the system described here was to produce a test space capable of handling parts up to 18 in. diameter and 24 in. long. This space was to be maintained at a pressure in the range of 10^{-9} mm Hg with test fixtures and samples in the chamber at 1000°F. It was the aim of the system to produce as clean a vacuum (minimum back diffusion) as feasible. The outgassing loads of indeterminate test parts and fixtures make calculations of actual loads impossible. The selection of the pumping system for this project was evaluated for various combinations of systems to give the maximum pumping capacity at all pressure ranges.

B. COMPARISON OF PUMPING SYSTEM

1. Mechanical Pumps

Mechanical pumps have been built to maintain their pumping speed below 10^{-9} mm Hg.² These pumps are precision machines operating at high speeds, but become expensive in large sizes, and therefore are usually limited to small capacities.

2. Two Gettering Systems

There are basically two gettering pump systems - the absorption pump and the getter ion pump. Absorption gettering systems are used to produce ultrahigh vacuum below 10^{-9} mm Hg in closed or static systems of low outgassing characteristics. These pumps are very effective but are limited by the gettering surface available, the conduction to the gettering surface, and the surface accommodation coefficient. The vacuum limit is the equilibrium between the gas being pumped and its re-emission from the gettering surface. For a dynamic system

or a high outgassing load the pump reaches a limit or saturation and the problem of supplying clean gettering surfaces is difficult. The accommodation coefficient varies for different gases, with the noble gases the most difficult to pump. These systems are very effective in maintaining a vacuum in static systems after pump-down, or as an aid to other systems in removing specific gases but are not too practical on large simulation chambers where the dynamic gas loads are high.

Getter ion pumps ionize, excite, and dissociate gas molecules and then drive them to gettering surfaces by electromagnetic fields. Getter ion pump systems consist of a power supply, magnet, and a pump. The capacity of the ion pump depends greatly upon the gas pumped, with hydrogen capacity approximately 2-1/2 times that of nitrogen, and helium approximately 10% of that of nitrogen, air approximately equal to that of nitrogen. The presence of oils or hydrocarbons decreases the capacity of the pump on all gases.

These pumps have the advantage of being clean and trouble free and ideally suited for small static low gas load systems. But like the absorption pump they have a limited quantitative capacity and if used at pressures above 10^{-6} mm Hg have a short life span. If used only at ultrahigh vacuum their life span is greatly extended. There is no back diffusion of vapors, etc., as in diffusion pump systems. They have the same advantages as absorption gettering with greatly increased capacity, and are a great aid as auxiliary to other systems.

3. Oil Diffusion Pump System

A popular system in current use is the oil diffusion pump. A mechanical pump is used to reduce the chamber pressure to the micron range and the diffusion pump is then used to further reduce the chamber pressure. Diffusion pumps do not operate above the micron range and mechanical pumps must be maintained to compress the diffusion pump discharge to atmospheric pressure. This oil diffusion pump system is very dependable and may operate for prolonged periods of time with automatic control without attendant personnel. The diffusion pump operates at approximately 30% of the theoretical capacity of the aperture of the mouth of the pump. The pump may have blank off (zero outgas load) pressure as low as 1×10^{-7} , but the pumping capacity approaches zero in that range. The back diffusion of the oil vapor to the chamber limits the capacity of the pump and contaminates the chamber atmosphere in the ultrahigh vacuum range.

The back diffusion can be greatly reduced by the use of traps to cool the vapors to their condensing temperature. The most effective of these traps requires the condensation of the vapors on liquid-nitrogen-refrigerated surfaces. The effectiveness of the trap depends upon the accommodation coefficient for condensation of the vapors. Consequently the more effective the trapping the greater the loss in conduction. The conduction of an effective trap is approximately 30% the conductance of the trap aperture. Therefore, the effective capacity of the trapped diffusion pump is in the range of 10% of the speed of the aperture of the area entrance to the pumping system.²

Although it is difficult to completely eliminate back diffusion of oil vapors, trapped oil diffusion systems have been effectively used into the 10^{-9} range. The capacity of the pump approaches zero in this range and the limit of system capacity is generally controlled by the number of pumps which may be installed on the chamber and the size of aperture to the pumps. On large systems, this is expensive, cumbersome, and space consuming.

4. Cryogenic Systems

Cryogenic pumping systems depend upon the accommodation coefficient of the gas pumped, the conduction to the cryoplates, the temperature of the cryoplates, and the freezing temperature of the gases pumped. The cryoplates can usually be located within the chamber so that the conductance is at maximum. Liquid nitrogen may be used as the refrigerant and all gases whose critical temperature is above that of the surface of the cryoplates can be pumped, the limiting pressure being the vapor pressure of the gases remaining. If liquid hydrogen is used for refrigerant, all gases except hydrogen, helium, and neon may be removed from the chamber atmosphere. Liquid helium refrigerant will remove hydrogen; however, because the heat of vaporization of helium is approximately 1/20 that of hydrogen, tremendous amounts of helium are required. A closed system is most economical and a cryostat or refrigeration system is required with the helium system in order to recover the helium. The operation of the hydrogen system is excellent when proper safety precautions for handling the hydrogen are provided. Cryogenic pumping remains effective in the high and ultrahigh vacuum ranges where mechanical and momentum systems cease to operate. Water vapor must be removed from the chamber atmosphere or the cryoplates will become frosted, and the surface temperature will drop to a

temperature below the freezing point of the atmospheric gases. One disadvantage of cryopumping is that no standard equipment is manufactured and all installations must be custom built. If a helium system is used, the cryostat cost is very high. If a hydrogen system is used, the cost of liquid hydrogen may be high, the safety precautions are stringent, and an auxiliary system for initial pumpdown is required. For ultrahigh vacuum an auxiliary system should be provided for gases not pumped by the hydrogen refrigerant.

5. System Selected

The ultimate in ultrahigh vacuum systems takes the advantages of a combination of systems, thus giving high capacity pumping in all ranges. The system selected is a combination of mechanical, oil diffusion, ion, and cryogenic systems. A 46-cfm Kinney mechanical pump roughs the system down to 20 microns through a 16-in. diffusion pump with a water-cooled and a liquid nitrogen trap in series between the chamber and the diffusion pump. At 20 microns a Welch holding mechanical pump and the diffusion pump are "cut into" the system and the Kinney pump is "cut out." The Welch pump, being a higher vacuum pump than the Kinney, reduces the diffusion pump forepressure to approximately 10 microns. A water-cooled trap between the mechanical and diffusion pumps prevents mixing of pump oils. This pump arrangement has been used very successfully to reduce the chamber pressure to 1×10^{-7} at elevated temperatures (1000°F). At this pressure, the diffusion pump is isolated from the chamber by a low conductance valve with a metal-to-metal seat to eliminate all back diffusion of oil vapor to the chamber. After the valve has been closed, the cryoplates located within the chamber are refrigerated with liquid hydrogen. The hydrogen cryopump now pumps the chamber-wall and test-fixture outgassing except for hydrogen, helium, and neon. To remove these gases, an ion pump is turned on. The ion pump is most effective for hydrogen and will pump limited amounts of helium and neon. By using a combination of systems, the most ideal pumping arrangement was made available. The system will now reduce the chamber pressure to well into the 10^{-9} mm Hg range with high gas loads of chamber fixtures and instrumentation.

C. COMPARISON OF CHAMBERS

1. Vertical Type

The vertical (or bell jar) type chamber design system permits easy access to the test setup mounted on the flat horizontal bottom plate. The pumping system

may be attached to and located below this plate. The bell jar can then be independent and is removable in a vertical direction by an overhead hoist.

In order to hoist the bell jar clear of the test setup with the pumping system below the base plate, a great deal of ceiling height is required. If diffusion pumps are used, the available connecting locations are limited to one or possibly two pumps. Cryoplates and ion pumps would have to be part of the bell jar, with required complicated connections adding greatly to the bell jar weight and size and cost.

Another method is to support the bell jar with the pumping system connections and controls attached to the jar at an elevated level. The base plate is then lifted to the bell jar by a vertical hydraulic ram or equivalent. All test setup, fixtures, etc., are mounted on the horizontal movable plate (see Figure 1). This system requires a special facility building and large expenditures for equipment for handling the base plate. On very large systems this has been proven practical but on intermediate size equipment (100 ft³) it is doubtful if the system can be made practical.

These types readily permit the use of double-walled chambers. The between-the-wall pumpout must be part of the bell jar or else be disconnected when the chamber is opened. Sealing between the two concentric jars is often cumbersome and a trouble spot. Leak checking and locating leaks is very difficult unless the space between the concentric walls can be tested. Chamber bakeout is virtually impossible. The space between the jars may be liquid-nitrogen-filled to give considerable cryopumping of low condensable gases and reduce wall outgassing, but insulation outside the outer chamber is required. Material expansion must be compensated for, and generally cracks or apparent leaks develop after repeated temperature cycles.

2. Horizontal Type

Horizontal chambers do not require special high ceilings, hoists, or vertical lifts. Pumps are usually attached to the sides or the bottom of the chamber. If they are attached to the bottom of the chamber, height is increased. If valves and traps are used between the pump and the chamber, the chamber height becomes excessive and the possibility of equipment, test samples, or tools falling into the pump will present a continual problem. If pumps are attached to the side of the chamber by an elbow, the chamber is lowered and the elbow helps to prevent back-diffusion of pump oils to the chamber. An angle valve may be used in place of the elbow to form the angle and provide an isolation valve between the pump and the chamber.

Figure 1. Types of Vacuum Chamber

Instrumentation may be located in a tube section isolated from the heated test zone by heat-reflecting baffles. Test fixtures may be mounted on a horizontal plate within the chamber or on extension arms attached to the chamber door or flange.

The horizontal chamber may be single- or double-walled but the same difficulties exist in sealing, repairs and bakeout as with vertical chambers.

3. Chamber Selected

The single-wall horizontal chamber has been selected, with a separate instrumentation section. The diffusion pumping system is attached to the side of the chamber by a right angle valve. The valve has full flow in the open position. The seat is stainless steel, the valve plate is stainless steel with an oxygen-free copper seal ring. The valve is air-operated with vacuum pump oil seal on the operating cylinder.

Water-cooled and liquid-nitrogen-cooled traps are located between the valve and the diffusion pump support plate. The support plate is attached to the chamber frame and carries the weight of the valve, traps, and the diffusion pump. The diffusion pump may be removed from the system for cleaning without disconnecting traps or the valve. The ion pump is located above the chamber and attached directly to the chamber by a shear-seal metallic gasket. Instrumentation is located in a separate section (Section III-B) with heat-reflective baffles to reduce heat flow to instrumentation components.

D. COMPARISON OF SPECIMEN HEATING SYSTEMS

1. External

One of the simplest systems of heating is a clam shell heater outside the chamber to heat the chamber walls. Response to change in setting is slow, heat-up times are long, and outgassing of chamber walls is excessive at high temperatures. To maintain a test part at 1000°F requires the chamber walls to be considerably above this temperature. The chamber must be constructed of special alloys to withstand the temperature. Seals must be located to permit cooling or must be of the metallic "O" ring or shear type seal, which are cumbersome, undependable, and expensive. Chamber bakeout is not required.

2. Internal

a) Induction

Induction heating is very effective under vacuum conditions because the induction coils need not get hot and can be water cooled to reduce outgassing. The temperature response is very fast and readily controllable. The system is particularly effective when all test parts are the same; however, where a high degree of flexibility is required and the size and shape of the test piece varies considerably, the balancing of the system is extremely difficult within a chamber where visibility is poor and changes require access to the vacuum chamber. Chamber walls can be externally cooled or baked-out without effect on the internal heating system. Induction heating equipment is extremely expensive and requires considerable laboratory space for power conversion equipment.

b) Radiant

Internal radiant heating systems, such as infrared quartz heater lamps or calrod heating elements, give fast response to temperature changes and lend themselves to excellent control by varying the voltage to the lamps or calrods. Chamber walls can be cooled or baked-out by external systems. Outgassing of lamps or calrods will be high initially or upon increase in temperature. However, the extremely high operating temperatures will soon drive off all gases.

3. System Selected

The object of the heating system is to maintain the test sample as close to the desired temperature as possible, with uniform heating of the test part and fast response to change in temperature.

An internal heating system using infrared quartz tubes and oxygen-free copper bus bars has been built into the chamber (Figure 6). Terminal wires for the heat lamps are welded to the lamp terminals and clamped to the bus bars. The lamps are supported by beryllium oxide insulators, the latter having a high thermal conductivity to remove the heat from the lamp ends. Reflectors are mounted behind the lamps to increase the effectiveness of the lamps and decrease chamber wall cooling requirements. Control of temperature is maintained by proportional control of voltage to the lamp through a motorized variable transformer.

III. DESIGN AND CONSTRUCTION

A. CHAMBER DESIGN AND CONSTRUCTION

The vacuum chamber for this project (Figures 2 and 3) is constructed of polished 1/4-in. Type 304 stainless steel plate, rolled into a cylinder 30 in. ID and 48 in. long. All welds exposed to the ultrahigh vacuum section were first inert gas arc-welded from the inside. All first-pass welds were dye checked, X-rayed, and helium leak checked. Any indications of surface cracks, pinholes, or internal porosity were ground out and rewelded. All welds were ground smooth on the inside and again leak checked. After acceptance of the inside weld, structural inert arc-welding was done from the outside. After completion of all welding the inside surface of the chamber was polished to a mirror finish. The back end of the chamber is a formed dome machined on the inside surface and polished to the desired finish.

All flanges were rough-machined before welding. The same rigid specifications were followed on the flange welds. After all welding on the chamber and flange units was completed, all parts were stress-relieved in a vacuum furnace at below 10^{-5} mm Hg. After cooldown under vacuum to below 300°F the furnace was backfilled with argon before exposure of parts to atmosphere. Flanges were then finish machined. All internal surfaces were RMS 32 finish or better.

All fixtures and fittings within the chamber are attached by stainless steel bolts or pins to brackets welded to the chamber prior to stress relief. Provisions are made for each part to expand at elevated temperatures.

B. INSTRUMENTATION FACILITY

The instrumentation section is 18 in. diameter by 18 in. long and houses all heat reflecting baffles, transducers, instrumentation, etc. The instrumentation tube was fabricated to the same specifications as the chamber.

The tube is supported on a mobile dolly that permits removal from or replacement to the chamber without use of hoists, etc., (Figure 4). It supports its own test fixture plate permitting all test setups, instrumentation, and calibration to be made outside the chamber. The fixture plate is supported on ramps within the chamber to prevent changes during elevated temperature operation.

Figure 2a. Chamber During Construction

Figure 2b. Chamber During Construction

Figure 3. Completed Chamber

Figure 4. Instrumentation Facility

The support ramps are thermally insulated from the chamber walls by lavite insulators to minimize heat loss to the cooled chamber walls.

C. FLANGES

Flanges, except the instrument tube flanges, are designed to accommodate either an "O" ring or be seal welded. The "O" ring is for setup and checkout of the system only. After all parts are in acceptable operating condition the "O" rings are removed and the flanges are welded together (Figure 5). The flange welds can be ground off and the flanges rewelded numerous times. The instrumentation tube flanges have double "O" rings with vacuum pumpout between them. Viton A "O" rings are used.

D. FEEDTHROUGHS

Electrical power feedthroughs, developed to handle 220 v, 30 amp (Figure 5), were temperature cycled from ambient to 1000°F and helium leak checked. These units were welded in, but may be replaced.

All facility power and instrumentation are fed into the chamber through the instrumentation-tube-adapter flange. All feedthroughs for test purposes are fed in through the instrumentation tube back flange. Therefore the instrumentation tube with all test hardware and instrumentation can be separated from the chamber without disconnecting any wires, thermocouples, etc. All thermocouples for tests and chamber instrumentation are floating junction stainless steel sheath type calibrated after fabrication. The sheath is welded to the chamber fitting, eliminating all possible leaking or insulation outgassing.

E. BAKEOUT SYSTEM

The chamber has a bakeout system external to the chamber wall. The bakeout system consists of 22 kw of strip heaters attached to the chamber. Thermal bond between the heaters and the chamber walls is provided by heat transfer cement.

The control of bakeout temperature is maintained by a pulse controller. Temperatures are controllable from ambient to 800°F without external insulation; however, removable insulation is recommended. Failsafe shutdown features are used in case of thermocouple burnout.

CHAMBER FLANGE DETAIL

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Figure 5. Chamber and Accessory Details

F. COOLING SYSTEM

The chamber walls are cooled by 3/8-in. OD copper tubing on the external surface bonded to the tank with thermal heat transfer cement. The cooling coils are divided into sections with an individual hand operated needle valve on each section. A water flow switch is located on the supply line to automatically cut off power to the diffusion pump and heaters should the water supply drop below the minimum required.

G. SPECIMEN HEATING SYSTEM

The heating system is composed of twelve 1600-w quartz tubular lamps connected into three parallel circuits (Figure 6). The lamps are supported by fittings welded to the chamber walls, BeO insulators electrically isolate the lamp terminals and thermally conduct the heat from the terminals to the chamber walls. Temperature control is maintained by varying the voltage across the lamps with a motorized autotransformer operated by an electronic proportional controller. Protection is provided for overheating, in case of failure of control, by a pulse control at a set point just above the setting of the proportional control. Thermocouple burnout protection cuts the power off.

H. CRYOPUMP

The cryopump system has been designed to give the maximum pumping surface area and maximum conductance to that surface (Appendix B). Every effort has been made to shield the cryoplate from the hot radiant surface of the test specimens and heat lamps. The liquid hydrogen cryoplate is exposed only to liquid nitrogen refrigerated surfaces. The nitrogen baffles are protected from direct radiation by water-cooled baffles, vacuum gold coated on the reflecting side and black oxide coated on surfaces looking toward the cold zone. To reduce heat reflected to the cryopump, the water baffles are serrated to reflect back into the hot zone (Figure 7). A balance between shielding and maximum conductance has been made.³

The liquid nitrogen cryoplate shields have been constructed of formed 304 stainless steel and welded to produce flow channels between the plate. The liquid hydrogen plate is a continuous reservoir type construction with indentations for structural support only. Cryoplates were helium leak checked after cycling to

Figure 6. Specimen Heating System

Figure 7. Cryopump - Schematic

liquid nitrogen temperatures. Feed lines into the system from the transfer and fill system are thermally isolated by vacuum jacketed transfer lines and thin, low thermal conductivity supports. The liquid hydrogen cryoplate is supported by the liquid nitrogen shield to minimize the thermal gradient across the support. The nitrogen plate is attached to the chamber by low-conductive supports.

I. CRYOGENIC TRANSFER

The liquid hydrogen transfer line (Figure 8) is constructed of 1/4-in. stainless steel tubing with a copper tubing vacuum jacket. A minimum of spacers is used and heat leak paths are kept to a minimum. Two hand-operated special cryogenic valves permit changing of liquid hydrogen dewars without contaminating the system. Exchange of dewars is accomplished by a procedure which includes purging with nitrogen exhausting into the hydrogen master vent (Section III-A). The flow of liquid hydrogen is controlled by an automatic cryo-valve (Appendix A) to keep the cryoplate filled at all times.

Liquid nitrogen is supplied to the laboratory from a 3000-gal. storage tank outside the laboratory building. Transfer to the laboratory is through a 1-in. vacuum-jacketed line. Control to the cryoplate shielding is by an automatic valve like the hydrogen control valve. Control of nitrogen to the diffusion pump cold trap is by a solenoid-operated air-powered Annin valve. Sensing for the valve is by a phase change bulb pressurized to 25 psig with nitrogen. The phase change of the bulb gas actuates a pressure switch to control the valve.

All transfer lines are stainless steel, vacuum jacketed.

Figure 8. Liquid Hydrogen Transfer Line

IV. CONTROL AND SAFETY

A. LIQUID HYDROGEN

To devise methods of handling liquid hydrogen in the laboratory, all known practiced methods of safety had to be considered. In order to effectively shield the hydrogen system from the laboratory and all electrical equipment, instrumentation, contactors, motors, and controls a separate room or enclosure of nonsparking materials was built around and sealed to the back end of the vacuum chamber. This enclosure was vented directly out of the room through the roof with a non sparking explosion-proof exhaust fan. The enclosure is maintained at negative room pressure with air input at the room floor level sufficient for two air changes per minute (Figure 9).

The liquid hydrogen dewar is connected to the control valve (Appendix A) by a vacuum insulated transfer line so installed to permit complete purging of the cryoplates with gaseous nitrogen and then gaseous hydrogen before admitting the liquid hydrogen to the cryoplates. The system is again purged with nitrogen at shutdown with all gases vented to the hydrogen vent. The vacuum-jacketed cryovalve feeds directly into the cryoplate. The exhaust from the liquid nitrogen radiation shield is heated, combined with the hydrogen cryoplate exhaust, and exhausted 10 ft above the roof in a nonsparking, leaktight 2-in. tube. To prevent backstreaming of air, two low-impedance check valves are installed in the exhaust line in series. This hydrogen-nitrogen exhaust is concentric with and inside the enclosure air-change exhaust duct.

No electrical components, light or electrical controls are installed within the reduced pressure enclosure. An air sampling thermoresistant hydrogen detector cell continually samples the exhaust air at the top of the enclosure and at ceiling level in the room.

The hydrogen detector system is tied into the plant control center to indicate, by means of a complete system of indicating lights and alarms, any traces of hydrogen leakage during operation.

A sailswitch is installed in the exhaust duct to give warning of any exhaust fan failure.

Figure 9. Hydrogen Safety Enclosure

B. POWER

All power supplied to the mechanical pumps, diffusion pump, and heaters is fed by one power transformer (Figure 10). The holding coil on the transformer line contactor is interlocked with a flow switch on the cooling water to the diffusion pump and the chamber walls. If the cooling water supply drops below the minimum set level the contactor opens and the power is automatically shut off. There is also an emergency switch near the laboratory exit to break the transformer primary circuit. Power to instrumentation and controls is from a separate source and is not affected by cooling water failure. On power shutdown the 12-in. vacuum valve automatically closes to isolate the diffusion pump from the chamber. A 4-in. normally closed valve isolates the holding pump from the diffusion pump. All backflow of oils is eliminated during emergency shutdown. A quick cooling coil controlled by a normally open valve cools the diffusion pump heater.

V. CONCLUSION

An ultrahigh vacuum chamber for simulation testing of SNAP components at 10^{-9} mm Hg and 1000°F has been built. An analysis of systems and components is given and conclusions drawn for the basis of the design selected.

The chamber is 30 in. in diameter and 48 in. long with an 18-in. diameter by 18 in. long instrumentation tube.

The facility incorporates a combination of pumping systems consisting of a 16-in. oil diffusion pump with water- and liquid-nitrogen-cooled baffles, 270-liter-per-second electronic ion pump, liquid hydrogen refrigerated cryoplates with liquid-nitrogen shielding.

The facility includes a 19.5-kw internal infrared quartz lamp heating system with proportional temperature control up to 1000°F. Bakeout of chamber to 750°F is provided by 22 kw of strip heaters external to the chamber. Provisions for cooling of chamber walls after bakeout is by water cooled copper coils on the external surface of the chamber.

The system has been in continuous operation with the exception of the liquid-hydrogen cryoplate, at pressures of 8×10^{-8} mm Hg at 1000°F with specimen under test.

Every indication is that pressure below design objective of 10^{-9} mm Hg will be achieved when the cryopumping system is in operation.

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APPENDIX A

LIQUID NITROGEN OR HYDROGEN CONTROL VALVE

The liquid level control valve, built to control the level of liquid hydrogen or nitrogen in the cryoplates, has no electrical components and is completely self-contained (see Figure 11). The dewar is maintained at a constant pressure and the flow of liquid is controlled by the operation of a stainless steel valve. Operation of the valve is dependent upon the phase change of a pressurized gas in the sensing bulb. When the bulb is above the liquid level, the pressure in the bulb overrides the spring and bellows and actuates the valve stem. When the sensing bulb is submerged in the cryogenic liquid, the pressurized gas is condensed and frozen in the bulb, thereby reducing the pressure against the bellows, and the spring returns the valve stem to the closed position. The valve is fail-safe to a leakage or loss of the pressurizing gas or bellows failure.

Figure 11. Automatic Cryogenic Valve

APPENDIX B

CRYOPUMP DESIGN

The design of a cryopump can be made with close approximation on a basis of heat transfer, cryoplate and shielding temperatures, and the mass flow equation.

Under "free molecular" flow (less than 1 micron), heat transfer due to free convection is negligible, and for radiation the Stefan-Boltzman equation^{4,5}

$$W = \alpha E A T^4 \quad \dots (1)$$

represents the heat transfer, where

W = the heat transfer due to radiation in watts per square foot,

α = constant $5.266 \times 10^{-9} \text{ w/ft}^2 (\text{°K}^{-4})$,

E = total emissivity at temperature T ,

A = area in square feet of radiation surface, and

T = temperature in °K.

With the cryoplate at liquid hydrogen temperature (20°K) and the test specimen heated to 928°K,

$$\begin{aligned} W &= 5.266 \times 10^{-9} (923^4 - 20^4) \\ &= 3790 \text{ w/ft}^2 \text{ of radiation surface.} \end{aligned}$$

$$\begin{aligned} 1/4 \text{ of radiating surface in direction of cryoplates} &= \frac{3790}{4} = 950 \text{ w/ft}^2 \\ &\text{(heat to the liquid nitrogen shields).} \end{aligned}$$

With the liquid hydrogen completely shielded from the heat source by liquid nitrogen cooled surfaces, assuming that 5% of radiation reaching LN_2 plates is reflected and 20% of reflected radiation strikes the hydrogen cryoplate with an absorptivity of 40%, then

$$950 \times 0.05 \times 0.2 \times 0.4 = 3.9 \text{ w/ft}^2$$

absorbed by the plates from the heat source (reflected from shields).

Radiation from the liquid nitrogen plates to the liquid hydrogen cryoplate is less than the error of assumptions made and is neglected.

The volume (V) of liquid nitrogen used in shielding is:

$$V = wak \quad \dots (2)$$

where

$$w = \text{heat flux to baffle } w/\text{ft}^2 = 950 \text{ } w/\text{ft}^2,$$

$$a = \text{area of baffle} = 1.77 \text{ ft}^2, \text{ and}$$

$$k = \text{heat of evaporation of LN}_2 = 0.54 \text{ liter/watt-day (24 hr);}$$

therefore,

$$V = 950 \times 1.77 \times 0.54 = 910 \text{ liters/day.}$$

The volume of liquid hydrogen used by the cryoplate because of radiation of the hot zone:

where

$$V = \text{liter/day (hydrogen)}$$

$$w = \text{heat to hydrogen cryoplate} = 3.8 \text{ } w/\text{ft}^2,$$

$$a = \text{area of hydrogen cryoplate} = 1.77 \text{ ft}^2, \text{ and}$$

$$k = \text{liter/watt-day (hydrogen)} = 2.71 \text{ liter/watt-day;}$$

therefore,

$$V = 3.8 \times 1.77 \times 2.71 = 18.2 \text{ liters/day.}$$

The ultimate pressure obtainable by the cryopump depends on the relation between temperature and vapor pressure of the gas pumped. For nitrogen, this relation is shown in Figure 12. At 21°K the vapor pressure is 10^{-10} mm Hg.

In systems where the molecular mean free path is large compared to the system,⁵ the flow of gas to and from a surface is controlled by the following equation:

$$F_m = 0.05833AP \frac{m}{T} \quad \dots (3)$$

Figure 12. Liquid Nitrogen Vapor Pressure

where

F_m = mass flow rate, gm/sec,

A = area in square centimeters,

P = pressure in millimeters Hg,

M = molecular weight of gas, and

T = temperature of gas in °K.

The ultimate pressure of a cryopump is not the vapor pressure of the condensate at that temperature, but zero pumping speed occurs when outward mass flow is equal to inward mass flow.

This equation is equally applicable for mass flow to the plate and re-evaporation from the plate. The temperature and pressure for condensation are that of the mass flow towards the plate, the re-evaporation is the temperature of the condensate surface, and the pressure is the vapor pressure of the condensate. Therefore,

$$\frac{P_v}{\sqrt{T_v}} = \frac{P_g}{\sqrt{T_g}} \quad \dots (4)$$

and

$$P_g = P_v \sqrt{\frac{T_g}{T_v}} \quad \dots (5)$$

When the cryoplates are shielded by liquid nitrogen refrigerated plates (77°K) and the cryoplate is liquid hydrogen boiling temperature (21°K), the ultimate pressure becomes:

$$P_g = 10^{-10} \sqrt{\frac{77}{21}} = 1.9 \times 10^{-10} \text{ mm Hg.}$$

At pressures above the ultimate the pumping speed will depend on the difference between the inward and the outward mass flow rate at the cryoplates and upon the conductance of the system. The conductance of such a shielded cryoplate depends upon the arrangement and spacing of the cryoplates and the

shields. Where $W = P/2$ and $h = P/4$ (Figure 13) a reasonable assumption would be a conductance of 0.5.

A good approximation of the pumping speed of a cryoplate 18 in. in diameter (1644 cm^2), assuming a volumetric flow rate of $11.6 \text{ liters/cm}^2\text{-sec}$ at a conductance of 1.0 and an accommodation coefficient of 0.4, then becomes $1644 \times 11.6 \times 0.4 = 7600 \text{ liters/sec}$. With a conductance of 0.5 the capacity becomes 3800 liters/sec .

Figure 13. Liquid Nitrogen Cryopumping Speed

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