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Test Facilities for High-Power Electric Propulsion

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Facility requirements for testing high-power electric propulsion at the component and thrust systems level are presented. The characteristics and pumping capabilities of many large vacuum chambers in the U.S. are reviewed and compared with requirements for kilowatt- to megawatt-class electric propulsion testing.

Introduction

TEST facility requirements for 1–5-kW-class electric thrusters can easily be met by many existing vacuum facilities.[1–3] Ongoing technology programs involve operations with 1.5-kW hydrazine arcjets, 5-kW xenon ion thrusters, and 100-kW argon and hydrogen magnetoplasmadynamic (MPD) thrusters.[1,4,5] Nearly all inert-gas electric propulsion tests have been conducted in facilities which employ oil diffusion pumps or helium cryopumps with overall vacuum pumping speeds less than 250,000 l/s.[3,4,6]

In order to implement performance and life demonstrations of electric thrusters at power levels from tens to hundreds of kilowatts, 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[7] and electromagnetic pumping,[8] large area helium cryopumping is the most promising near-term technology for hydrogen and inert gas systems. Differential pumping schemes employing liquid helium cryopumps and conductance limiting baffles have been successfully employed to minimize pumping requirements and also allow the plasma itself to act as a pump in the downstream regions of the vacuum chamber.[9,10] 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 article will define general facility requirements for testing high-power electric propulsion at the component and subsystem level. The characteristics and pumping capabilities of many large vacuum chambers will be reviewed and compared with the requirements for high-power electric thruster testing.

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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 likely 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 successfully for nearly all solar powered electric propulsion flight systems.[11–13]

Xenon, krypton, and argon are propellants used for high-power ion thrusters, while hydrogen, deuterium, and lithium are propellants of choice for MPD thrusters. Vacuum facilities will have to accommodate electric thrusters at power levels of a few kilowatts to hundreds of kilowatts.[13–15] Propellant flow rates will be in the 1×10^{-6} to 1×10^{-3} kg/s range. Performance test periods may be only a few hours, but life tests may extend to 10,000 h.

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 2×10^{-3} Pa.[4] Background gas ingestion can increase or decrease MPD thruster performance, depending on the propellant and facility background pressure, and facility pressures less than 4×10^{-2} Pa are required.[16,17] The experience base from extended tests of ion and MPD thrusters indicates that no-load facility pressures of less than 1×10^{-4} Pa are adequate to protect the integrity of thruster refractory materials under normal operating conditions.[18–20] It has been observed, however, that the sputter erosion rates of some thruster materials can be considerably reduced if the partial pressure of reactive background gases is high. For example, the molybdenum grid erosion rate of an ion thruster decreased from 30 to 5 nm/h when the facility no-load varied from 7×10^{-5} to 3×10^{-4} Pa.[21] 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 leads 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.[22,23]

Given the types of propellants, flow rates, and facility pressures, the required facility pumping speeds are $\sim 1 \times 10^5$ l/s for 5-kW xenon ion thrusters to $\sim 3 \times 10^7$ l/s for MW-class MPD thrusters. High hydrogen pumping speeds will probably dictate the use of helium liquifaction systems to provide 5 K cryopanels. Activated charcoal cryotraps are also capable of pumping hydrogen, helium, and neon at temperatures of 10–15 K. Xenon, krypton, and argon pumping systems can use close-loop helium refrigeration systems with cryopanel temperatures of about 54, 40, and 28 K, respectively. Assuming panel effective pumping speeds that are 25% of ideal speeds,[9] and the use of differential pumping,[10,24] helium cryopanel areas range from about 10–1000 m^2. For high-power electric thruster tests operating at ~100 kW to a megawatt, closed-loop nitrogen systems will probably be required, and helium refrigeration systems will require 1–5 kW capacities. Short-term hydrogen tests could be undertaken by batch-processing liquid helium with subsequent venting.

Using the differential pumping concept, the vacuum tank would be partitioned into multiple chambers so that the downstream chamber(s) pump at higher pressure, and 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. Assuming similar benefits of the differential pumping, inert gas ion thrusters will require more than four times the cryopanel pumping surface than hydrogen MPD thrusters when operated at the same power levels. Obviously, the most advantageous propellant from the pumping effectiveness standpoint would be lithium, which condenses at room temperature and does not require large area cryopumps.

Since the electric thrusters will have flow rates of about 1×10^{-6} to 1×10^{-3} kg/s, and life-test durations will be in the 1000- to 10,000-h range, a means of regenerating the helium cryopumps will be required. Propellant frost will build on the cryopump surfaces and eventually will limit the pumping speed. Very large amounts of hydrogen collected on the pump surfaces may also pose a safety problem during regeneration of the pump. At present, most long-term thruster tests are performed in segments where the thruster is shut down after a few thousand hours and the cryopump is allowed to shed the gas load[25] after which the test is resumed. Subscale experiments have also been performed to investigate continuous cryopumping at high flow rates. These methods involve mechanically scraping the frost on the pump surface or removing it by local heating so the material can be removed by a secondary pumping station separated from the main vacuum chamber by a conductance limiter.[26,27]

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 of ion thrusters will require special designs for the power dumps because significant sputter erosion would be expected from high-energy inert gas ions. The sputtered efflux from the targets must also be controlled so the optical properties of critical cryogenic surfaces of the pumping system will not be affected. Energetic particle sputter erosion will be much more severe using inert gas ion thrusters than hydrogen plasma 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,[28] while the yield for hydrogen on molybdenum at energies of interest is less than 1×10^{-4} atoms/ion.[29] At the very high-power end, erosion rates of carbon or molybdenum targets located about 25 m from a 1-MW argon ion thruster would be as high as 0.3–2 μm/h. Carbon-lined surfaces at about 25 m would lose about 100 kg during the course of a 1000-h test of a MW-class ion thruster.

In order to provide for cryopumps that have areas of 100–1000 m^2, to accommodate large thrust stands,[30] and provide for testing of thruster clusters,[31] 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.[30] 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.[32]

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.

Description of Large Test Facilities

Selected facilities 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 1.[3,24,33–38] The basic characteristics of other large vacuum test facilities in the U.S. are shown in Table 2.[33]

NASA Lewis Facilities

NASA Lewis Research Center's Electric Propulsion Laboratory (EPL) houses two large space simulation chambers, tanks 5 and 6 (Fig. 1). Both chambers employ 20, 0.8-m-diam oil diffusion pumps, rotary lobe blowers, and a stage of roughing pumps.[3] Both tanks 5 and 6, using 20 diffusion pumps, can provide pumping speeds for nitrogen, argon, and hydrogen of 0.25, 0.6, and 0.2×10^6 l/s, respectively. A facility no-load pressure of about 1×10^{-5} Pa can be obtained in less than 24 h. 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 h, while it takes about 7 h 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 yr. They have been used for the development of electric power and propulsion systems (1–200 kW), and also for the thermal-vacuum testing of spacecraft and spaceflight systems.

EPL's tank 5 has a 4.6-m diam and a length of 19 m. The chamber includes four gate-valved, 1-m-diam test ports. The relatively high pumping speed of tank 5 is augmented by helium cryopanels mounted in the chamber. The cryopumping system consists of ~27 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 10 K or with LHe at 4.6 K. The pumping speeds for xenon and argon are 0.12 and 0.23×10^6 l/s, respectively.

Tank 6 has a 7.6-m diam and a length of 22 m. After a rehabilitation project is completed in 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-diam end-cap will be removable to accommodate test articles as large as 7 m. The facility also has a 3-m-diam, 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-diam oil diffusion pumps.

The EPL facility has three operational electric thruster test stands that can be used in either tank 5 or 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 30 m in diam and 37 m high (Fig. 2). 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

Table 1 Characteristics of large vacuum facilities compatible with high-power electric propulsion testing

	NASA Lewis			LLNL	AEDC	ORNL
	Tank 5	Tank 6	SPF	MFTF	MARK I	LCTF
Chamber size, diameter/length, m	4.6/19	7.6/22	30/37	11/64	13/25	10/9
Existing pumping system	ODP/GHe	ODP	ODP	LHe	ODP/GHe	ODP/TM
Maximum pumping speeds for	(a)	—	—	(b)	—	—
Nitrogen, l/s	2.5×10^5	2.5×10^5	2.5×10^6	3×10^7	1.5×10^7	6×10^4
Hydrogen, l/s	6×10^5	6×10^5	6×10^6	1×10^8	1.5×10^7	7×10^4
Argon, l/s	2×10^5	2×10^5	2×10^6	2.5×10^7	1.2×10^7	6×10^4
No-load pressure, Pa	1×10^{-5}	1×10^{-5}	1×10^{-6}	1×10^{-6}	5×10^{-7}	1×10^{-5}
Helium cryopumping						
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
LHe storage capability, l	1,000	*	*	85,000		19,000
Cryopanel area, m²	41	*	*	~1,000	~1,000	*
GHe storage, standard liters	6×10^5	6×10^5	*	6×10^7	—	1×10^7
Liquid nitrogen						
Liquifaction, kW	*	*	*	500	90	*
LN_2 storage capability, l	2.2×10^6	2.2×10^6	1×10^6	—	1×10^5	1×10^5
Time to attain 10^{-4} Pa, h	~24	~24	~24	36 (0.1 Pa)	7	—
Time to open ports, h	0.5	0.5	—	—	—	—
Time to open chamber, h	7	7	24	—	—	—

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

Table 2 Other government and industry vacuum facilities

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

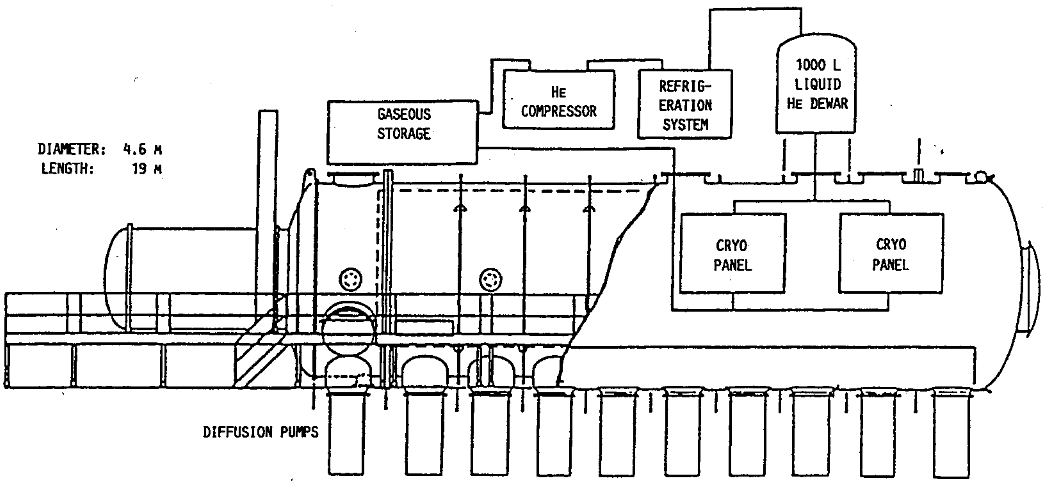

Fig. 1 NASA Lewis Research Center's tank 5.

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. Vacuum chamber access for test article installation or removal is accomplished by two 17- × 17-m electrically operated doors with pneumatic locks and double O-ring seals. There is also a 2.7- × 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 in diam and 33-m high with a mass of 20 metric tons. The vacuum pumping system consists of 32, liquid nitrogen trapped 1.2-m-diam oil diffusion pumps which are backed by two,

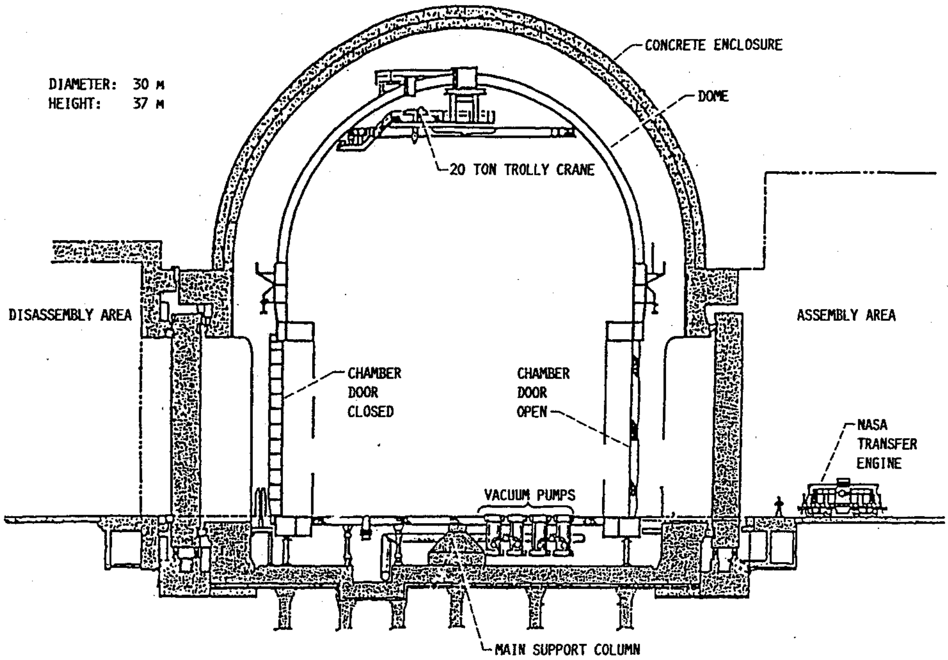

Fig. 2 NASA Lewis Research Center's Space Power Facility.

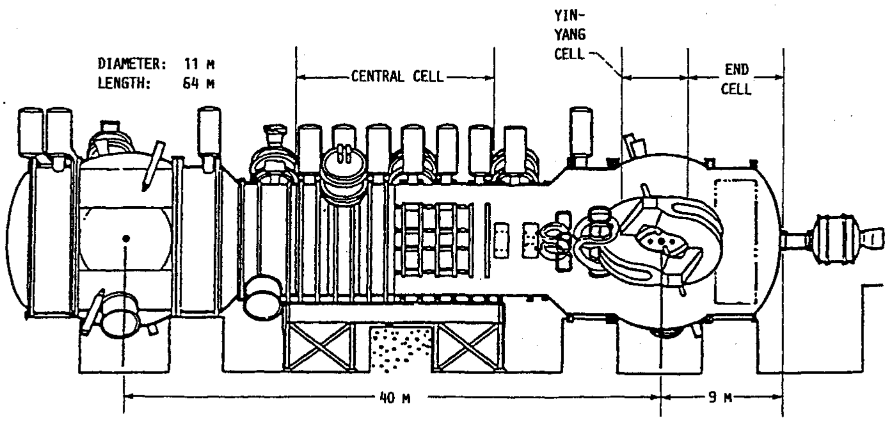

Fig. 3 Lawrence Livermore National Laboratory's Magnetic Fusion Tandem Mirror Test Facility.

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 1×10^{-4} Pa in a 10- to 24-h period. The facility provides nitrogen, argon, and hydrogen pumping speeds of 2.5, 6, and 2×10^6 l/s, respectively. For breaking the vacuum, the chamber can be backfilled with nitrogen or air. Time for bleed-up to atmosphere is about 24 h. The SPF has a 12-m diam by 12-m high removable coldwall which is fed from a 1×10^6 l 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.[9,34–36] The vacuum vessel is fabricated from 304 stainless steel. The cylindrical chamber is oriented horizontally and is comprised of three joined sections (Fig. 3). The two end chambers are 10.6 m in diam and 16 m long. The center section is 8 m in diam 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 diam of 8–10 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 20 small tanks attached to the main chamber. Each of these tanks is 3.1 m in diam 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 U.S. The two helium systems provide 8 and 3 kW of refrigeration cooling, respectively, 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- and 8-kW refrigeration systems have storable capabilities of 25,000 and 60,000 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/h, and the large system has a rate of 1700 l/h. The gas storage capability is 6×10^7 standard liters. The MFTF pumping speed for nitrogen, hydrogen, and argon is estimated to be 30, 100, and 25×10^6 l/s, respectively. The estimates are based on pumping speeds of 10 l/cm^{2}s for hydrogen, 3 l/cm^{2}s for nitrogen, and 2.5 l/cm^{2}s for argon. Estimates are about 25% of ideal pumping speeds. The entire cryosystem, magnets, cryopanels, and 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.[34]

The external pumping system utilized a combination of mechanical, 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 h. 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.

Arnold Engineering Development Center Facility

The Aerospace Environmental Chamber (Mark I) is a large vertical tank, 12.8-m diameter and 25-m high.[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. 4). The building which houses the Mark I chamber has 10 working floors with test article buildup and facility service areas. The Mark I facility has two pumping systems to evacuate the chamber. One system has 19, 0.8-m-diam 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 setup using nitrogen and hydrogen are approximately 0.2 and 0.3 $\times 10^6$ l/s, respectively.[38] The facility also has approximately 1000 m^2 of helium cryopanels which are generally serviced by 2 to 4-kW helium refrigerators operating at about 20 K.[37] A 1-kW helium liquifaction capability is also available. The chamber pumping speed for nitrogen is 15×10^6 l/s. The 1-kW liquifaction system is undersized to provide closed-loop operation for MW-class hydrogen thruster systems, but batch processing with ongoing and subsequent liquifaction could be accomplished with a large GHe storage capability. There is approximately 1×10^5 l of liquid nitrogen storage available at the Mark I site with a 90-kW nitrogen reliquifier. With the cryopanel system operational, base pressures of 5×10^{-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.

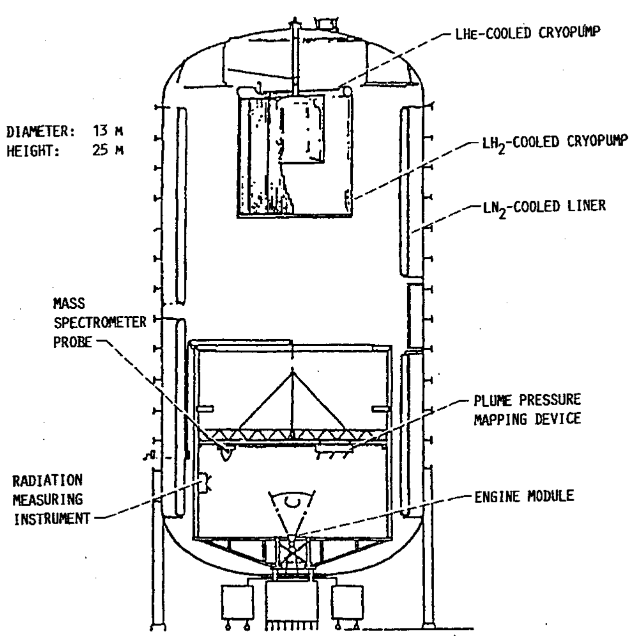

Fig. 4 Arnold Engineering Development Center's Mark I Facility.

Oak Ridge National Laboratory (ORNL) Facility

The ORNL Large Coil Test Facility (LCTF) is a 10.7-m-diam 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 and 9.1 m, respectively.[39] 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 diam oil diffusion pump, two turbomolecular pumps, three rotary lobe blowers, and four mechanical pumps. Nitrogen pumping speed is about 6×10^4 l/s. A no-load pressure of 1×10^{-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/h. The system has a 19,000-l liquid helium storage capability, and the gas management system provides a capacity of about 1×10^7 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. 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 the test hardware, such as the large cryomagnet system.

The LCTF checkout and magnet testing occurred during 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 downtime to the facility.[39]

Other Government and Industry Vacuum Facilities

Table 2 itemizes some other large vacuum facilities located in the U.S. that have a major dimension >7 m.[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 in diam 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.

Vacuum facilities at the Boeing Company (Seattle) and the Jet Propulsion Laboratory (Pasadena), not shown in Table 2, have become operational with helium cryopumping systems. Electric thrusters are being tested in these facilities at xenon pumping speeds in the 50–100-kl/s range.[40,41]

Summary of Facilities Adaptable to High-Power Testing

The broad range of electric propulsion applications involves testing of 5-kW-class xenon ion thrusters in the near-term to testing of MW-class electric thrusters in the far-term. Based on experiences at U.S. laboratories, the preferred pumping concept for inert gases, hydrogen, or deuterium is helium cryopumping. The inert gases can be pumped easily at gaseous helium temperatures of ~10 K, while hydrogen will require panel temperatures of ~5 K. Lithium MPD thruster testing requires minimal pumping since the exhaust can be condensed at room temperature.

With modifications, all six facilities described in Table 1 are capable of performance testing electric thrusters from 5 kW to hundreds of kilowatts. For example, the facilities at NASA LeRC and AEDC now satisfy the requirements for testing the 5-kW-class ion thrusters. Based on the indicated pumping speeds for argon and hydrogen, the NASA LeRC SPF and the AEDC MARK I facility are now capable of short-term testing of 100–200- and 500–600-kW electric thrusters, respectively. The larger chambers, LLNL's MFTF, AEDC's MARK I, and NASA LeRC's SPF are more appropriate for testing electric thrusters at power levels of hundreds of kilowatts since these facilities have large volumes to accommodate helium cryopanels and exhaust power dumps. All three facilities would require modifications or rehabilitation of components to provide cryopumping, conductance limiters, exhaust power dumps, and cryopanel regeneration systems.

Facilities such as NASA LeRCs tanks 5 and 6, AEDCs MARK I, or possibly a "fraction" of the LLNL MFTF capability could be modified for electric thruster testing at power levels from 5 to 100 kW. Such facilities would require 30–150 m^2 of helium cryopanels, conductance limiters to provide differential pumping, appropriate cryopanel regeneration procedures, and 100–1000 W of helium refrigeration capability. If a gaseous helium storage capability of 0.5–2 standard 10^6 l were available, the helium could be liquified after each test segment for subsequent hydrogen testing.

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