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ABSTRACT

Electric propulsion has applications for orbit raising, maneuvering of large space systems, and interplanetary missions. These missions involve propulsion power levels from tenths to tens of megawatts, depending upon the application. General facility requirements for testing high power electric propulsion at the component and thrust systems level are defined. The characteristics and pumping capabilities of many large vacuum chambers in the United States will be reviewed and compared with the requirements for high power electric propulsion testing.

INTRODUCTION

Electric propulsion has applications for orbit raising, maneuvering of large space systems, and interplanetary missions. In NASA's Space Exploration Initiative, nuclear electric propulsion systems have been proposed for robotic precursors, lunar and Mars cargo vehicles, as well as piloted Mars vehicles (refs. 1, 2). These missions involve propulsion system power levels from tenths to tens of megawatts, depending upon the application. Ion and magneto-plasmadynamic (MPD) thrusters are the most advanced electric propulsion technologies for applications that have mission velocity (delta V) requirements in excess of 3000 m/s. The performance, life, and thermal vacuum testing of high power electric propulsion systems place significant demands on the requirements for propulsion test stands and vacuum facilities.

Near term uses of arcjets and xenon ion thrusters for satellite stationkeeping require only a few kilowatts, and test facility requirements can easily be met by many existing vacuum facilities (refs. 3-5). Ongoing NASA technology programs involve operations with 5 to 20 kW inert gas ion thrusters and 200 kW MPD thrusters using krypton, argon, and hydrogen. Nearly all inert-gas electric propulsion tests have been conducted in facilities which employ oil diffusion pumps or helium cryo-tubs with overall vacuum pumping speeds less than 250,000 l/s (refs. 6-8). Such facilities can support tests involving 10 kW-class ion thrusters for orbit raising or precursor planetary flight applications. The existing facilities have also been used to explore the performance, lifetime, and scaling of 100 kW-class MPD thrusters. High facility background pressures limit testing at higher power levels. For example, the inert gas ion and applied-magnetic-field MPD thrusters require facility background pressures less than $2X10^{-3}$ and $4X10^{-2}$ Pa, respectively in order to adequately assess thruster performance and life (refs. 6, 9, 10). If vacuum facility no-load pressure is high and the pumping speed is low, the ion thruster internal and external erosion processes can be impacted such that unrealistic life estimates will result. At high background pressures propellant can be ingested into MPD thrusters resulting in uncertainties in performance, thermal characteristics, and life.

High power solar or nuclear electric propulsion technology programs will focus on applications involving 100 kW-class robotic precursor spacecraft for orbit raising, megawatt-class cargo vehicles, and multimegawatt piloted vehicles. Thruster and power processor feasibility and practicality issues involve the demonstration of specfic impulses in excess of 5000 s, thruster efficiencies greater than 50 percent, and low specific masses at power levels of interest. Life verification diagnostics and extended tests will be undertaken to insure thruster lifetimes up to 10,000 hours. In order to implement performance and life demonstrations at power levels from 0.1 to 2.5 MW, vacuum facility upgrades will be required to provide high fidelity measurements of performance and life. Although previous studies have explored the possibility of using titanium getter pumping (ref. 11) and electromagnetic pumping (ref. 12), large area helium cryopumping is the most promising near-term technology for hydrogen and argon systems. Differential pumping schemes employing LHe cryopumps and conductance limiting baffles have been successfully employed at the Lawrence Livermore National Laboratory to minimize pumping requirements and also allow the plasma itself to act as a pump in the downstream regions of the vacuum chamber (refs. 13, 14). High fidelity thrust stands and thruster exhaust thermal management systems will also have to be a major part of a high power electric propulsion facility.

This paper will define general facility requirements for testing high power electric propulsion at the component and thrust system level. The characteristics and pumping capabilities of many large vacuum chambers will be reviewed and compared with the requirements for high power electric propulsion testing.

GENERAL FACILITY REQUIREMENTS

High power electric propulsion test stands will be required to verify thruster performance and life, provide data for scaling criteria, integrate power processing, and provide definition of critical electrical/thermal/mechanical interfaces. Overall test philosophy will involve separable solar or nuclear electric power source and thrust subsystems with clearly defined interfaces. No end-to-end system ground tests from power source to the thrusters should be required. This approach has been used for nearly all solar powered electric propulsion flight systems (refs. 15-17). It is likely that the power source, power conversion , and segments of the thermal management system will be evaluated at one test bed while the thrusters and power processing will be tested at a separate test-stand.

Table I shows typical system and component performance requirements for various mission applications. Precursor flights involving orbit transfer or planetary science applications will require 50 to 150 kW from the power source (refs. 2, 18, 19). Based on fuel efficiency and technology maturity considerations, 15 to 25 kW krypton or argon ion thrusters represent prime candidates for near term flight opportunities. Flow rates of only 5 mg/s would not place severe demands on existing facilities pumped by relatively small helium cryopanels.

Technology demonstrations of the feasibility and practicality of electric propulsion for lunar or Mars cargo vehicles and Mars piloted vehicles will require facilities to accommodate 1 to 2.5 MW thrusters (ref. 2). Thrust efficiencies in excess of 50% at a specific impulse from 5000 to 8000 s will be necessary. Baseline technologies will likely be hydrogen MPD and argon ion thrusters although other propulsion concepts such as electrodeless and pulsed plasma devices will also need feasibility demonstrations which require large facilities. Thruster flow rates are expected to be in the range 0.5 to 1.2 g/s. Although most thruster life assessments will be made by short-term diagnostics, 5000 to 10,000 hour life validation tests will be required.

Both 25 kW-class and MW-class thruster facilities will likely be pumped by helium cryogenic systems which also employ liquid nitrogen shrouds. Thruster exhaust power dumps will be required to protect the cryogenic system from thermal loading. Simple water-cooled targets can be used for short term tests. Long-term tests will require special designs for the power dumps because significant sputter erosion would be expected. The sputtered efflux from the targets must also be controlled so the optical properties of critical cryogenic surfaces of the pumping system are not significantly affected. Energetic particle sputter erosion will be much more severe using argon ion thrusters than the hydrogen MPD thrusters because of the large difference in sputter yields. For example, at 1500 eV the sputter yield of argon ions on molybdenum is nearly 2 atoms/ion (ref. 20) while the yield for hydrogen on molybdenum is only 0.002 atoms/ion (ref. 21). Erosion rates of carbon or molybdenum targets located about 25 m from a one megawatt argon ion thruster would be as high as 0.3 μm/hr to 2 μm/hr. Carbon-lined surfaces at about 25 m would lose nearly 100 kg during the course of a 1000 hr test.

In order to provide for cryopumps that have areas of 100 to 1000 m^2 (ref. 22), to accommodate large thrust stands (ref. 23), and provide for testing of thruster clusters (ref. 24), a facility should have a diameter greater than 5 m with a length greater than 10 m. For example, the height of the thrust stand used to evaluate 100 kW-class MPD thrusters was in excess of 2 m (ref. 23). A large facility diameter is necessary to minimize wall thermal loading and wall-plume interactions. The vacuum chamber must be large enough to allow detailed simulations of plume effects on the cleanliness of spacecraft surfaces, thruster/power processor interactions with other spacecraft systems, and plume impacts on the transmission/reception of communication signals (ref. 25).

Since the density of thruster efflux generally varies inversely as the square of the distance from the thruster, a large diameter, long vacuum chamber will ease problems associated with first-wall (or target) sputter erosion and sputtered efflux control. A long facility (>10 m) will also allow the use of conductance limiters and differential pumping schemes in order to reduce the overall cryopanel requirement. The cryopanels will periodically have to be regenerated by warming the panels to remove the condensed propellant.

Facility pumping specifications will be driven by the maximum facility pressure allowed for performance and life testing of ion and MPD thrusters. To minimize facility induced charge exchange erosion of the ion thruster negative grids, the facility pressure must be less than $2X10^{-3}$ Pa (ref. 6). Background gas ingestion can increase or decrease MPD thruster performance depending on the propellant and facility background pressure, and facility pressures less than $4X10^{-2}$ Pa are required (refs. 9, 10). The experience base from extended tests of ion and MPD thrusters indicates that no-load facility pressures of less than $1X10^{-4}$ Pa are adequate to protect the integrity of thruster refractory materials under normal operating conditions (refs. 26-28). It has been observed, however, that the sputter erosion rates of some thruster materials can be considerably reduced if the partial pressure of certain background gases is high. For example, the molybdenum grid erosion rate of an ion thruster decreased from 30 to 5 nm/hr when the facility pressure was increased from $7X10^{-5}$ to $3X10^{-4}$ Pa (ref. 29). The high nitrogen partial pressure promoted chemisorption of nitrogen on the molybdenum grid. At low ion energies chemisorption was found to be the mechanism that most likely lead to a reduction of the sputter yield of molybdenum in the presence of the reactive nitrogen gas. The impact of this effect on the validity of thruster life diagnostics depends on the type of thruster, type of life-limiting erosion, and the magnitude of the sputter erosion rate (refs. 30, 31).

Table II shows some of the fundamental facility requirements for 25 kW precursor class and MW-class electric thrusters. Facility requirements are for single thruster operation. For cluster test requirements, the specifications can be scaled. Facility pumping system sizing assumed the use of helium liquifaction systems to provide 5 K cryopanels for the hydrogen propellant. Krypton and argon pumping systems can use closed-loop gas refrigeration with cryopanel temperatures of about 40 K and 28 K for krypton and argon, respectively. Panel effective pumping speeds were conservatively estimated to be about 25% of ideal speeds (ref. 13). The flow rate for the 25 kW-class thruster is 5 mg/s which results in a minimum pumping speed of about $2X10^5$

l/s. The effective cryopumping area, driven by argon requirements, is only 6 m^2 without the use of differential pumping schemes. The sensible heat imparted to the system due to the argon enthalpy change and heat of fusion is only a few watts. A small refrigerator (<<100 W) could easily provide closed-loop or batch processing of the liquid helium. It is likely that an open-loop liquid nitrogen system would be used for the helium pump outer shroud during the short-term and life-tests of the 25 kW-class electric thruster. Estimated liquid nitrogen flow rates would be less than 80 l/hr.

Early tests of MW-class electric thrusters will be necessary to assess the feasibility and practicality of these devices at the high power levels. Ion and MPD thrusters in the 1 to 2.5 MW range will have argon and hydrogen flow rates in the 0.5 to 1.2 g/s range (Table II). Facility pumping speeds will have to be in the 10 to 40 ML/s range to accommodate thruster testing. Without differential pumping the MW-class MPD thrusters would require 140 to 400 m^2 of helium cryopanels while argon ion thrusters operating at the same power level would require about four times the panel area. Clearly it would be advantageous to employ conductance limiters in the facility to partition the amount of pumping and thus reduce cryopanel area requirements (refs. 14, 32). By separating the vacuum chamber into multiple chambers using baffles, the pumping capacity of the downstream chambers may be decreased and the pressure increased if most of the energetic thruster exhaust is carried to the downstream chambers. The pumping speed of the chamber in the vicinity of the thruster would be sized to meet the critical pressure requirements for high fidelity performance and life measurements.

Long term test requirements of MW-class electric thrusters will probably dictate the employment of closed-loop helium and possibly closed-loop nitrogen systems. With a hydrogen flow rate of 1.2 g/s, for example, at least 1.7 kW is needed just to freeze 100 K hydrogen on the panel. Depending on the panel thermal loads and the detailed design, a closed-loop helium liquifaction system with a capacity of about 3 to 5 kW would be required for extended tests of MW-class thrusters. Short-term tests could be done by batch processing liquid helium with subsequent venting and/or liquifaction at a lower rate using a smaller liquifaction system.

DESCRIPTION OF LARGE TEST FACILITIES

Selected facilities used in NASA and DOE programs will be generally described with a focus on ultimate use to accommodate high power electric propulsion test stands. The size, pumping capabilities, and cryogenic systems of six major test facilities will be described in the following paragraphs and synopsized in Table III (refs. 7, 22, 33-38). The basic characteristics of other large vacuum test facilities in the United States are shown in Table I (ref. 33).

NASA Lewis Facilities

NASA Lewis Research Center's Electric Power Laboratory (EPL) houses two large space simulation chambers, Tanks 5 and 6 (Figs. 1, 2). Both chambers employ

20 - 0.8 m diameter oil diffusion pumps, rotary lobe blowers, and a stage of roughing pumps (ref. 7). Both Tanks 5 and 6, using 20 diffusion pumps, can provide pumping speeds for nitrogen, argon, and hydrogen of 0.25 Ml/s, 0.6 Ml/s, and 0.2 Ml/s, respectively. A facility no-load pressure of about $1X10^{-5}$ Pa can be obtained in less than 24 hours. Each facility has large test ports ranging from 1 to 3 m diameter. The test ports can be isolated from the main chamber by vacuum gate valves. Utilizing the test ports minimizes the lengthy vacuum-to-atmosphere recycling time of the main chamber. The test ports can be brought to atmospheric pressure in about 0.5 hr while it takes about 7 hr to recover the main chamber. Both chambers are operated and controlled using programmable controllers to provide automatic fail-safe unattended facility operation. Each facility uses a closed-loop freon refrigeration system to cool diffusion pump baffles for oil migration control. Each chamber is constructed from 1.4 cm thick clad material. The interior layer consists of 3.1 mm 304 stainless steel bonded to the outer mild steel layer. The EPL facilities have been operational for the last 30 years. They have been used for the development of electric power and propulsion systems (1 to 200 kW) and also for the thermal-vacuum testing of spacecraft and spaceflight systems.

EPL's Tank 5 has a 4.6 m diameter and a length of 19 m. The chamber includes four gate-valved, one meter diameter test ports. The relatively high pumping speed of Tank 5 is augmented by helium cryopanels mounted in the chamber. The cryopumping system consists of 41 m^2 of effective pumping area, a helium liquifier/refrigerator, a liquid helium storage dewar, and a gas recovery system. The liquid nitrogen shrouded helium surfaces can be cooled with GHe at 20 K or with LHe at 4.6 K. The projected pumping speed for nitrogen, argon, and hydrogen is expected to be 1.2 Ml/s, 4.1 Ml/s, and 1.0 Ml/s, respectively. The electric propulsion test scenario would include batch processing LHe or GHe for periods from 1 to 8 hr, storage of about $5.7X10^5$ standard liters of GHe, and liquifaction using a 110 W liquifier (4.6 K).

Tank 6 has a 7.6 m diameter and a length of 22 m. After a rehabilitation project is completed in January 1993, Tank 6 will be equipped with a 3-section liquid nitrogen cooled coldwall which will be capable of >0.35 MW thermal power loading. A 8.3 m diameter end-cap will be removable to accommodate test articles as large as 7 m. The facility also has a 3 m diameter, gate-valved test port. The main chamber is pumped by 20 oil diffusion pumps, and the 3 m test port also has two 0.8 m diamenter oil diffusion pumps. All diffusion pumps have a nitrogen pumping speed rating of 30,000 l/s.

The EPL facility has three operational electric thruster test stands that can be used in either Tank 5 or Tank 6. There are two ion thruster test stands with 40 kW capability and a MPD thruster test stand with 0.4 MW available.

The NASA Lewis Space Power Facility (SPF) is a 30 m diameter by 37 m high. The facility encloses about 23,000 m^3 of unobstructed volume. The chamber walls and floor are constructed of 2.2 cm thick 5083 aluminum plate while the dome is made of the same material, 3.1 cm thick. To provide vapor corrosion protection, all interior surfaces are covered with a cladding of 3.1 mm thick 3003 aluminum. The entire chamber is surrounded by a 2 m thick reinforced concrete shell with a 5 m annular gap separating the shell from the chamber. The gap is evacuated to 3 kPa during vacuum operation (Fig. 3). Vacuum chamber access for test article installation or removal is accomplished by two 17 m X 17 m electrically operated doors with pneumatic locks and double O-ring seals. There is also a 2.7 m X 2.7 m personnel door. Three sets of railroad tracks run through the test chamber, the equipment assembly area, and the disassembly area to aid in movement of large test equipment. The test article can be as large as 30 m diameter and 33 m high with a mass of 20 metric tons. The vacuum pumping system consists of 32 - liquid nitrogen trapped - 1.2 m diameter oil diffusion pumps which are backed by two, five stage roughing trains. In total the roughing system contains 10 large rotary lobe blowers and 6 rotary piston mechanical pumps. The chamber can be pumped to $1X10^{-4}$ Pa in a 10 to 24 hr period. The facility provides nitrogen, argon, and hydrogen pumping speeds of 2.5 Ml/s, 6 Ml/s, and 2 Ml/s, respectively. For breaking the vacuum, the chamber can be backfilled with nitrogen or air. Time for bleed-up to atmosphere is about 24 hr. The SPF has a 12 m diameter by 12 m high removable coldwall which is fed from a 1 Ml liquid nitrogen storage system. About 1 MW of heat released from the test article can be absorbed by the cryowall. Power is furnished to the SPF through two 50 MW power transformers. A large diesel generator provides about 1.5 MW of emergency power. The SPF has hard lines for about 190 low power circuits and 700 lines for instrumentation and control.

Lawrence Livermore National Laboratory Facility

The Magnetic Fusion Tandem Mirror Test Facility (MFTF) at Lawrence Livermore National Laboratory was completed and checked out in 1982. Full-scale tests were run in the first half of 1986 (refs. 13, 34, 35). The vacuum vessel is fabricated from 304 stainless steel. The chamber is cylindrical, horizontally situated, and comprised of three joined sections (Fig. 4). The two end chambers are 10.6 m diameter and 16 m long. The center section is 8 m diameter and 20 m long. The MFTF still has large magnet systems mounted inside. With the magnets removed, a thruster would have an unobstructed path of more than 55 m with a diameter of 8 to 10 m. There are over 500 ports throughout the skin of the chamber, some with isolation vacuum valves. The endcaps are removable with some effort. There are twenty small tanks attached to the main chamber. Each of these tanks is 3.1 m diameter and 3.4 m long. These vessels contained the neutral beam injectors and were isolated with valves. The facility is designed to have an external vacuum pumping system and an internal cryopumping system to pump deuterium while performing fusion experiments. The function of the external vacuum system is to provide pumping speed to evacuate the vessel from atmosphere to 10^{-4} Pa. This is accomplished with a series of mechanical pumps, lobe blowers, turbomolecular pumps, and cryopumps. The internal cryosystem comprises 1000 m^2 of cold helium surfaces. The MFTF has two helium refrigeration systems. The closed-loop helium and nitrogen systems are one of the largest in the United States. The two helium systems provide 8 kW and 3 kW of refrigeration cooling, and each can operate as a refrigerator or a liquifier system. As cryopump components are cooled the system is run as a refrigerator and later as a liquifier. The 3 kW and 8 kW refrigeration systems have storage capabilities of 25,000 l and 60,00 l, respectively. The liquid helium storage capability is so large that estimates indicate that a MW-class thruster could be operated continuously for more than 2 days without employing the liquifaction system. The liquifaction rate for the small system is 600 l/hr, and the large system has a rate of 1700 l/hr.

The gas storage for both of these systems are pressure vessels capable of storing $6X10^7$ standard liters. The MFTF pumping speed for nitrogen, hydrogen, and argon is estimated to be 30 Ml/s, 100 Ml/s, and 25 Ml/s, respectively. The estimates are based on pumping speeds of 10 l/cm^2s for hydrogen, 3 l/cm^2s for nitrogen, and 2.5 l/cm^2s for argon. Estimates are about 25% of ideal pumping speeds. The entire cryosystem, magnets, cryopanels, cryopods are shielded by a liquid nitrogen baffle. The nitrogen system is a closed-loop type, and there are two reliquifiers, one providing 100 kW of cooling, and the other providing 400 kW of cooling. The larger system is capable of delivering 1600 l/min and the smaller system produces about 400 l/min (ref. 34).

The external pumping system utilizes a combination of rough, turbomolecular, cryosorption, and cryocondensation pumps. This system together with the cryopanels provides a base pressure of 10^{-6} Pa and was designed to operate at about 10^{-4} Pa. The system handles the experimental gas load, outgassing, and leaks during the experimental cycle. The pumpdown to 0.1 Pa range for crossover to the cryosystem requires 36 hr. In addition to the external pumping system, there is a locally operated leak detection station. This system allows for gross leak hunting and by using 20 K cryopumps can perform fine leak detection.

The MFTF facility demonstration tests were completed in 1986.

Arnold Engineering Development Center Facility

The Aerospace Environmental Chamber (Mark I) is a large vertical tank 12.8 m diameter and 25 m high (refs. 37, 38). The chamber shell is constructed of 304L stainless steel with cylindrical vessel walls 2.2 cm thick and 3.7 cm thick elliptical heads (Fig. 5). The building which houses the Mark I chamber has ten working floors with test article buildup and facility service areas. The Mark I facility has two pumping systems to evacuate the chamber. One cystem has 19 - 0.8 m diameter oil diffusion pumps backed by rotary lobe blowers and mechanical pumps. All diffusion pumps have liquid nitrogen baffles to prevent migration of pump oil. Ports for an additional 29 diffusion pumps are also available. The pumping speeds for this set-up using nitrogen and hydrogen are approximately 0.2 Ml/s and 0.3 Ml/s, respectively (ref. 38). The facility also has approximately 1000 m^2 of helium cryopanels which are generally serviced by 2 - 4 kW helium refrigerators operating at about 20 K (ref. 37). A 1 kW helium liquifaction capability is also available. The chamber pumping speeds for nitrogen, hydrogen, and argon are 15, 50, and 12 Ml/s, respectively. The 1 kW liquifaction system is undersized to provide closed-loop operation for MW-class hydrogen thruster systems, but batch processing with on-going and subsequent liquifaction could be accomplished with a large GHe storage capability. There is approximately $1X10^5$ l of liquid nitrogen storage available at the Mark I site with a 90 kW nitrogen reliquifier (refs. 37, 38). With the cryopanel system operational, base pressures of $5X10^{-7}$ Pa have been readily achieved. The facility also has a quartz-iodide lamp solar simulator, a 0.75 MW tungsten-lamp heat flux simulator, and a liquid nitrogen cold wall using the closed-cycle 90 kW liquifaction system. About 0.2 MW of thermal power, released from a test article, can be removed by the cold wall operating in the open-cycle mode. The facility also has a continuous motion, test article handling system, a 21 m free-fall test capability, rocket plume test stands as well as a clean-room and assembly/disassembly areas.

Oak Ridge National Laboratory (ORNL) Facility

The ORNL Large Coil Test Facility (LCTF) is a 10.7 m diameter cylindrical chamber with a removable lid. The chamber and lid are fabricated from 304L stainless steel. Chamber heights to the lid center and edge are 11.8 m and 9.1 m, respectively (ref. 36). The chamber has 39 ports ranging in diameter from 30 to 122 cm. The chamber has a removable liquid nitrogen cryopanel system that lines the walls. The space inside the coldwall has a diameter of 10.1 m and a height of 9.9 m at the center of the chamber. Since the facility was not designed to handle high gas loads, the pumping system comprises only one 0.9 m diameter oil diffusion pump, two turbomolecular pumps, three rotary lobe blowers, and four mechanical pumps. Nitrogen pumping speed is about $6X10^4$ l/s (ref. 36). A no-load pressure of $1X10^{-5}$ Pa can be obtained.

The LCTF has a large helium system which was assembled to cool-down cryomagnets and associated test equipment. The cryogenic system is composed of a helium liquifier with a capacity of 1 kW at 4.2 K. The helium liquifaction rate is about 400 l/hr. The system has a 19,000 l liquid helium storage capability, and the gas management system provides a capacity of about $1X10^7$ standard liters of helium. The cryogenic system helium inventory during the course of magnet testing was about 3000 kg. The average helium loss rate was estimated to be 40 kg/day due to leaks, purging, and shutdowns (ref. 36). The gas system also employs a helium purifier composed of liquid nitrogen cooled absorption beds, gas dryers, charcoal beds, and molecular sieve beds to remove most impurities except neon which is naturally supplied with the helium. The gas leaving the purifier contained less than 5 ppm oxygen and nitrogen. The LCTF has 94,000 l of liquid nitrogen storage tanks which supply the LHe refrigerator, the helium purifier, the vacuum chamber coldwall, and test hardware such as the large cryomagnet system.

The LCTF checkout and magnet testing occurred during the period October 1982 through September 1987. The long term operation of this facility offers some valuable insight into what might be expected during electric thruster tests which employ helium cryosystems. Over a 22 month period towards the end of the program, the facility was available for testing about 57% of the time. Most of the lost time was due to the helium refrigeration system which was periodically inoperable because of problems associated with leaks, impurities in the helium, and compressor seal and bearing failure. The diffusion pump, turbomolecular pumps, and liquid nitrogen system caused very little down-time to the facility (ref. 36).

Other Government and Industry Vacuum Facilities

Table IV itemizes some other large vacuum facilities, located in the United States, that have a major dimension >7 m (ref. 33). The facilities were built to support NASA, DOE, and the Department of Defense programs related to low Earth orbit satellites, planetary spacecraft, as well as communications satellites and military missiles. Many facilities were constructed to provide integration and thermal-vacuum simulation tests for satellites and thus do not have high throughput pumping systems. Because of ongoing commitments to various agencies and institutions, many of the facilities would not be available for the long term tests required for high power electric propulsion. Some of the facilities have strong capabilities to test high power thrusters. For example, The AEDC 12V chamber is served by a 90 kW nitrogen reliquifier and 8 kW of helium refrigeration. The 12V chamber is about 4 m diameter by 9 m long. The Lawrence Livermore TMX facility has a diameter greater than 4 m and a length of 24 m and has access to 8 kW of helium refrigeration.

FACILITIES ADAPTABLE TO HIGH POWER ELECTRIC PROPULSION TESTING

All six facilities described in Table III, with modifications, are capable of testing electric thrusters in the 0.02 to 2 MW range. The larger chambers namely Lawrence Livermore's MFTF, NASA Lewis's SPF, and the AEDC Mark I would probably be more appropriate for cluster testing since the length of all chambers exceeds 25 m, and diameters are 11 m, 30 m, and 13 m, respectively. In any case, after test requirements are defined a detailed pumping system design study would have to be conducted to define the size and appropriate location for exhaust power dumps, conductance limiters, and helium cryopanels. Specifications for liquifaction/refrigeration and preliminary cost trades would also result form such an effort.

Early technology programs will likely involve testing of 25 kW-class thrusters and thruster clusters for precursor SEP or NEP mission applications. At the same time performance and life diagnostics of MW-class electric thrusters will be undertaken to establish the feasibility and practicality of the devices. The early feasibility test program will likely involve single thruster operation for relatively short periods on the order of 1 to 10 hr. This test period is sufficient to provide performance and life diagnostics and does not place a severe requirement on facility refrigeration/liquifaction systems since gas can be stored and liquifaction can occur after the test segment. Smaller facilities like NASA Lewis's Tanks 5 and 6 or possibly a "fraction" of the MFTF capability are potentially the most economical facilities for the early technology program. The AEDC Mark I chamber is also a candidate, but the long-term testing of electric thrusters may conflict with the needs of other facility users. The facilities used for MW thruster feasibility demonstrations may only require helium cryopanels of 50 to 150 m^2 with appropriate differential pumping, 100 to 1000 watts of helium liquifaction capability at 4.6 K, and simple batch/vented liquid nitrogen system. If a GHe storage capability of 0.5 to 2 standard Ml were available, the helium could be liquified after each test segment.

After high-power electric thruster feasibility demonstrations, performance assessments, life diagnostics, and integration with power processing systems, the electric thrusters will be life tested for periods of hundreds to thousands of hours. The long term tests as well as thruster-cluster demonstrations place a more demanding set of requirements on the facilities (Table II). Cluster tests might involve tests of 2 to 4 thrust subsystems including thrusters, power processors, and propellant management hardware. Closed-loop helium liquifaction or refrigeration systems and possibly nitrogen closed-loop systems will be needed for the extended tests. Cryopanel regeneration will have to be done periodically, or methods must be developed to continuously remove the condensed propellant (refs. 39, 40). Depending on the thruster cluster test requirements and the impact of employing differential pumping techniques, the cryopanel effective pumping area will probably be in the 200 to 1000 m^2 range. Given these demanding requirements, the very large facilities, namely the Livermore MFTF and the NASA Lewis SPF, are probably the best candidates for the megawatt-class long term tests. Availability and detailed technical assessments of these facilities as well as those at ORNL and AEDC will have to be made early in the high power electric thruster development program.

CONCLUSIONS

General requirements for high power electric propulsion test facilities can readily be defined for solar and nuclear electric flight applications that involve robotic precursors, lunar and Mars cargo vehicles, and piloted Mars vehicles. Overall test philosophy will involve separable solar or nuclear electric power source and thrust subsystems with clearly defined interfaces. Thruster power requirements vary from about 25 kW to 2.5 MW with flow rates up to about 1 g/s. Cluster testing requirements would multiply power and flow rates by a factor fo 2 to 4. With modifications, there are at least six vacuum facilities that could perform the early feasibility and practicality demonstrations including performance and life diagnostics, development of scaling relations, and integration of power processors. One or more of these facilities could also be used for all facets of a robotic precursor spacecraft technology and flight program. At least two of the facilities, with upgrades of the pumping, thermal management, and efflux control systems, could perform life tests of MW-class thruster and thrust clusters. Technical assessments of the life test facilities and detailed cost studies have to be undertaken early in the development program.

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Table I. - Typical system and thruster performance requirements.

	ROBOTIC PRECURSOR (ref. 2)	CARGO VEHICLE (ref. 2)		PILOTED VEHICLE (ref. 2)
TYPICAL MISSION (Nominal trip time)	PLUTO RENDEZVOUS (One-way ~ 10 yr)	LUNAR CARGO (One-way ~ 1 yr)	MARS CARGO	MARS PILOTED (Round-trip ~ 400 days)
Nominal system power, kW	100	3000	5000	10,000
o per thruster, kW	25	1000	1000	2500
Nominal specific impulse, s	8800	5000 *	5000 *	5000 *
Thrust, N	1.7	73.5	122	245
o per thruster, N	0.4	24.5	24.5	61.2
Mass flow rate, kg/s	1.9×10^{-5}	1.5×10^{-3}	2.5×10^{-3}	5×10^{-3}
o per thruster, kg/s	4.8×10^{-6}	5×10^{-4}	5×10^{-4}	1.2×10^{-3}
Typical propellants	Kr, Ar	H_2, Ar	H_2, Ar	H_2, Ar
Thrusters	Ion	MPD or Ion		MPD or Ion

* Argon ion thruster specific impulse would be ~ 8000 s with thrust and flow rates about 60% and 40% lower than the 5000 s specific impulse thruster.

Table II. - Facility requirements for single thruster operation.

	ROBOTIC PRECURSOR, 25 kW-CLASS	MW-CLASS
Baseline thrusters	Ion	MPD or Ion
Thruster power, kW	<25	1000 - 2500
Propellants	Kr or Ar	H_2 , Ar
Facility power dump, kW	<25	1000 - 2500
Thruster flow rate, kg/s	$<5X10^{-6}$	5 to $12X10^{-4}$
Maximum facility pressure, Pa		
o Kr, Ar	$2X10^{-3}$	$2X10^{-3}$
o H_2	-	$4X10^{-2}$
Facility minimum pumping speed, l/s (one thruster)		
o Ar ion (or Kr)	$2X10^{5}$	2 to $4X10^{7}$
o H_2 MPD	-	1.4 to $4X10^{7}$
Typical helium cryopanel pumping area (1), m^2 (one thruster)		
o Ar ion (or Kr)	6	800 - 1600
o H_2 MPD	-	140 - 400

(1) Cryopanel area requirements can be significantly reduced by using conductance limiters and differential pumping.

(2) Pumping speeds are assumed to be 10 l/cm^{2}s for hydrogen and 2.5 l/cm^{2}s for argon. These values are about 25% of ideal pumping speeds because of effects of the nitrogen louver impedance and non-ideal gas condensation.

Table III. - Characteristics of large vacuum facilities compatible with high power electric propulsion testing.

	NASA LEWIS			LLNL	AEDC	ORNL
	TANK5	TANK 6	SPF	MFTF	MARK I	LCTF
1. Chamber size, diameter/length, m	4.6/19	7.6/22	30/37	11/64	13/25	10/9
2. Existing pumping system	ODP/GHe	ODP	ODP	LHe	ODP/GHe	ODP/TM
3. Maximum pumping speeds for:	(a)			(b)		
o nitrogen, l/s	$2.5X10^5$	$2.5X10^5$	$2.5X10^6$	$3X10^7$	$1.5X10^7$	$6X10^4$
o hydrogen, l/s	$6X10^5$	$6X10^5$	$6X10^6$	$1X10^8$	$1.5X10^7$	$7X10^4$
o argon, l/s	$2X10^5$	$2X10^5$	$2X10^6$	$2.5X10^7$	$1.2X10^7$	$6X10^4$
4. No-load pressure, Pa	$1X10^{-5}$	$1X10^{-5}$	$1X10^{-6}$	$1X10^{-6}$	$5X10^{-7}$	$1X10^{-5}$
5. Helium cryopumping						
o refrigeration, kW	0.11, at 4.6 K	*	*	11, at 4.6 K	8 at 20 K 1 at 4.6 K	1 at 4.2 K
o LHe storage capability, l	1000	*	*	85,000		19,000
o Cryopanel area, m^2	41	*	*	~1000	~1000	*
o GHe storage, standard liters	$6X10^5$	$6X10^5$	*	$6X10^7$		$1X10^7$
6. Liquid nitrogen						
o liquifaction, kW	*	*	*	500	90	*
o LN_2 storage capability, l	$2.2X10^6$	$2.2X10^6$	$1X10^6$		$1X10^5$	$1X10^5$
7. Time to attain 10^{-4} Pa, hr	~24	~24	~24	36 (0.1 Pa)	7	
8. Time to open ports, hr	0.5	0.5				
9. Time to open chamber, hr	7	7	24			

Notes: *implies capability does not exist; ODP: oil diffusion pump; LHe: liquid helium; TM: turbomolecular pump; (a): pumping speed with ODP's; (b): 25% of ideal pumping assumed, 10l/cm²s for hydrogen, 3 l/cm²s for nitrogen, and 2.5 l/cm²s for argon.

TABLE IV. - Other Government and industry vacuum facilities

FACILITY/LOCATION	CHAMBER SIZE	PUMPING	MINIMUM PRESSURE, Pa
1. NASA Johnson Space Center, Chamber A, Houston	20 m dia. X 36 m high	ODP	$1X10^{-4}$
2. McDonnell Douglas, St. Louis	11.6 m dia. X 10.7 m long	ODP	$1X10^{-6}$
3. McDonnell Douglas, Huntington Beach	11.9 m dia. sphere	ODP	$1X10^{-7}$
4. Boeing Company, Chamber A, Seattle	9.1 m dia. X 12.2 m high	Ion-titanium	$1X10^{-8}$
5. Jet Propulsion Laboratory, Pasadena	7.6 m dia. X 26 m high	ODP	$1X10^{-4}$
6. Rockwell International, Seal Beach	8.2 m dia. X 9.1 m long	Cryopumps	$1X10^{-6}$
7. Grumman Aerospace	5.8 m dia. X 7.9 m long	ODP	$1X10^{-4}$
8. Boeing Company, Tulalip Test Site, Marysville, WA	4.3 m dia. X 6.1 m long	ODP	$1X10^{-5}$
9. NASA Marshall Space Flight Center, Huntsville	4.6 m dia. X 6.1 m long	ODP	$1X10^{-7}$
10. NASA Goddard Space Flight Center, Greenbelt, MD	8.2 m dia. X 12.2 m high	Cryopumps	$1X10^{-7}$
11. Lawrence Livermore National Laboratory, TMX Facility, Livermore	4 m dia. X 22 m long	Titanium getter	$1X10^{-7}$
12. Arnold Engineering Development Center, 12 V Facility, Arnold Air Force Station, TN	3.6 m dia. X 10.7 m high	Cryopump	$1X10^{-7}$

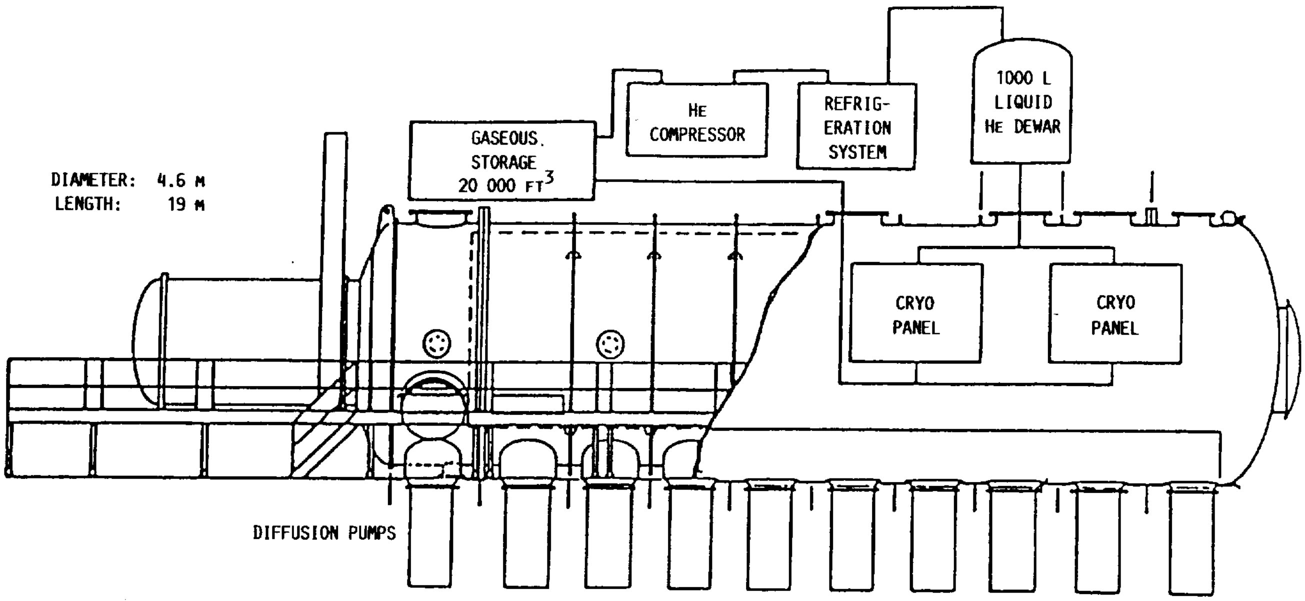

FIGURE 1. - NASA LEWIS RESEARCH CENTER'S TANK 5.

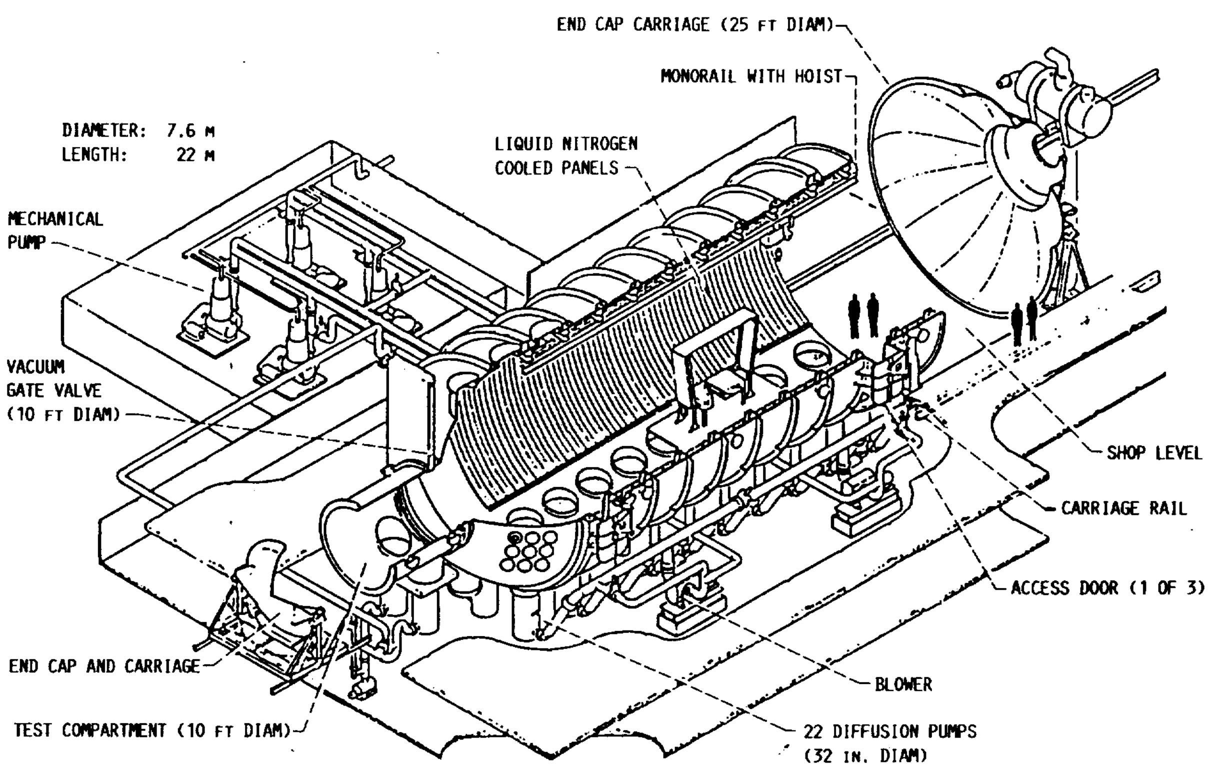

FIGURE 2. - NASA LEWIS RESEARCH CENTER'S TANK 6.

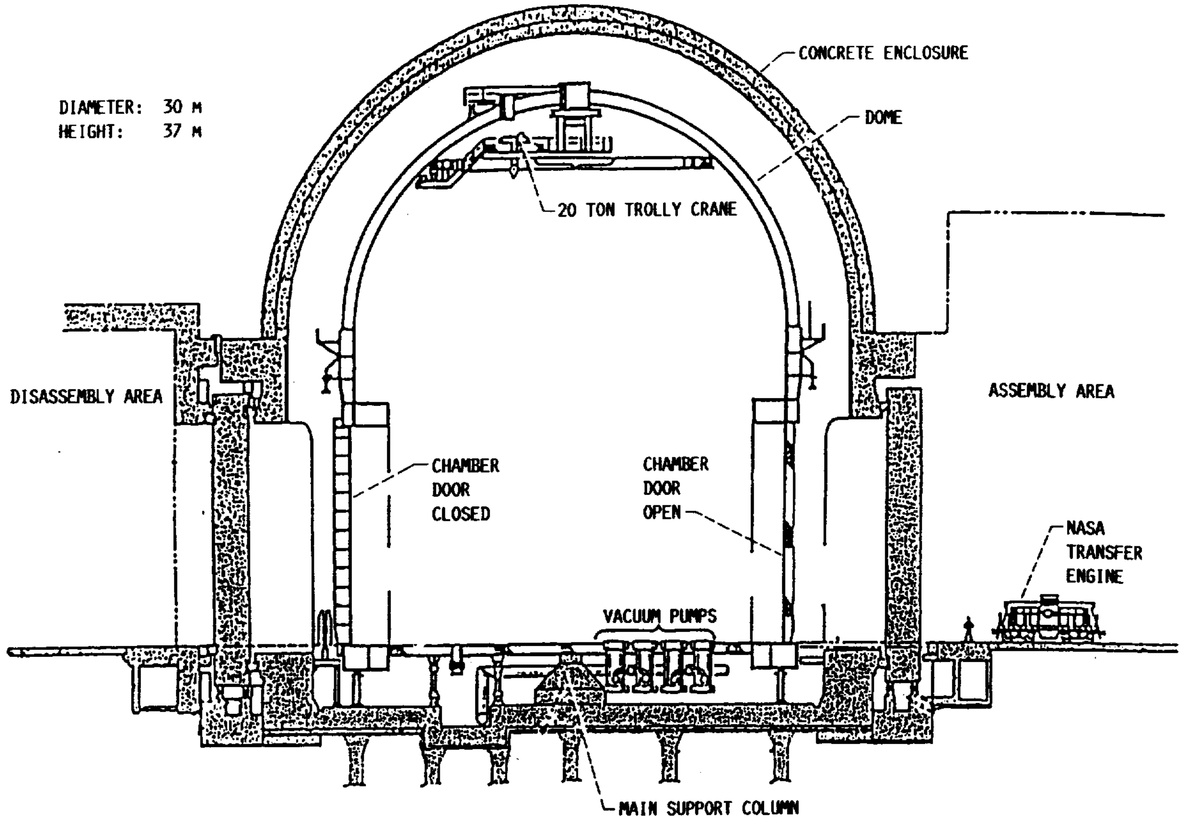

FIGURE 3. - NASA LEWIS RESEARCH CENTER'S SPACE POWER FACILITY.

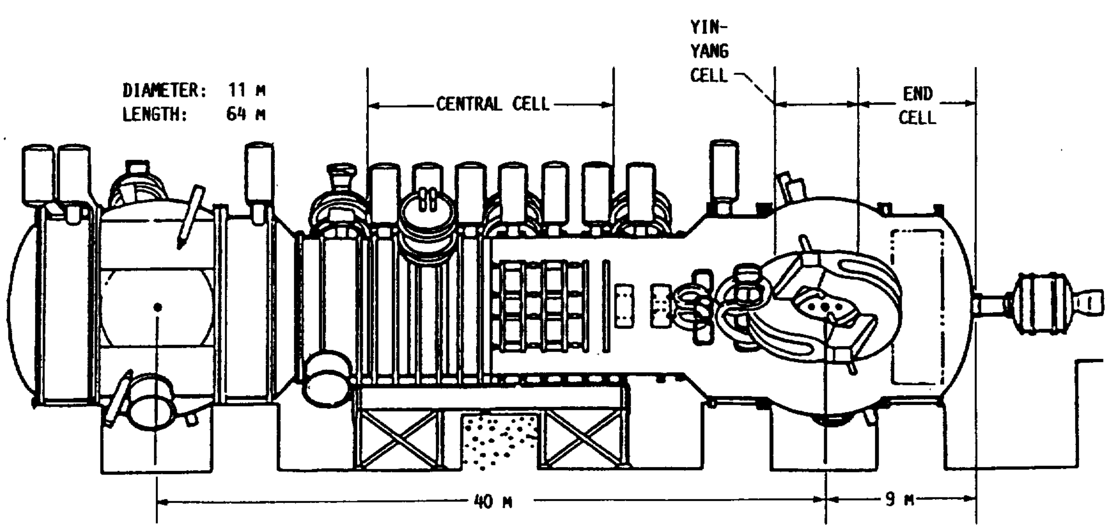

FIGURE 4. - LAWRENCE LIVERMORE NATIONAL LABORATORY'S MAGNETIC FUSION TANDEM MIRROR TEST FACILITY.

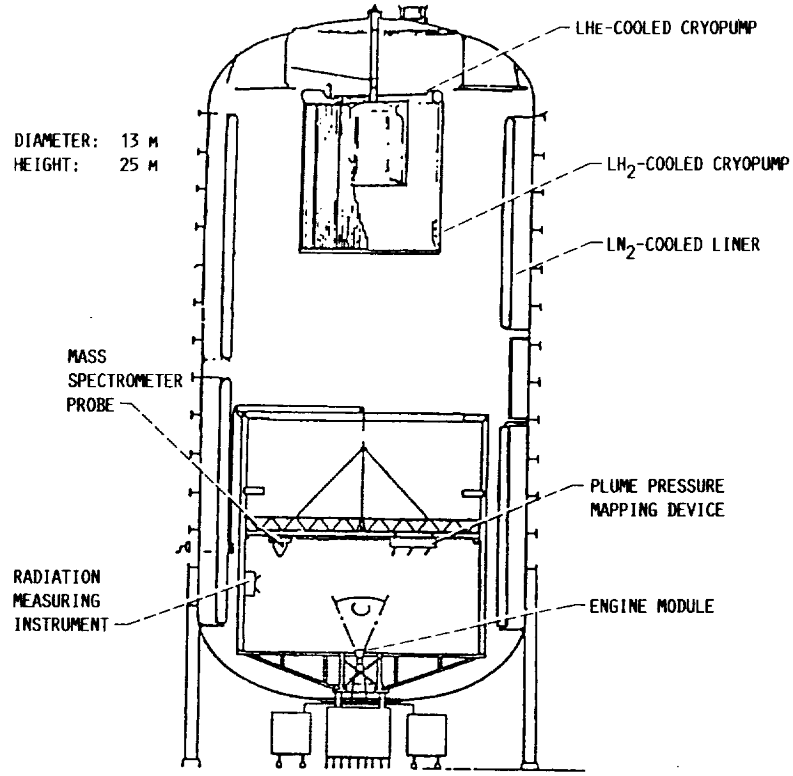

FIGURE 5. - ARNOLD ENGINEERING DEVELOPMENT CENTER'S MARK I FACILITY.

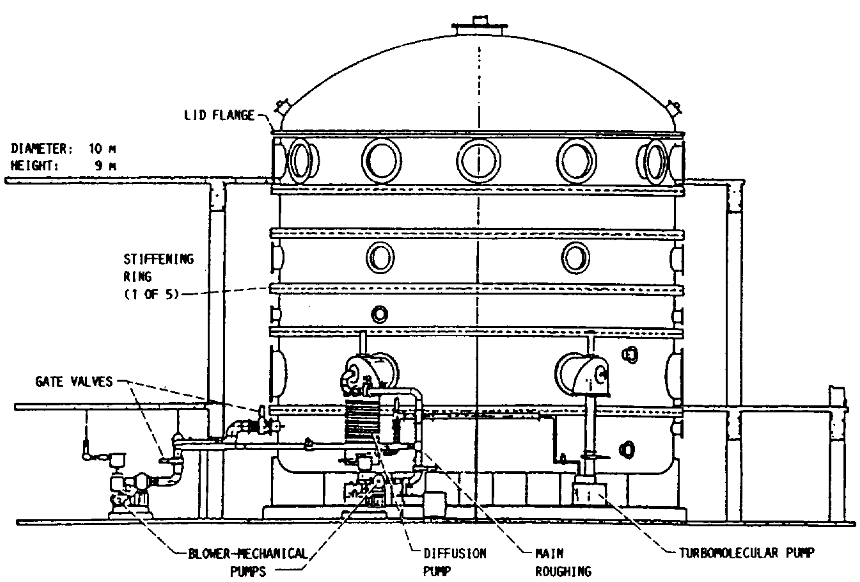

FIGURE 6. - OAK RIDGE NATIONAL LABORATORY'S LARGE COIL TEST FACILITY.

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13. ABSTRACT ***(Maximum 200 words)***

Electric propulsion has applications for orbit raising, maneuvering of large space systems, and interplanetary missions. These missions involve propulsion power levels from tenths to tens of megawatts, depending upon the application. General facility requirements for testing high power electric propulsion at the component and thrust systems level are defined. The characteristics and pumping capabilities of many large vacuum chambers in the United States will be reviewed and compared with the requirements for high power electric propulsion testing.

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