**Description of an Innovative
Vacuum Pumping and Energy
Absorption System for a
Multi-Megawatt Electric
Propulsion Test Facility**

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ABSORPTION SYSTEM FOR A MULTI-MEGAWATT ELECTRIC
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ABSTRACT

The development of high power magnetoplasmadynamic (MPD) thrusters is rapidly approaching an impasse to further development: the lack of a facility with adequate vacuum pumping and energy removal capacity to support the resolution of key MPD life and performance issues by FY-93. Several studies have been performed that identify vacuum systems or facility concepts that would alleviate this problem. Although feasible, the proposed vacuum systems require significant research and development; and the proposed facility concepts all require the added development of a gas dynamic diffuser.

To date, the workhorse for the vacuum processing industry for evacuating systems with high gas loads in the 10^{-4} to 10^{-5} Torr range is the circular cross-sectioned oil diffusion pump. Diffusion pumps can and have been operated with either low vapor pressure oils or suitable liquid metals. An innovative variation of the time-proven and reliable diffusion pump (known as the "strip" pump), coupled with current liquid metal technology, and a thorough understanding of the sputtering phenomenon, provides a viable vacuum pumping and energy absorption system concept. The major advantages of the strip pump are that its rectilinear geometry utilizes the inlet port area and floor space more efficiently than the conventional cylindrical diffusion pump and that pumping capacity scale-up is obtained by adding replicate sections of pumps. Practical speeds for these pumps in the molecular flow range are estimated to be 1×10^5 l/s/m². The proposed MPD thruster test facility would require approximately 285 m² of pump throat area. If all the strip pumps were placed on the bottom of the test chamber, a vessel 21 m/dia would be required.

The development of an experimental electric propulsion test facility based on this innovative vacuum pumping system would provide the facility resource needed by developers of large-scale MPD thrusters. This facility would also be valuable to those developing lower power thrusters that would function together as a cluster since these engine clusters could be tested in the facility to evaluate multi-engine interactions and operations.

EXECUTIVE SUMMARY

The future deployment of SDI systems and the success of advanced NASA missions are all dependent on the development of advanced high-efficiency propulsion systems. Cost-effective systems must be developed that will provide the capability to move satellites, delivered to low earth orbit (LEO) by the shuttle or the planned advanced launch system (ALS), outward to their operational orbits, which could be as far as geosynchronous orbit for SDI missions and well beyond this to Lunar and even Mars orbits for advanced NASA missions. The prime candidate for these advanced highly efficient propulsion systems is electric propulsion because its high specific impulse (Isp) offers the greatest fuel efficiency, and higher thrust electric engines are being developed. However, the development of high-power, high-thrust electric propulsion systems is currently test-facilities-limited. Existing facilities have very limited capability to support the testing of high-power electric propulsion systems, both because of limited vacuum pumping capacity and commitments to support other space system test needs. To alleviate this problem, a high-capacity, high-vacuum test facility is needed that would be dedicated to the support of electric thruster testing and that would be available for use by the National Aeronautics and Space Administration (NASA), the U.S. Department of Defense (DOD), university, and private industry researchers involved in advanced high-power electric propulsion development.

NASA, in Project Pathfinder, and SDI, through the Office of Innovative Science and Technology (IST), has identified the need to perform long-term testing on the high-power, high-thrust engines associated with these systems to address key lifetime and materials issues. NASA identified the development of a high-capacity vacuum capability and associated facility as the critical issue that must be resolved so the needed testing can be accomplished. The availability of these advanced electric propulsion systems to support SDI and NASA missions in the 1990's and post-2000 time frame is paced by test facilities capability.

The development of an electric propulsion test complex would allow the continued development of the advanced high-power electric propulsion systems

and would be a national asset. A three-phased test facilities development program has been proposed that would provide the testing support required by near-term systems being considered as well as advanced systems for post-2000 mission needs. In this phased development approach a low-power test facility would be developed as a pilot-scale facility that could support continuous testing of electric thrusters of 500 kwe input or more. This pilot-scale facility would initially serve as a test bed to verify the vacuum pumping scheme, to integrate the vacuum and thermal management system, and to quantify data on the high-power thruster exhaust plume. This information is needed to optimize the design of a full-scale megawatt level test facility. The first and second phase activities would make use of existing equipment and facilities to the maximum extent possible. At the completion of these two phases, the pilot-scale facility would be available to electric propulsion researchers and would allow testing of thrusters with three to five times the power of the current systems being tested anywhere in the world. This facility could be available within 4 years of the program start at a cost of less than \$20M.

Based on the information obtained in the first and second phase, a full-scale facility would be designed and built in the third phase. This facility would support continuous testing of electric thrusters up to the 4 Mwe level. This effort would involve the design and construction of an integrated vacuum test facility specifically dedicated to megawatt class electric thruster testing. The tests run in this facility will range from a few hours to as much as a year in duration. At full power the full-scale facility will require 10 to 15 megawatts of electrical power. The availability of low-cost surplus power makes the northwest a prime location for this facility. The third phase of this activity would take 4 years to complete at a cost on the order of \$200M. When completed, this facility would be the world's largest electric propulsion test facility and could attract foreign researchers, thus stimulating international joint programs in electric propulsion development.

The development of this high-power, high-capacity vacuum facility is the critical path for high-power electric propulsion systems. NASA has set as a goal the resolution of all critical technology and lifetime issues in the 1992-93 time frame. The actual propulsion systems will be needed by advanced

NASA missions now being planned for the late 1990's and beyond and by DOD in the post 2000 time frame, should the decision be made to go forward with deployment of SDI systems. In this document the preliminary designs for the development of this facility are presented, and this could serve as initial step toward the development of a national asset that would provide long-term support for the development of high-power electric propulsion systems.

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DESCRIPTION OF AN INNOVATIVE VACUUM PUMPING AND ENERGY ABSORPTION SYSTEM FOR A MULTI-MEGAWATT ELECTRIC PROPULSION TEST FACILITY

INTRODUCTION

The development of high-power magneto-plasma dynamic (MPD) thrusters has been identified in Project Pathfinder as an enabling technology for the Lunar/Mars cargo transfer vehicle. Using this electric propulsion system, a high-performance Mars cargo vehicle would have a reduced propellant need, over that of a chemical-based vehicle, of 1 million pounds in orbit. This equates to eliminating five heavy lift vehicle (HLV) launches with a corresponding savings of approximately \$750 M. However, this promising technology is rapidly approaching an impasse to further development: the lack of a facility with adequate vacuum pumping and energy removal capacity to support the resolution of key MPD life and performance issues by FY-93.

Studies (Brackman and Jahn 1974, Reed et al. 1985, Guss et al. 1987) have been performed to identify systems or concepts that would alleviate this problem. Although feasible, these system concepts require a significant research and development effort and still may not meet the need without the added development of a gas dynamic diffuser, which is a major research and development program in and of itself. There are also many concerns over the impact on thruster test data of actually using a gas dynamic diffuser that yet to be addressed for high power thruster testing. The only approach with a chance of providing the facilities needed, at a reasonable cost and in time to support continued MPD development, is to develop a system based on a modest extrapolation of the state of the art in vacuum pumping technology. An innovative variation of the time-proven and reliable diffusion pump (known as the "strip" pump), coupled with current liquid metal technology, and a thorough understanding of the sputtering phenomenon, provides a viable vacuum pumping and energy absorption system concept without the need for pressure amplification that may be possible with the yet to be demonstrated gas dynamic diffuser.

The development of this system will be implemented through three readily defined phases:

- Phase I - a laboratory-scale proof of principle
- Phase II - an integrated pilot-scale demonstration
- Phase III - the full-scale system development.

Execution of this program would produce a ground-based high-capacity testing capability that will support the high-power MPD thruster development need for long duration life-time testing.

Developers of the MPD thruster have only two requirements of a test facility; it must be cost effective and it must meet their testing needs. This provides several real challenges for the test facility developer. A very high capacity and reliable pumping system must be provided at reasonable development, capital, and operating costs. The structural materials and processes must be carefully selected to ensure compatibility with the MPD ionized plasma exhaust plume that could be produced from the variety of propellants of interest to the engine developer. Also, a method must be developed to manage the energy deposition from the thruster exhaust to preclude damage to the facility over continuous long-term operation that will be needed during lifetime testing of the MPD thruster.

MPD THRUSTER TEST CONDITIONS AND ASSUMPTIONS

The successful resolution of the key technology issues associated with the MPD thruster depends on the development of a ground-based vacuum facility that can provide the environmental conditions necessary for MPD thruster testing and operation. For lifetime testing, facilities development must focus on providing the required vacuum while accommodating the large volumetric flow of high-velocity, high-temperature exhaust gases generated by the MPD thruster.

A review of current literature shows that a significant effort has been committed to the study of electric thruster exhaust plumes and, although much has been learned, many of the phenomena occurring within the plume are not clearly understood (Brackman and Jahn 1974). A better understanding of these phenomena and a more precise characterization of the exhaust plume is required. It is assumed that this information can be obtained by close interaction with the engine developers during the integrated pilot-scale demonstration in Phase II, and this knowledge will be incorporated in Phase III of the program. Both the pilot-scale system and the multi-megawatt facility should be designed to accommodate plume diagnostic studies, thus allowing verification of data from previous work as well as generation of additional information regarding exhaust velocity, temperature, ion density, plume geometry, and many other diagnostic evaluations necessary for the development and optimization of long-life megawatt-class MPD thrusters.

The velocity of ions in the exhaust plume of an MPD engine has been measured up to 1.7×10^4 m/s (Brackman and Jahn 1974). Exhaust temperatures are assumed to be several thousand degrees Kelvin; however, thermal source characterization parameters for a steady-state exhaust plume are not known. It is assumed that these parameters will be obtained in the integrated pilot scale demonstration in Phase II and used to design an optimized energy management system for the full-scale facility.

Steady-state ground testing of multi-megawatt (up to 2 MW exhaust energy) MPD thrusters requires a chamber and pumping system capable of handling a high mass flow while maintaining a low base pressure. The gas flow rate of interest is 6 g/s (2.55×10^7 l/s) at a base pressure of 1×10^{-4} Torr. The

primary propellant is expected to be argon; however, carbon dioxide, ammonia, or hydrogen may be used. Materials of construction and safety requirements for handling these propellants will be considered in the design of the test chamber and vacuum pumping system.

Mitigation of sputtering effects will be a significant challenge, since the ionized exhaust plume will erode all materials on which it impinges. It will be necessary to develop a method to protect materials and components from these effects to make possible long-term testing. A regenerative energy absorption system will be demonstrated in Phase I and the system optimized and tested in Phase II prior to implementation in the full-scale facility.

The plume geometry varies with the vacuum pressure of the environment and the propellant being used. At space-like pressures using the proposed propellants, the exhaust plume may diverge from free expansion by as much as 130° from the central axis of the thruster (NACA 1953). Other factors specifically related to the MPD thruster may further increase this angle of divergence to as much as 180° .

To conduct thruster lifetime studies, the vacuum pumping system and test chamber heat rejection system should be designed to operate continuously in excess of 1 year (10,000 h). The fluids involved with vacuum pumping and heat rejection will require processing to remove contamination to maintain a high integrity environment within the test chamber during these extended test periods.

VACUUM PUMP SYSTEM DESCRIPTION

The workhorse for the vacuum processing industry for evacuating systems with high gas loads in the 10^{-4} to 10^{-5} pressure range is the circular cross-sectioned oil diffusion pump. Diffusion pumps can and have been operated with either low vapor pressure oils or suitable liquid metals.

A thruster test facility capable of pumping 6 g of argon per second at 10^{-4} Torr would require a very large number of conventional diffusion pumps, making them unsuitable for the application because of excessively large space requirements and complexity of support systems. As an example, the largest commercially available diffusion pumps are 48 in. in diameter with an advertised pumping speed of 100,000 liters/sec. Roughly 260 untrapped 48-in.-dia pumps installed on the chamber floor would be required to handle a throughput of 2.6×10^3 Torr l/s, demonstrating the practical difficulty with using the conventional diffusion pump with its poor packing density and correspondingly large footprint. Since the pump must function in the molecular flow regime, it must be installed as close and direct to the vessel being pumped as possible to utilize its rated pumping speed. To have sufficient area to mount the required number of pumps on the bottom of the chamber, an excessively large diameter chamber must be built. Another alternative would be to mount the pumps on the outside walls of the chamber. However, if this were done, the number of pumps required would necessarily be doubled because of conductance restrictions caused by connecting piping.

A modified diffusion pump called a "strip pump" is proposed for achieving the necessary vacuum during MPD thruster testing (Figure 1). During operation, the major advantages of the strip pump are that its rectilinear geometry utilizes the inlet port area and floor space more efficiently than the conventional cylindrical diffusion pump, and that pumping capacity scale-up is obtained by adding replicate sections of pumps. Strip pumps were first reported in U.S. Patent 3,101,169 in 1963 by H. R. Smith. These pumps were developed for use in the pressure range of interest for increasing the melting rates in

FIGURE 1. Strip Pump Cross Section

the electron beam melting of metals and also for more efficient pumping of large accelerators. Two pumps were built at Stauffer Chemical Company and one at the University of California at Berkeley.

The rectangular cross section of the first pumps was approximately 0.3 m wide by 0.9 m long. The pump throat width was composed of 80% of the distance between the peripheral walls. Practical speeds for these pumps in the molecular flow range are estimated to be approximately 1×10^5 l/s/m². The proposed MPD thruster test facility would require approximately 285 m² of pump throat area. If all the strip pumps were placed at the bottom of the test chamber, a vessel 21 m in diameter would be required. A variation of the strip pump concept

could be produced that would allow a portion of the pumps to be side mounted. This configuration would permit a fraction of the pumps to be directly mounted on the walls of the vessel while maintaining full-rated pumping capacity, thereby potentially decreasing the required vessel diameter. Such a configuration was also patented by H. R. Smith, but was never tested. This concept will be investigated in Phase I of the development program. However, the facility concept that is described later in this paper includes only the bottom-mount strip pump.

A three-stage strip pump is proposed (Figure 1). During operation, the pumping fluid is vaporized in the boiler at the bottom of the pump, and the vapor is driven by expansion up through the internal pump channels and exits the nozzles which are located at the top of each stage. The high-velocity pumping vapor, upon exiting the three stages of nozzles, imparts momentum to the gas molecules in the region and drives them down into the higher pressure region of the pump. Gases being pumped are swept into fore-line ports installed in the side walls of the strip pumps in the high pressure region and are then drawn out into the roughing system and exhausted. The peripheral walls of the strip pump are cooled to remove heat from the pumping vapor, causing the vapor to condense, cool, and run by gravity back to the pump boiler, thus completing the loop.

Pressure at the boiler is approximately 0.1 to 0.3 Torr, while pressure at the top of the pump is 10^{-5} to 10^{-6} Torr. The temperature in the boiler and at the nozzles (the hot leg temperature) is consistent with the boiling point of the pumping fluid at the boiler operating pressure (0.1 - 0.3 Torr). The lowest temperature (the cold leg temperature) is obtained by cooling and condensing the vapor and is engineered to produce an insignificantly low-vapor pressure in the pumping fluid as it re-enters the boiler. This minimizes back streaming of pumping fluid vapors that would decrease net pumping efficiency and inhibit migration of pumping fluid vapor into the fore lines. Initial phases of development will optimize the boiler pressure for the selected pumping fluid.

The temperatures of operation of the pump depends on the selection of pumping fluid. Diffusion pumps are usually driven with specialty pumping

oils costing several hundred dollars per liter and are composed of perfluorinated polyethers or polyphenyl ethers. These fluids have very high molecular weights, on the order of 400 to 2900, and have a very high thermal stability. They operate at temperatures of 30 to 260°C for the cold leg and hot leg, respectively. These oils will be used for initial development and are very likely usable for short-duration MPD thruster tests. However, as ion fluence increases, exposure to the ion plume will cause sufficient degradation of the oil molecules, and backstreaming of low molecular weight fractions will seriously reduce pumping efficiency. When this condition is reached, pumping oils will no longer be of use, and an alternate pumping fluid must be identified.

Liquid metals are the best choice for a pumping fluid in prolonged exposure to the ionized exhaust plume, since no degradation of elemental molecules is caused from interaction with the ion plume. Mercury has been successfully used in diffusion pumps; however, further research is necessary prior to consideration of mercury as a prime candidate pumping fluid for this application. If nitrogen-bearing propellants such as ammonia are anticipated, mercury azide could be formed as a by-product of ammonia and mercury that is violently explosive. Further, the potential personnel hazard involving mercury vapors would require special provisions in facility design and operation to achieve a high level of safety.

Bismuth is another metal that has been used successfully in experimental diffusion pumps. It is compatible with most propellants and is readily obtainable in the required quantities. The required operating temperatures are relatively high to produce the necessary vapor pressures; 475°C for the cold leg and 800°C for the hot leg (assuming a 0.1 Torr boiler pressure). Though bismuth is the present choice for the vacuum pumping fluid, additional trade-off studies regarding alternative pumping fluids are necessary prior to reaching a final selection.

MITIGATION OF SPUTTERING EFFECTS

Sputtering is defined as the removal of material from a surface when that surface is bombarded by energetic ions or atoms. The removal of the material from the surface is caused by momentum transfer of this energy to dislodge the surface atoms and eject them into the gas phase. Approximately 95% of the bombarding particle energy is dissipated as heat with only 5% causing the removal of the atoms. The basic phenomena of physical sputtering has been reviewed in detail (Wehner and Anderson 1970) and actual sputtering rates are well documented (Wehner and Anderson 1970, Laegreid and Wehner 1961, Weston 1968, Guss et al. 1987).

Because of the high energies associated with the exhaust ions from an MPD thruster, materials placed in the path of the plume will be sputtered. Assuming that the average energy of the argon ions in the plume is 100 eV and the current density at the surface of an energy absorbing copper shield placed in the plume is 100 ma/cm², then the removal rate of the copper due to sputtering would be approximately 0.13 cm/h (0.005 in./h) or about 0.3 cm/day (1/8 in./day) of continuous operation. A comparison of other materials sputtering rates is presented in Table 1. From this comparison, it can be seen that no metal is practical for use in a long-duration test (10,000 h or more), but many could be used in short-term tests (several minutes or hours). These calculations were made assuming normal incident ions striking the surface with no compensation for redeposition due to sputtering in a dense plasma as reported by W. C. Guss, et al. (1987). Additional characterization of energy deposition patterns will be necessary before sputtering rates caused by MPD thrusters can be precisely quantified.

Another important consideration is the angle of incidence of the ions. In general, the sputtering yield increases with more oblique incidence of the ions, because less directional change of the momentum is required for ejecting atoms in the forward direction. One may be able to take advantage of this phenomenon to keep all of the material, argon ions, and sputtering metal going in the same general direction to reduce upstream movement of material, even though the sputtering rate will be higher.

TABLE 1. Comparison of Sputtering Effects for Different Materials In Argon at 100 eV and 100 ma/cm²

Material	Yield(1) Ar-100eV at/ion	Yield Ar-100eV g/amp-h	Removal Rate μ m/h	Removal Rate mils/h	Removed in 10,000 h Test (in.)	Atomic Weight	Density
Copper	0.480	1.14	127.9	5.03	50.3	63.5	8.94
Nickel	0.280	0.62	69.3	2.73	27.3	58.7	8.9
304 ss	0.200	0.41	52.9	2.08	20.8	55	7.8
Molybdenum	0.130	0.47	45.9	1.81	18.1	96	10.2
Tantalum	0.100	0.68	40.9	1.61	16.1	180.9	16.6
Niobium	0.068	0.24	27.7	1.09	10.9	92.9	8.55
Tungsten	0.068	0.47	24.3	0.96	9.6	183.9	19.3
Carbon	0.005	0.00	1.2	0.05	0.5	12	1.88

(1) Yield data taken from "Sputtering Yield Data in the 100-600 eV Energy Range", General Mills Report 2309, July 15, 1962.

Even though the sputtering effect would be significant, early short-duration thruster tests could be accomplished using sacrificial energy absorbing shields. During these tests, the sputtering effects in the plume would be determined and appropriate energy absorbing shields designed and tested for the longer-term tests lasting up to 10,000 h.

To permit long-term testing, a regenerative energy absorber is needed that could be applied to all surfaces exposed to the ionized exhaust plume. This includes the vertical walls of the vessel and the exposed surfaces of the strip pumps. The regenerative energy absorber would have the outer surface constantly replaced during operation. The approach would be to continuously replenish the absorber surface with a low-vapor-pressure liquid metal such as tin. For the regenerative energy absorber to be effective, a continuous liquid metal film must be present on all absorber surfaces. This will be accomplished by providing a porous metal frit over the surfaces to be protected through which the low-vapor-pressure liquid metal will be forced (Figure 2). Surface tension of the liquid metal will create a continuous film on the surface that will protect the surfaces from sputtering damage. The porosity of the sintered metal can be adjusted to produce the desired pressure drop and flow rate combination.

FIGURE 2. Sintered Metal Frit

After the liquid tin has been forced through the sintered metal, it will flow downward by gravity, where a fraction will enter the pump cavities and combine with the pumping fluid and the remainder will be separately collected, cooled, and recycled.

LIQUID METAL HANDLING SYSTEM

Two metal species must be accommodated that are mixed as they leave the vacuum chamber and enter the liquid metal handling system where they are separated, purified, and returned for reuse. While the choice of metals has not been finalized, the initial candidates are bismuth for the pumping fluid and tin for the regenerative energy absorber.

The process flow is depicted in Figure 3. Liquid tin cascades from the regenerative energy absorber, and a portion is ultimately mixed with the molten bismuth in the reservoirs at the bottoms of the strip pumps. The tin/bismuth mixture will be continually removed from the strip pump reservoirs and admitted into the liquid metal handling system. Separation of tin from bismuth will be necessary to maintain extended continuous operation.

The tin/bismuth eutectic alloy that is formed limits the possible separation methods. The most attractive approach for separating the metals is vacuum distillation of the alloy, driving off the bismuth vapor and recondensing it.

A metal separation module in the liquid metal handling system will employ vacuum distillation to separate the two species, and electro-magnetic pumps will control the flow of liquid metal back to the vacuum chamber at specified flow rates. Vacuum distillation will purify the bismuth as it is boiled off; however, impurities, such as oxides and intermetallics left in the tin, will tend to build up and filtering will be required to control them.

Rather than separating the two liquid metals in a dedicated module, it may be possible to integrate the vacuum distillation function as an intrinsic part of the strip pump design. Vacuum distillation could be accommodated with innovative fixturing in the strip pump fore lines. Still another approach would be to perform vacuum distillation inside the strip pump boilers. A tin-rich alloy of the two metals could be preferentially captured and routed to a secondary boiler in the strip pump. Temperature would be controlled in this boiler independently to evaporate the bismuth and force the vapors into the strip pump. The remaining tin would be drained off and recombined with

FIGURE 3. Process Flow Diagram

the liquid tin recirculation system. Complete reseparation of the tin from the bismuth would likely not be necessary. Alternative approaches will be further addressed as part of the initial development phase.

If pressure system components are constructed of iron-bearing alloys, tin-iron intermetallics will likely be formed that would cause a corrosion problem. Additions of minute quantities of zirconium or magnesium have been found to be effective in buffering this condition (Mitchell 1949).

The entire liquid metal handling system will be trace heated for preheating prior to filling with molten metal. A dump tank (Figure 3) is provided for each metal species that will store the entire metal inventory, including the metal from the pump boilers, during shutdown conditions.

With bismuth and tin as the chosen metals, the design temperature for the hot legs of the strip pumps and liquid metal handling system will be approximately 900°C. This temperature is generally incompatible with commonly available pressure system materials. The high temperature portions of the strip pumps and liquid metal handling system will require special materials of construction, such as niobium or niobium/zirconium alloy. Availability of necessary shapes and quantities of these materials may be an issue. Lower temperature portions of the system will be constructed of commonly used stainless steel alloys.

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HEAT REJECTION SYSTEM

During steady-state operation, the design-basis four megawatt thruster will produce 2 MW in the exhaust plume. The same thruster could produce a flow as high as 6 g/s of ionized argon or other high energy plasma. The power requirement for the vacuum pumping system with a throughput of 6 g/s at the desired operating vacuum is approximately 6 MW. Efforts will be made to recover significant portions of this energy by incorporating regeneration to the maximum possible extent in the full-scale system.

Energy from the engine will be transferred by two mechanisms. The sensible temperature of the engine exhaust might be expected to be on the order of several thousand degrees Kelvin, creating a radiant heat load on the walls of the vessel and on the surfaces of the pump components. The energy transferred during deceleration of the ions will produce most of the heat load on the portion of the vessel walls where the exhaust plume impinges and on the pump component surfaces. The energy distribution can be assumed as 25% taken up in anode/cathode heating (with only a small fraction of this radiated to the test chamber), 50% to the exhaust plume as kinetic energy and 25% as radiant energy in the exhaust plume (Brackman and Jahn 1974). Experiments performed at Arnold Engineering Development Center indicate that, depending on the propellant used, the exhaust plume divergence may range from 90° to 180° from the centerline, thus causing significant plume impingement and energy transfer to the vessel walls. Since the pump surfaces will be operating at temperatures as high as 800°C., there will be significant radiant transfer from the pump surfaces to the walls of the vessel.

The regenerative energy absorber, intended to protect the inner surfaces of the test chamber and the pumps, has extensive heat removal capability. It is desirable to match the bismuth cold leg temperature of 475°C with the tin hot leg temperature. Since tin freezes at 232°C, a 200°C temperature rise is conservative. Assuming a right circular cylindrical vessel 21 m/dia and 9.1 m high (Figure 4) and assuming simplistically that the both the radiant and kinetic energy is deposited evenly on the vessel surfaces (the actual distribution is yet to be determined and would be part of the data obtained in the

FIGURE 4. Multi-Megawatt Test Chamber

pilot-scale facility), approximately 1.2 MW would be transmitted to the vertical surfaces. Then a regenerative liquid tin surface produced on the walls of the vessel would require a replenishment rate of approximately $5 \text{ cm}^3/\text{s}/\text{m}^2$ of surface area to produce the desired heat removal capability and maintain temperatures within the defined limits.

Again, based on the simplistic assumption that energy is evenly distributed on the surfaces that intercept it, approximately 0.8 MW would be deposited on the strip pump surfaces located in the bottom of the vessel. Exposed surfaces of the pumps will be protected with the same regenerative liquid tin surface

that was described to protect the vertical walls of the vessel. While the exposed surface areas of the pumps have not been calculated, the required tin flow rate can be developed using the sintered metal frits. The liquid tin that is discharged from the regenerative surfaces that protect the pumps will very likely drain into the pumps and mix with the bismuth pumping fluid. Maintaining the maximum tin temperature at the bismuth cold leg temperature will minimize thermal shock to structural components and will minimize heating/cooling requirements.

The strip pumps operating with a bismuth pumping fluid will function on a temperature cycle of approximately 800°C boiler/vapor temperature and a 475°C cold leg temperature. Since liquid tin is already available in the system, it would be a reasonable coolant fluid for the cold leg. The cold leg temperature is compatible with the maximum temperature for the regenerative liquid metal surface. Tin at approximately 275°C would be inlet to the cold walls, and a heat rise of 150°C could be produced by adjustment of the flow rate. The tin will be pumped through a liquid metal-to-air dump heat exchanger to reduce the temperature to 275°C.

Assuming a 0.1 Torr boiler pressure, the flow rate of bismuth per meter of strip pump would be 19.6 g/s. Assuming 212 lineal meters of pumps, the total bismuth flow would be 4.2 kg/s. Maintaining the tin coolant for the pump cold legs within the above defined temperature limits would necessitate a tin flow rate of approximately 16 kg/s.

PRESSURE AMPLIFICATION

The strip pump system as described herein will produce the desired pumping capacity. However, savings in energy or an increased pumping capacity could be realized if pressure amplification were employed. Gas dynamic diffusers have been described by others (Mitchell 1949) that are capable of pressure recovery in hypersonic flows. While the proposed system will meet all of the operating requirements without a diffuser, the development of such a device by others would be a worthwhile addition to the strip pump-based electric thruster test facility to optionally increase pumping capacity or to reduce pumping energy requirements. Sufficient space would be available between the thruster exhaust and the strip pumps at the bottom of the vacuum vessel to accommodate a variety of diffuser configurations to be incorporated at a later time.

Since the diffuser would likely reside directly in the exhaust plume, protection from sputtering effects would be required. The regenerative liquid metal surface could be applied to exposed surfaces of the diffuser with positive benefit.

SYSTEM DEVELOPMENT

A three-phase development program has been defined to bring the technologies previously described to function as an operational multi-megawatt MPD thruster test facility.

PHASE I

Phase I will establish proof of principle through completion of laboratory-scale tests on the strip pump, first using vacuum oil for initial characterization and optimization and then selecting and testing with an appropriate liquid metal as the pumping fluid. Using bench-scale hardware, the liquid metal regenerative energy absorber will be demonstrated relative to hydraulic characteristics of reliably producing the free surface. Issues relating to mixing and separation of two liquid metal species will be addressed and bench-scale tests will demonstrate feasibility of processes. A conceptual design of a pilot-scale pumping facility will provide basis for preparation of a reliable estimate for cost and schedule of the Phase II activity.

PHASE II

Phase II will provide the design, manufacture, and test operation of an integrated "Pilot-Scale Facility" (PSF) of approximately 1/10 the pumping and heat rejection capacity of the full scale Multi-megawatt Test Facility. The PSF will include all systems required for the Multi-megawatt Test Facility so that actual operating data on the integrated system can be obtained as basis for design of the larger facility. A final cost and schedule estimate for provision of the Multi-megawatt Test Facility will be produced at completion of this phase. It is expected that the PSF will continue operation as a test bed for intermediate-sized thrusters after pumping system development testing is complete. The PSF would also be useful for evaluation of advanced pumping system components developed by others, such as gas dynamic diffusers.

PHASE III

Phase III will involve final design, construction, and acceptance testing of the Multi-megawatt Test Facility. Full-sized systems will be designed for the Multi-megawatt Test Facility based on data obtained from actual operation of the PSF. There should be no development required at this point to support the Multi-megawatt Test Facility design.

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