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Modification of a Very Large Test Chamber for Plasmasphere Simulation

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No large-volume chamber existed which could simulate the ion and electron environment of near-Earth space. The existing large-volume chamber provided a suitable near-Earth thermal-vacuum environment and was modified to provide for the manipulation of the test volume magnetic field, and for the generation and monitoring of plasma. Plasma densities of 10^6 particles per cubic centimeter were generated in the chamber where a variable magnetic flux density of up to 1.2×10^{-4}T (1.2 G) was produced. Plasma temperature, density, composition, and visual effects were monitored, and plasma containment and control were investigated. Initial operation of the modified chamber demonstrated a satisfactory capability for a wide variety of experiments and hardware tests which require an interaction with the plasma environment.

Introduction

VARIABLE magnetic fields and various species of ionized gas (plasmas) were identified as possible environments to be simulated in combination with thermal and vacuum environments in some of the earliest conceptual studies for large space environment simulation chambers. These capabilities have never actually been included in any of the large space chambers built until now because of a combination of undefined requirements, lack of interest by potential facility users, and added facility complexity and cost.

Potential facility users have since developed a considerable interest in plasma-related effects. Spacecraft charging by magnetospheric plasma was discovered to be a space hazard that can virtually destroy a spacecraft in Earth orbit if the spacecraft is not properly designed, and spacecraft charging technology symposia have been held to review spacecraft charging and other plasma-related effects.[1,2]

Definite requirements were established to provide for the simulation of near-Earth magnetic fields and plasmas in a ground test chamber. Because many of the characteristics of the plasmasphere are difficult or impossible to scale, and to avoid interaction of some plasma effects with the chamber walls, the capability to provide plasma is most useful when installed in a very large chamber. The modification of one such chamber to meet these requirements is the subject of this paper.

Requirements

Preliminary requirements were established by the potential users of the facility with strong consideration given to cost and ease of installing the modifications without interfering with the capability of the facility to continue its normal thermal-vacuum test activity. Cost was to be minimized by adapting existing equipment if possible, even though this meant accepting less than maximum performance or ease of operation.

In general, the plasmasphere (Fig. 1) was used as a requirements model for ion density and variable magnetic-flux density. The plasmasphere is a toroidally-shaped volume of dense plasma which is an extension of the ionosphere guided by the Earth's magnetic field lines out to a sharp boundary which changes with magnetic substorms.

Typical plasmasphere positive ion densities are in the range of 10^3-10^6 per cm^3 with magnetic flux densities varying up to about 0.6×10^{-4}T (0.6 G). Chamber performance goals were to provide up to 10^8 ions/cm^3 and a variable magnetic field of up to 1×10^{-4}T (1 G). Chamber vacuum capabilities dictated that neutral gas background pressure would be about 10^{-4} Pa (10^{-6} Torr), corresponding to an altitude of about 200 km (124 miles).

Chamber Modifications

Basic Chamber Configuration

The test chamber is an upright cylinder with a hemispherical dome and working dimensions of 16.8-m (55-ft) diameter by 27.4-m (90-ft) height. The chamber shell is constructed of 304 stainless steel with re-enforcing bands and structural supports of carbon steel.

Inside the chamber wall are two layers of aluminum reflective panels, and further in from these panels are the

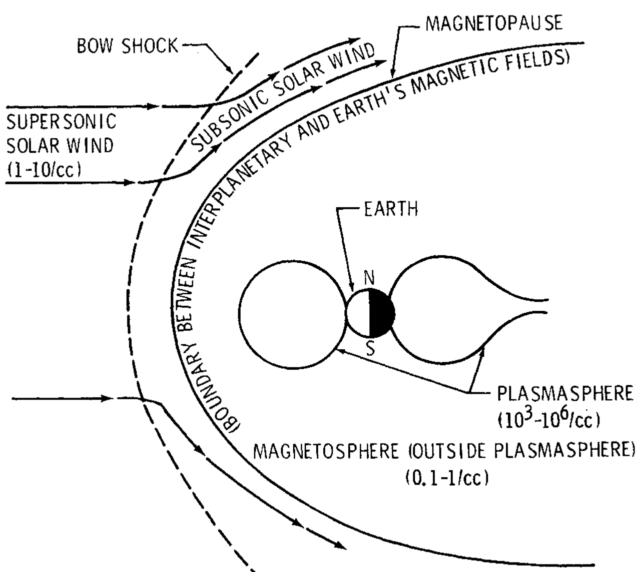

Fig. 1 The natural plasma environment (near-Earth).

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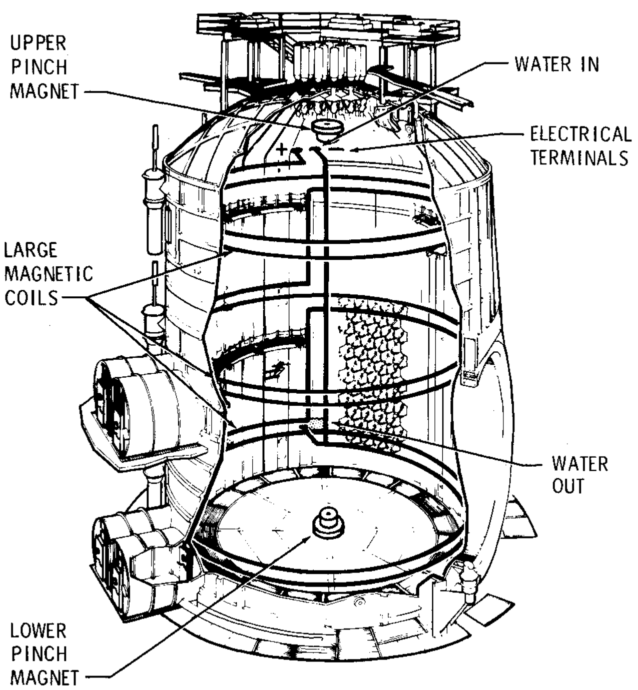

Fig. 2 Test facility magnets.

chamber cold shrouds and cryopumping surfaces which are also aluminum.

The chamber is capable of maintaining pressure below the 10^{-4} Pa (10^{-6} Torr) range using valved and trapped oil diffusion pumps and 20-K helium cryopumps. All gases except hydrogen, helium, and neon are condensible on the cryopumping surfaces, and these gases are evacuated by the diffusion pumps. At 1.33×10^{-4}-Pa (1×10^{-6} Torr) pressure, the chamber has a pumping capacity of 2×10^4 m^3/s for condensibles and 3×10^2 m^3/s for noncondensibles, and an average chamber inleakage of less than 8×10^3 m^3/s of air. There were no requirements established to modify the chamber pumping capacity nor leak rate.

Because some of the equipment to be used inside the chamber was not designed for low-temperature operations, that portion of the chamber used for cryopumping was shielded with aluminized mylar from the test volume.

Several gases, including hydrogen, were planned to be used as sources for plasma. Since hydrogen is a fuel within certain mixture limits, existing hydrogen detectors and an air diluent system were used in the final stage of the mechanical backing pumps with alarms set at a 2% hydrogen mixture (50% of the lower explosive limit).

The natural magnetic field inside the chamber was mapped with a three-axis magnetometer with a specified performance of $\pm 6 \times 10^{-7}$T (0.006 G) with alignment to ± 0.25 deg. The field was found to be twisted and slightly nonuniform with height in the chamber, as shown in Table 1.

Modifications for Magnetic Field Variation

The capability to vary the magnetic field within the test volume was provided by the addition of a large solenoid made of coils of copper tubing (see Fig. 2). The copper tubing was 2.5 cm in diameter and was arranged in six continuous horizontal coils inside the chamber and around the test volume. Two coils were near the bottom, two near the center, and two near the top. Special chamber penetration plates and insulated tube supports were fabricated to electrically isolate the solenoid from all chamber structure. After installation, the solenoid was wrapped with two layers of mylar tape. An existing 0-500 A (at 38 V) dc power supply was connected to the solenoid to provide for up to 3000 A turns. To remove the heat generated by the electrical current, the interior of the tubing was water cooled with up to 7×10^{-2} m^3/min (15 gal/min) at 30×10^4 Pa (30 psig) pressure and single pass flow. The electrical resistance of the water was found to be sufficiently high at 38 V, so that the only electrical isolation required between the coils and the facility water supply piping was provided by 1-m segments of rubber hose from the water supply to the copper. An evaluation by medical and safety organizations indicated there was no hazard to personnel resulting from the magnetic field.

Table 1 Natural magnetic flux density and direction

Location in chamber	Magnetic flux density, $\times 10^{-5}$T	Angle from north, deg	Angle down, deg
Top	3.05	350	50
Center	2.94	344	63
Bottom	2.90	332	73

Modifications for Plasma Generation and Containment

Initially, a Kaufman electrical propulsion thruster, a hollow cathode variable plasma source, and an experiment including a rocket payload keV electron beam were planned to be the only plasma generators used. However, during operation of a very low frequency (VLF) antenna experiment, it was determined that a reasonably intense and homogeneous plasma could be generated throughout the chamber by exciting the tenuous residual gases in the chamber with MHz-radio signals on the antennas.

The VLF antennas were installed as an experiment to study antenna impedance due to plasma sheath loading. Three antennas were used and were each built of 1.27-cm diam copper tubing. One loop antenna, 5 m in diameter, and two dipole antennas, each 5 m long, were used. The plane of the loop was parallel to the Earth's magnetic field at the installed elevation with the dipoles perpendicular to the field. See Ref. 3 for experiment results.

Two means of controlling plasma distribution and reducing plasma losses were investigated. The primary means of plasma control and containment that was investigated employed two wire-wound electromagnets (pinch magnets) in conjunction with the large magnetic coils that surrounded the test volume in three horizontal planes (see Fig. 2). A pinch magnet was located at the top of the chamber, and another was installed at the bottom of the chamber. Each pinch magnet was a 25-cm spool with 500 turns of #12 AWG wire connected to an existing 0-20 A (at 50 V) dc power supply to provide up to 10,000 A turns each. Cooling was provided by bolting the electromagnets to a water cooled aluminum plate. A thermally conductive epoxy was also used to insure adequate heat transfer from the electromagnets while in vacuum. Temperature of these magnets while energized never exceeded 340 K. Plasma containment augmentation by the use of electrostatic shields was also investigated. The shields were aluminized mylar with the aluminum side toward the test volume and electrically biased at ± 50 V dc. One shield covered the chamber floor and one was suspended by nylon ropes over the test volume.

Special Instrumentation

Plasma temperature, density, composition, and visual effects were monitored by Langmuir probes, a mass spectrometer, and two low-light-level television cameras.

Twenty-three Langmuir probes at various chamber locations monitored plasma temperature and density, and the data were logged manually. Six of the Langmuir probes were 12.7-cm diam and seventeen were 1.27-cm diam.

Two low-light-level television cameras were used which were developed originally for monitoring auroral phenomena. The camera sensitivity for a horizontal resolution of 600 lines was approximately 10.7 lm/m^2 (10^{-5} fc) illumination, which is about 2000 times more sensitive than a commercial vidicon tube. The camera could accommodate changes in light level of 10,000:1; but to observe the low-light-level plasmas, precautions were taken to prevent damage to the camera. Opaque covers were placed over all the chamber viewports, and the camera was shielded from the chamber ionization gages. According to the test procedure, the normal chamber lights were not turned on while either camera was operated.

Each camera was mounted on a remotely operated pan and tilt unit and was used for five purposes: 1) to evaluate the operation of the plasma generators; 2) to observe light emitted in other areas of the chamber where detectors and experiment systems excited the field; 3) to monitor the actual paths taken by electron beams as the magnetic field was varied; 4) to provide the position readout of movable probes and experiments; and 5) to provide hard copy data of glow, direction, and intensity of the plasma.

With the large magnetic coils energized, the chamber was "mapped" in magnetic flux density and direction at ambient pressure using the three-axis magnetometer. The power to the main coils was varied and the corresponding magnetometer readings noted.

Special Provisions for Moving Equipment in Vacuum

Several experiments and probes were movable during test conditions to allow for extensive reconfiguration of the chamber experiments and for real-time plasma mapping without repressurizing the chamber. Selected experiments and probes were suspended by nylon ropes rather than metal cables so that exposed electrical conductors would not be in the plasma active test volume. If conducting cables were used, they would force the nearby plasma to the electrical potential of the cable, thereby modifying the boundary conditions and the plasma sheaths. Although the nylon ropes interacted with the plasma, the ropes assumed the electrical potential of the plasma. The nylon ropes were connected to existing vacuum-compatible electric motors, pulleys, and counterweights near the chamber walls. From outside the chamber, the electric motors could be energized to reposition the experiments or probes as needed.

Operations

A detailed test procedure and test timeline were prepared. The tests were conducted from September 22, 1977 to December 16, 1977, with test participants time-sharing the facility. There were 17 chamber pumpdowns and repressurizations. The only significant operating problem encountered with the magnetic field generating equipment was that, on one occasion, the water flow to the large coils was not started and the water in the coils near the cold shroud froze. The coils were energized and quickly thawed the frozen water inside. During tests, one fixed magnetometer was used to check the magnetic field. The plasma generating equipment operated reasonably well except that various high-temperature subsystems in the thrusters burned out several times and had to be replaced.

In addition to checking out the magnetic and plasma generating equipment and calibrating the environment, some experiments were conducted and are reported in Ref. 3.

Results

Chamber pressure was limited to a simulation of about 200 km (124 miles) altitude.

Operation of the large magnetic coils shown on Fig. 2 produced a variable vertical component of magnetic flux density of up to about 1.2×10^{-4}T (1.2 G) and modified the plasma environment. Together with the natural magnetic flux density shown on Table 1, the coils developed a total magnetic flux density of from about 1.5×10^{-4}T (1.5 G) downward to about 0.9×10^{-4}T (0.9 G) upward. Magnitude varied with

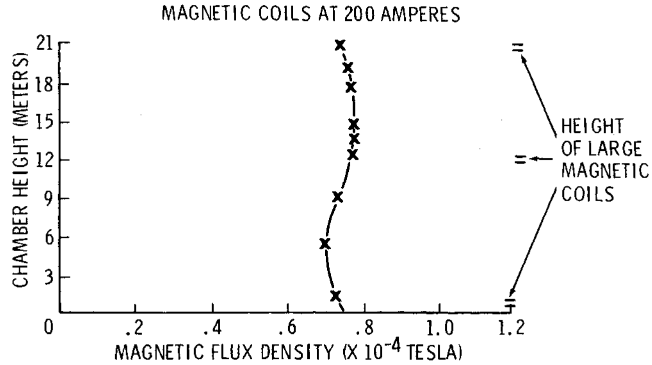

Fig. 3 Magnetic flux density vs chamber height.

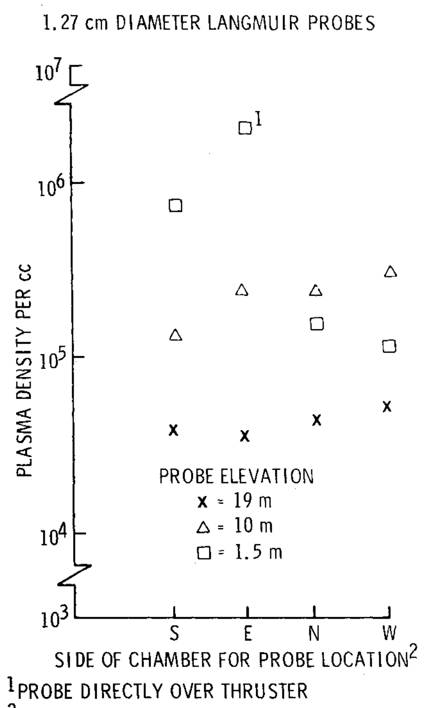

Fig. 4 Plasma density vs probe location.

current, and the direction depended upon polarity. The uniformity of the magnetic flux density varied with height in the chamber (see Fig. 3). Temperature of the coils was monitored at all times while the coils were energized and never exceeded 6 K above ambient temperature.

Plasma densities of 10^6 particles/cm^3 were generally obtained, however, plasma densities as high as 5×10^7 particles/cm^3 were occasionally recorded. The cause for this variation was not determined. Ion species were derived from argon, nitrogen, helium, and hydrogen. Electron temperature was about 1 eV equivalent (11,600 K). As shown on Fig. 4, except for the area immediately over the thruster, the plasma density could be held to within about one order of magnitude over a volume of 15.2 m (50 ft) diameter by 17.5 m (57.4 ft) height. The results of the plasma containment investigation were erratic, but generally the ion density was doubled.

Analysis of ion current and electron current data from the Langmuir probes indicated that the larger probes (12.7-cm diam) appeared to disturb the plasma somewhat more than did the smaller probes (1.27-cm diam).

Plasma sheath dimensions surrounding large structures at up to 5000-V potential were measured with the smaller probes, as well as currents between the structures and the surrounding plasma.

The probes and experiments that were movable at test conditions allowed for extensive repositioning of the test hardware to change and/or measure real-time test conditions. Considerable time and money were saved by the use of the movable items because several hardware configurations were tested without repressurizing the chamber.

Conclusions

The facility provided a reasonable simulation of the upper atmosphere/ionosphere in terms of pressure and electrical (magneto/plasma/dynamic) environment.

Chamber absolute pressure was satisfactory for experiments that were not dependent upon chamber pressure below 10^{-4} Pa (10^{-6}Torr).

A variable magnetic flux density, representative of the plasmasphere, was produced. The upper portions of the chamber were more uniform in magnetic flux density (see Fig. 3) because there was less distance between the upper pairs of coils than between the lower pairs.

Plasma density equal to that of the plasmasphere was achieved; however, electron temperature was higher than that found in the plasmasphere. The investigation to control and contain the plasma succeeded fairly well in control of the plasma distribution, as shown on Fig. 4. Smaller Langmuir probes apparently disturb the plasma less and therefore provide for more reliable data.

The chamber provided a unique capability to observe the interaction between large- and/or high-voltage structures and a surrounding plasma under controlled conditions of chamber pressure, electron/ion density, magnetic field strength, and ion and electron energies.

Now that a very large facility for plasmasphere simulation exists, fairly large spacecraft may be ground tested in the plasma environment to investigate possible spacecraft-plasma interactions such as the following: 1) high-voltage surfaces interactions with the environment; 2) ion thruster efflux interactions with, and electrostatic contamination of, spacecraft systems; and 3) electric fields around spacecraft as they may interact with scientific instruments.

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