A Facility for Long-Term Ion Thruster System Testing

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A space simulation facility was modified to provide the required orbital environment for operational testing of a NASA-furnished SERT II mercury ion thruster system for nearly a year of continuous operation. The test required that the thruster exhaust plume energy be absorbed without sputtering of material detrimental to the thruster. This was accomplished by developing a mercury collector and liner cooled by cryogenic nitrogen. A further requirement for electrical and thermal isolation of the collector and other items (at potentials as high as 5000 v in the presence of mercury vapor) was met by designing shielded insulators and vacuum passthroughs. Automatic safety features were incorporated to protect the test article, which eliminated the need for continuous staffing. The facility provided fail-safe control of the environment with only a very few minor malfunctions throughout the life test of the thruster system. The facility was subsequently cleaned and employed in other test programs; no contamination or degradation traceable to the long-term operation with mercury has been observed.

Introduction

THE SERT II mercury ion thruster system, designed and fabricated by NASA Lewis Research Center, is representative of the type being developed for orbital transfer, attitude control, station keeping, and interplanetary propulsion. It consists essentially of a flight-type 15-cm-diam Kaufman thruster and power conditioning unit (PCU). Previous experimental work with SERT II thruster systems has been reported elsewhere,[1-4] as has the present work.[5] This test program was performed to determine the long-term operational characteristics and potential operating problems of the thruster system and to provide solutions to any such problems before and during the flight test of two thruster systems orbited in Feb. 1970. Ground testing was continued until the mercury propellant supply was depleted.

The long-term ground test required a facility with special features and high reliability. The facility, located at the McDonnell Douglas Corp. (MDC) Engineering Laboratories in St. Louis, was required to maintain safe temperature and vacuum conditions for 8000 hr without opening the chamber for maintenance or repair and without shutting down the facility.

Facility Description

Space Simulation Chamber System

It was required that the thruster be tested with its exhaust plume expanding into a vertical, cylindrical enclosure with dimensions of approximately 4.5 ft (1.37 m) in diameter and 5 ft (1.52 m) long, concentric with the thruster. The thruster itself required a space 18 in. (0.46 m) long and 16 in. (0.41 m) in diameter, and the power conditioning unit (PCU) required a $2 \times 2 \times 1$-ft ($0.61 \times 0.61 \times 0.31$-m) space. The pressure in the test zone was required to remain below 5×10^{-6} torr during operation.

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A horizontal stainless steel space simulation chamber, 8 ft (2.43 m) in diameter and 15 ft (4.57 m) long, provided all the basic features and redundancy needed for the test. Its two 50,000-liter/sec diffusion pumps, utilizing DC-704 silicone pumping fluid, provided ultrahigh vacuum relatively free from contaminants. Evaluation of the residual atmosphere of the chamber with a quadrupole mass spectrometer demonstrated that the vacuum remained adequately uncontaminated when cooling water, instead of liquid nitrogen, was used in the optically-tight antibackstreaming baffles; hence, water was selected to improve economy and reduce maintenance problems. Another advantage of water cooling is that the pump fluid does not freeze and collect on the baffle, but returns to the pump, permitting longer continuous operation without depletion of the pump fluid. Sight gages were installed on the diffusion pumps to permit monitoring fluid levels during operation, and valves were incorporated to allow adding fluid while the pumps were running. A foreline crossover pipe and foreline valves provided mechanical pumping redundancy by means of one 50-cfm (0.024-m^3/sec) and two 530-cfm (0.25-m^3/sec) pumps.

The chamber also incorporated a bakeout system which was utilized to prepare the chamber and supporting test hardware for high-vacuum compatibility. The horizontal configuration with the chamber door mounted on a dolly provided easy access to the test article and supporting hardware. Several large passthroughs were utilized for electrical and fluid lines and for visual observation.

Mechanical and Thermal Equipment

To minimize contamination of the thruster and PCU by mercury, it was necessary to line the exhaust plume test zone with surfaces which would effectively collect mercury. The mercury ions leaving the thruster in the general direction of the thruster centerline had sufficient energy to sputter and erode a metal surface, and contamination of the thruster by metals other than mercury could have been detrimental to the thruster; therefore, the collector was required to be surfaced with mercury. Preliminary design information indicated that solid mercury at approximately $-100°F$ ($-73°C$) or lower was desirable to minimize sputtering. Some mercury ions in the exhaust plume flared outward from the thruster centerline, and some mercury atoms sputtered off the collector; therefore, a liner was necessary to enclose the sides of the test zone. The rate of mercury deposition on the liner was known to be sufficient to prevent exposure and subsequent sputtering of the liner material by the thruster exhaust plume. For these reasons, a 4.5-ft (1.37-m) diam pool of frozen mercury was maintained on the cryogenically cooled collector, and cryogenically cooled panels of Type 304 stainless steel were used to enclose the 5 ft (1.52 m) long cylindrical test zone. Preliminary design information indicated that the mercury in the center of the collector might erode as much as $\frac{1}{2}$ in. (0.013 m) during the thruster life test. Hence, the collector was designed to contain mercury $\frac{3}{4}$ in. (0.019 m) deep; this required approximately 1000 lb (454 kg) of mercury.

The cryogenic liner was manufactured from commercially procured panels which were formed by resistance-welding two sheets of Type 304 stainless steel along parallel strips and then hydraulically inflating the spaces between the welds to form a coolant channel. The panels were also edge welded to provide a vacuum-tight seal. The square collector, with a circular dam to contain mercury, was mounted below the liner. The collector and liner were supported on a frame resting on two rails welded to the chamber. The thruster and PCU were mounted on a second frame above the liner. Substantially all hardware, including the flexible metal hoses used to supply LN_2 to the liner, were of stainless steel. The general arrangement of test fixtures in the chamber is shown schematically in Fig. 1.

A comparison was made between two-stage freon refrigeration and liquid nitrogen cooling of the collector and liner. The liquid nitrogen system was chosen for several reasons: 1) The laboratory is equipped with a 15,000-gallon (56.7-m^3) supply tank, cryogenic lines, pumps, separator, etc., with recirculating LN_2 piped directly to the chamber; hence, no additional refrigeration equipment was needed. 2) The liquid nitrogen, at -320°F (-196°C), provided a wide margin of safety to prevent melting of mercury at what might have become "hot spots" in a -100°F (-73°C) freon system. 3) Reliability of the three-pump LN_2 system had been demonstrated in previous test programs in the laboratory.

A PCU base plate heat exchanger, maintained at 100°F $\pm$ 20°F (38°C $\pm$ 11°C) by controlling water flow and temperature, was designed to absorb up to 300 w of heat from the PCU. The heat exchanger was also used for baking out the PCU to reduce outgassing and the likelihood of glow discharge and arcing within the PCU during its operation. This was accomplished by closed-loop circulation of heat transfer fluid at 163°F $\pm$ 5°F (73°C $\pm$ 3°C) through the heat exchanger flow passages. Also, to prevent the contamination of the PCU by mercury sputtered off the collector surface, baffles were installed surrounding the PCU region. To prevent freezing of mercury in the propellant tanks and feed lines during standby operation (which included collector and liner cooldown prior to thruster startup) three quartz-envelope heat lamps were installed around the thruster.

Water and LN_2 lines were brought into the chamber through the passthrough shown in Fig. 2. To maintain thermal and electrical isolation of the collector, liner, and PCU base plate heat exchanger, the fluid lines of these units were installed with nonconductive fittings and a nonconductive passthrough plate.

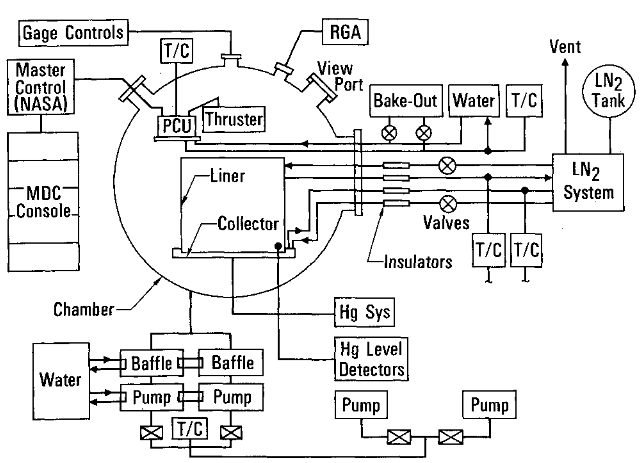

Fig. 1 Ion thruster test setup diagram.

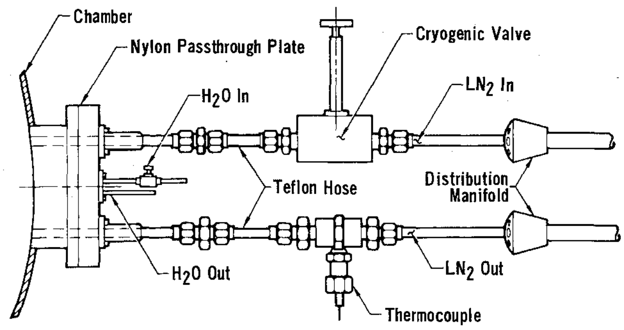

Fig. 2 Fluid line insulation system.

Control valves were installed on the electrically grounded side of the lines. The cryogenic lines, valves, and insulated fittings were encapsulated in cryogenic insulation to avoid condensation of moisture and formation of frost on the parts. Only the vacuum-jacketed portions of the lines, near the passthrough plate, were not encapsulated. They were kept dry by forced convection of ambient air from a small fan. Teflon tubes and caps were used to ensure electrical isolation of the fluid lines inside the passthrough.

The fill and drain system, shown in Fig. 3, was capable of transferring mercury to and from the collector with the chamber evacuated or at ambient pressure. A cooling coil was installed in the insulated tank to permit the use of cold nitrogen gas to chill the mercury to approximately 0°F (-17°C) to reduce its vapor pressure. The cold gas was produced by evaporating liquid nitrogen and heating the gas electrically.

A viewport was provided to permit visual observation of the thruster accelerator grid, neutralizer, and collector surface. The glass was protected from mercury deposition by an internal shutter controlled by an external handle. An internal mirror provided additional viewing capability.

Instrumentation and Control

The master control consoles required to command and power the thruster system and to monitor and record thruster system operational parameters were furnished by NASA. Consoles for operating the facility, for monitoring and recording facility and environmental parameters, and for performing automatic alarm and shutdown functions were designed and built by MDC to function in harmony with the NASA items. In general, the concept was to provide redundant instrumentation for critical parameters and to provide fail-safe automatic alarm and shutdown capabilities to protect the thruster system. In the event of a momentary interruption in electrical power to the facility, the safety system was designed to shut off the main power to the thruster system and to set off battery-powered alarms.

The safety system was also designed so that a rise in pressure above 2×10^{-5} torr on the chamber pressure recorder would set off an annunciator in the laboratory and start a timer. The timer circuit was designed to shut off the main power of the thruster system and to set off an alarm if the pressure remained above 2×10^{-5} torr for 15 min. The timer was designed to reset itself if the pressure dropped below 2×10^{-5} torr within 15 min. The alarm system was also designed to respond to a collector or liner temperature above a set point, usually -150°F (-101°C), or a PCU base plate temperature outside the range 100°F $\pm$ 20°F (38°C $\pm$ 11°C).

Additional safety features included an ultraviolet-type mercury vapor detector, which was provided mainly to warn of hazardous concentrations of mercury during loading, unloading, and cleanup operations. The detector was capable of indicating concentrations of 0.005 to 3.0 mg/m^3 and was operated in the vicinity of the chamber. To supplement the mercury detector during chamber cleanup operations, chemical-type mercury detectors were also utilized.

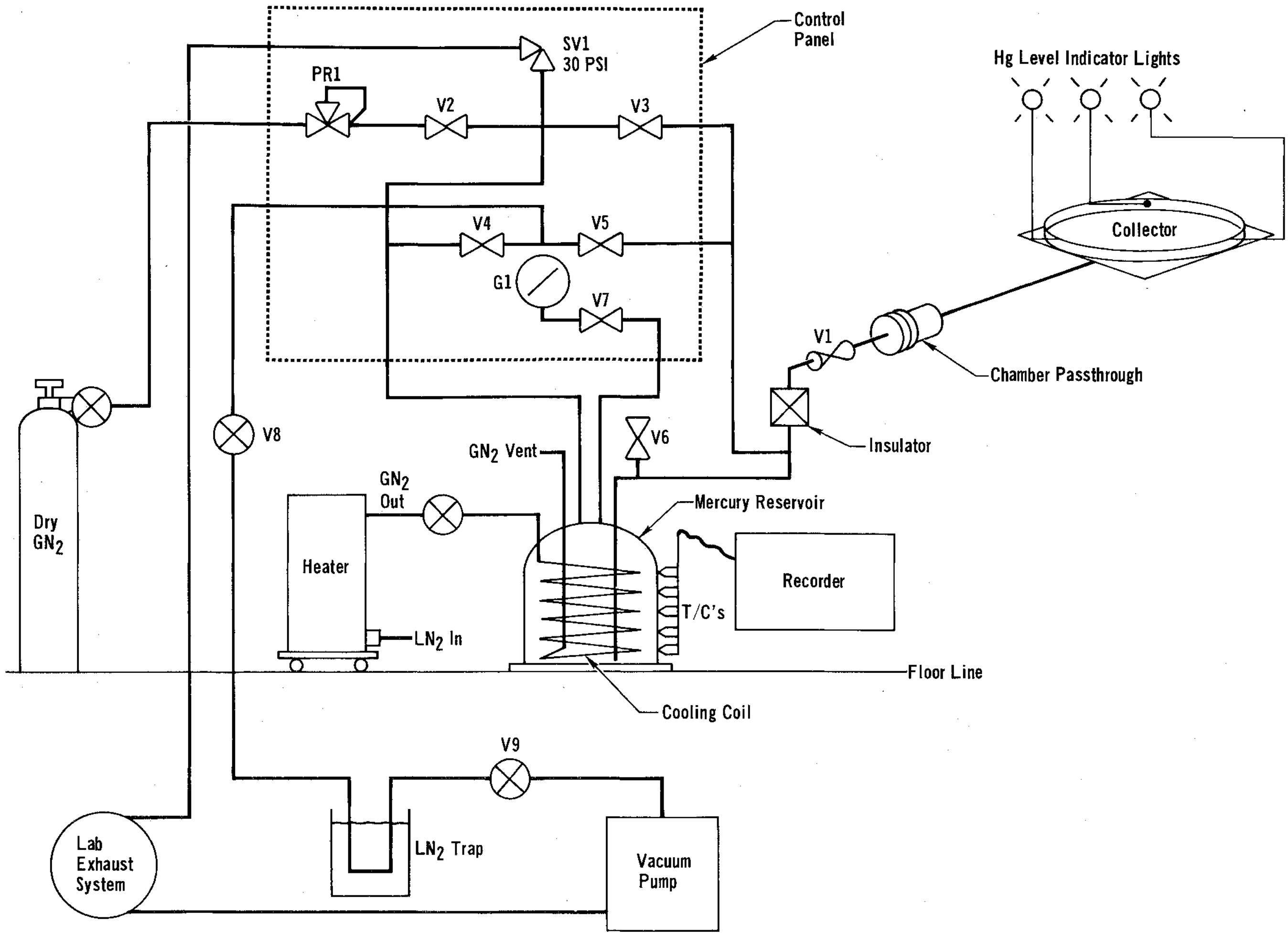

Fig. 3 Mercury transfer system.

Four vacuum gages were used to measure pressures in the various test zones. One Bayard-Alpert-type gage was located in front of the thruster and was aimed toward the collector and liner. Because of possible contamination of this gage by mercury vapor, a Nottingham-type gage was installed; it was also aimed toward the collector and liner, but was protected by a spherical baffle designed to trap the mercury vapor. A second Bayard-Alpert-type gage was located so that it measured pressures near the top of the PCU. A second Nottingham type-gage, for monitoring over-all chamber pressure, was installed on a port which opened through a valve into the top of the chamber; the valve permitted replacement of this gage without repressurization of the chamber.

In addition to the four vacuum gages used for measuring pressures at various locations in the chamber, a quadrupole mass spectrometer residual gas analyzer (RGA) was installed to analyze the chamber atmosphere. The sensing head was installed in a separate enclosure attached to a chamber passthrough port by means of a vacuum valve. Except when the instrument was in use, the valve was closed. This permitted removal of the sensing head for use on other chambers.

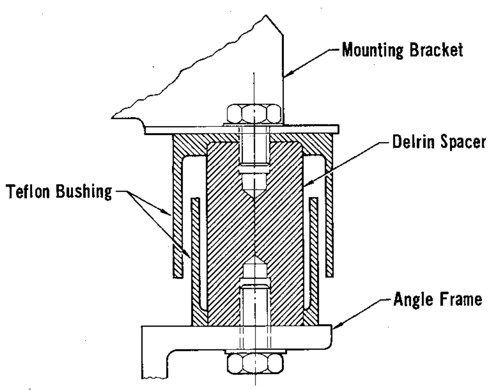

Fig. 4 Typical electrical insulator.

In order to monitor the depth of the mercury pool during the filling operation with the chamber closed, three electrical probes were installed in the collector. The mercury collector was electrically isolated from ground (the chamber support rail and wall), and the liner was electrically isolated from the collector and ground by high-voltage insulators. This was done to electrically "float" the collector and liner at up to 5000 v, with respect to ground, if desired. Similar insulators were provided for mounting the thruster and PCU base plate. The cylindrical insulators, shown in Fig. 4, prevented loss of electrical resistance due to mercury or other conducting films. Means were provided, outside the chamber, to bypass the insulators so that the collector and liner could be electrically grounded.

Facility Operation

Demonstration Test

A test was conducted to demonstrate the capability of the facility to achieve the required environmental conditions within the specified time limits and to maintain these conditions with a simulated thruster heat load. The test consisted of: a) A timed evacuation ("pumpdown") of the chamber from ambient pressure to 1×10^{-6} torr or less, followed by continuous operation of the chamber system for a minimum of 50 hr.

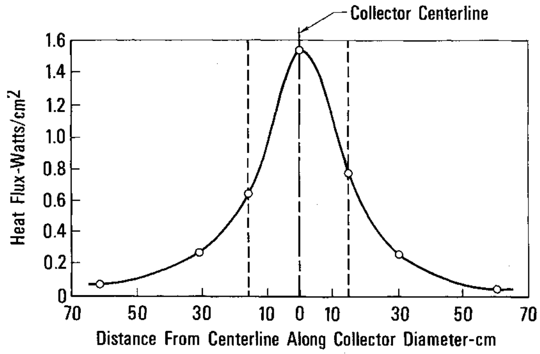

Fig. 5 Power distribution curve for a simulated thruster heat load of 2000 w.

b) Operation of the cryogenic collector and liner so as to freeze a pool of mercury $\frac{3}{4}$ in. (0.019 m) deep and maintain the frozen state during the 50 hr of the chamber system test. c) Operation of an electron bombardment device (to simulate the heat load of the thruster on the frozen mercury) during the 50 hr of the chamber system test. d) Analysis of the residual atmosphere gas species from 1–200 atomic mass units (AMU), at a chamber pressure of 1×10^{-6} torr or less, with the collector and liner cold and the mercury frozen during the 50 hr test. e) A timed warming of the collector and liner to near room temperature followed by analysis of the residual gas species. f) Repressurization, opening, resealing, and re-evacuation of the chamber to a pressure of 1×10^{-6} torr or less, following the 50-hr test.

The test setup used for the facility demonstration test employed an electron bombardment device to apply a simulated thruster heat load to the frozen mercury surface. The power distribution over the surface was adjusted to simulate a condition equivalent to a thruster output of 2000 w. The power distribution curve is shown in Fig. 5. The locations of thermocouples in the mercury and on the liner are shown in Fig. 6, along with the positions occupied later by the thruster and PCU. Eight thermocouples were located in the mercury and six were attached to the inner surface of the liner.

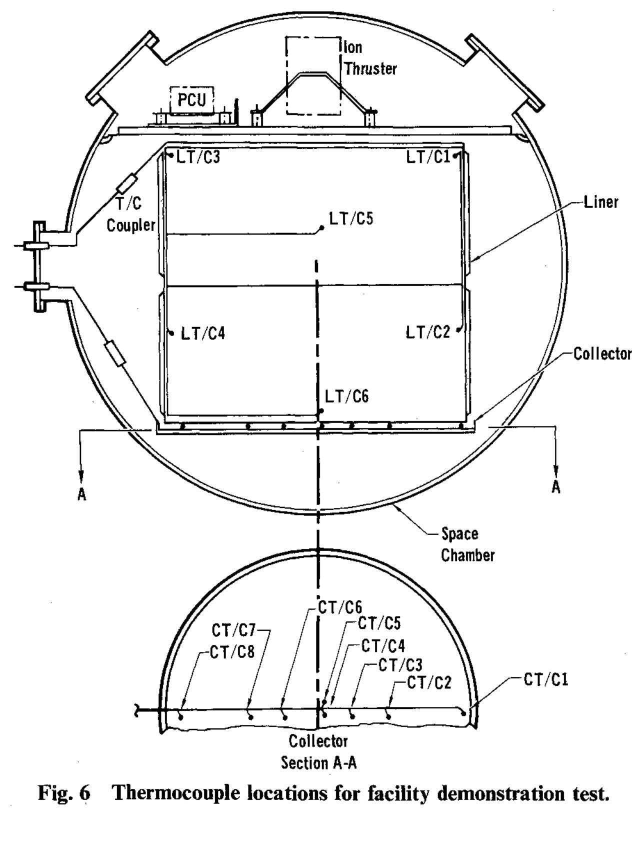

Fig. 6 Thermocouple locations for facility demonstration test.

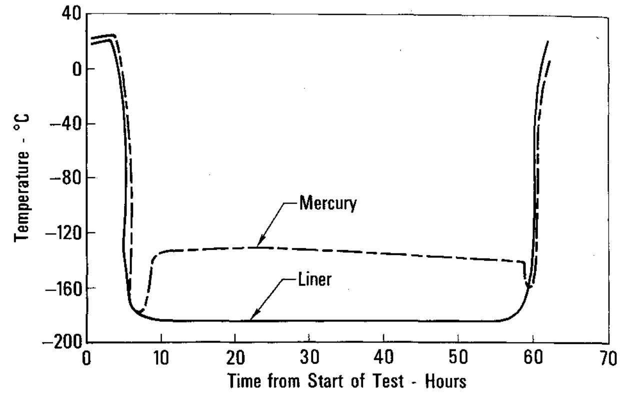

Fig. 7 Mercury and liner temperature—time history during facility demonstration test.

The timed evacuation of the chamber from ambient pressure to 1×10^{-6} torr was accomplished in less than 7 hr, using cooling water in the antibackstreaming baffles. The facility achieved and maintained the desired pressure level for testing the thruster system even with the simulated thruster heat load of 2000 w applied to the cryogenic mercury and liner surfaces. The mercury remained completely frozen, as shown by the low temperatures along a diameter of the collector (Fig. 7). The liner also remained at a temperature well below the melting point of mercury (Fig. 7). Residual gas analyses conducted with the collector and liner at both cryogenic and ambient temperatures showed that the chamber atmosphere was free from undesirable contaminants.

During the facility demonstration test one ion gage was affected by operation of the electron bombardment device. This gage was subsequently supplied with an electronic null signal to compensate for this interference. Later, the gage leads were shielded to circumvent the problem, and an operational evaluation was performed which proved that the original compensated pressure data were correct.

Test Procedure

Before installation of test fixtures in the chamber, all hardware was thoroughly cleaned to minimize outgassing in vacuum. Electrical insulators were cleaned to remove deposits that might have become electrically conductive or might have caused electrical discharges in vacuum. After cleaning, equipment was handled with white nylon or plastic gloves. Electrically powered fork lifts were used, with fixtures designed for the purpose, to carefully insert the test apparatus in the chamber. The completed installation is shown in Fig. 8.

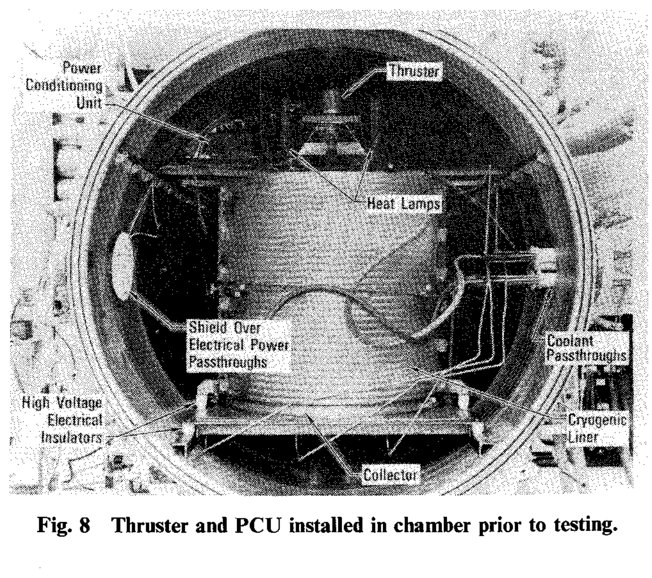

Fig. 8 Thruster and PCU installed in chamber prior to testing.

Before startup of the thruster system, the PCU was baked out at 163°F ± 5°F (73°C ± 3°C) for 12 hr in vacuum in order to remove moisture and volatile materials which could cause glow discharge and electrical arcing during initial operation in vacuum. Then the collector and liner were cooled to approximately −320°F (−196°C) and the PCU was cooled to 100°F ± 20°F (38°C ± 11°C). Having achieved the desired test conditions, the thruster system was started and testing begun.

Normal operation included monitoring of test article and facility parameters at least once every 8 hr by laboratory personnel. This was done to supplement the recorders and to provide a check of system operation throughout the test, including nights, weekends, and holidays.

Following completion of nearly a year of life testing, the chamber was repressurized with dry nitrogen gas, which prevented condensation of moisture, carbon dioxide, and oxygen on the cold mercury and liner surface. As soon as the chamber was opened, a large clear plastic sheet was draped over the end of the chamber and test personnel wearing air-line respirators and special protective clothing entered the chamber to examine the frozen mercury. The liner was kept cold to prevent liner deposits from falling on the collector. The mercury was examined to determine how much the frozen mercury surface had been eroded by impingement of the high-energy mercury exhaust plume from the thruster. The mercury showed no measurable erosion when checked with a straightedge laid along a diameter of the frozen surface. The surface was observed to be covered with small needles, evidently of mercury, which projected upward from the surface and which disappeared when the mercury melted. While the cold surfaces were being photographed, air entered the chamber and the cold surfaces became obscured by frost.

After examination of the cold surfaces, the chamber was closed and the collector and liner were warmed to ambient temperature. The thruster and PCU were removed from the chamber by personnel protected by appropriate safety equipment including air-line respirators (inside the chamber), special filter respirators (outside the chamber), plastic coveralls, disposable shoes, and plastic gloves. The work was performed over a plastic sheet to collect any spilled mercury. The mercury vapor level was monitored in compliance with the prearranged procedures. Calcium polysulfide was applied to spilled mercury to reduce the evaporation of mercury and to aid in cleanup employing an approved vacuum device especially designed for this purpose. After preliminary examination, the thruster was sealed in its shiping container and returned to NASA for a more thorough inspection.

Following the removal of the thruster and power conditioning unit, the test fixtures were disassembled and removed from the chamber. Promptly thereafter, parts to be saved were scrubbed in a large vat of alcohol (to remove all accessible mercury) and were then wrapped in two layers of heavy clear plastic film to minimize the escape of any residual mercury. Parts to be scrapped were wiped with alcohol-soaked cloth to remove most of the mercury and then double-wrapped in plastic for disposal. The chamber, pumps, and vacuum lines were disassembled sufficiently to permit thorough removal of mercury. Mercury deposits were found in the pumping system, including portions of the foreline between the diffusion pumps and mechanical pumps. Some mercury was found inside the mechanical pumps, but none reached the traps in their exhaust lines, and no damage resulted to the pumping system. Cleaning of the interior walls of the chamber by wiping with squeegees and alcohol-soaked cloths did not remove all of the deposited film. Some of the chamber surfaces were sanded to remove this deposit.

Results and Conclusions

The collector and liner functioned flawlessly during the test and showed no signs of damage due to bombardment by high-energy mercury. The thermal design, using LN_2 as a coolant, would have been able to handle even greater heat loads if desired. The liquid nitrogen system operated without equipment failure. The temperature and vacuum instrumentation showed no degradation during the test. The PCU and upper part of the thruster showed no contaminating deposits, thus substantiating the mass spectrometer (RGA) demonstration of adequate vacuum cleanliness for long-duration simulated space testing. The viewport and mirror used to observe the thruster system and collector functioned well throughout the test. No problems were encountered with the electrical insulators and electrically insulated coolant lines despite deposits containing mercury on their outer surfaces.

During the long-term test, the only facility problems encountered were: 1) Three momentary (up to 2 sec) interruptions in the main laboratory electrical power supply, resulting in automatic main power cutoff to the thruster system, which required restarting the thruster system on each occasion. 2) One zero-speed switch malfunction on a mechanical vacuum pump which caused a slight temporary rise in chamber pressure. 3) One instance of LN_2 depletion (due to a delivery schedule problem) which caused a temporary rise in the temperature of the collector and liner above −150°F (−101°C) but which did not result in melting of the mercury in the collector. 4) One instance of a random fuse failure in the power supply to one diffusion pump, resulting in a slight rise in chamber pressure. The problem did not reoccur after replacement of the fuse.

The facility performed very well throughout the test program and was still in good operating condition after nearly a year of continuous operation. The chamber has been employed in subsequent test programs and has exhibited no contamination or degradation problems traceable to long-term operation with mercury.

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