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GROUND-BASED TESTING OF SPACE NUCLEAR POWER PLANTS

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ABSTRACT

Small nuclear power plants for space applications are evaluated according to their testability in this two part report. The first part introduces the issues involved in testing these power plants. Some of the concerns include the oxygen embrittlement of critical components, the test environment, the effects of a vacuum environment on materials, the practicality of reusing an activated test chamber, and possible testing alternatives. The second part of the report describes the conceptual design of a disposable vacuum system which would be used to test a specific power plant, the SEHPTR, being developed at the Idaho National Engineering Laboratory.

GROUND-BASED TESTING OF SPACE NUCLEAR POWER PLANTS

PART I: TESTABILITY ISSUES

Introduction

A small nuclear power plant can deliver more power to a spacecraft during a long duration mission than a solar panel or an RTG (radioisotope thermoelectric generator) can provide. Heat produced by a small nuclear reactor is converted into electricity by means of power converters. The power plants examined in this report use either thermionic or thermoelectric power converters having typical power conversion efficiencies of 13 percent and 4 percent, respectively [1]. A power plant capable of generating 40 kW of electrical power, for example, would require approximately 300 kW of thermal power if thermionic converters were used. The heat from the reactor is transferred to the power converters by direct conduction through the reactor core or by circulating a liquid metal coolant between the reactor core and the converters. The excess heat must be dissipated to space by heat pipe radiators which use liquid metals as their working fluid.

Testing the operation and performance of these space-based nuclear power plants on earth presents certain problems not usually encountered in ground-based nuclear plants. Simulating a space environment on earth requires that all power tests be conducted in a large vacuum chamber. The test chamber must provide a heat sink (at or below 300 K) for removing the excess heat radiating from the power plant.

Heat pipe radiators operate at high temperatures (800–1000 K) and are constructed of refractory metals to contain the high-temperature liquid metal used as the working fluid. Some power plants transfer heat from the reactor core to the power converters via high-temperature (1375 K) liquid metals in refractory metal pipes. Refractory metals suffer from embrittlement due to reactions with oxygen or other impurities at high temperatures. Embrittlement of the refractory metal components could promote coolant leaks which would cause the power plant to fail. A vacuum environment minimizes such embrittlement by reducing the partial pressures of these impurities near the power plant. However, the partial pressures of these impurities that cause incipient damage to the refractory metal components during power tests are not yet well defined.

An examination of some of the candidate power plant designs (up to 100 kW electric) reveals certain features which make ground-based testing difficult and expensive. Such features include the intensity of neutron flux and gamma radiation, the method of waste heat rejection, the power plant's configuration and its materials' characteristics in a high-vacuum environment, the embrittlement of refractory metal parts at high-temperatures, and the use of liquid metal as coolants in the power plant. Some of the features which make ground testing difficult may also

influence a power plant's performance and longevity while operating in space. Other testing problems include the design of the nuclear radiation shielding and the design of the vacuum test chamber and its associated pumps, hardware, instrumentation, seals, and waste heat removal system in the presence of a radiation environment.

This report investigates the designs and materials used in proposed space nuclear power plants to assess their testability on earth. It also examines the problems associated with performing the power tests (nuclear and non-nuclear) within a vacuum chamber and the problems associated with designing such a chamber. A conceptual design is included of a vacuum chamber for testing the SEHPTR (Small Ex-core Heat Pipe Thermionic Reactor, Figure 1), a space nuclear power plant which is being developed at the INEL (Idaho National Engineering Laboratory).

Ground-Based Power Tests

A variety of tests must be performed on the power plant as a whole and on each component separately before the power plant can qualify for a space mission. A few of the non-power tests include shock, acoustic, and vibration testing of the assembly. Power tests of the assembly are performed to test the reactor and its controls, the integrated power plant and its materials, and the power converters.

Both non-nuclear and nuclear power tests must be performed on each power plant assembly to evaluate its performance during several months of power cycling tests. During these tests the power plant is operated throughout its entire power range while several critical parameters like component temperatures, power output, and radiation levels are monitored. The non-nuclear power tests use an electrically heated core simulator instead of the nuclear reactor core to generate heat for the power plant. The simulator performs all of the functions of the reactor core during the non-nuclear power tests without generating nuclear radiation. After the non-nuclear power tests are successfully completed, a full nuclear power test is performed to test the reactor's power controls and to test the other power plant components in their operating environment.

Power Plant Design Concerns

Reactor-based space power plants share certain design features. They all use small nuclear reactors to supply the heat for conversion to electricity and they employ liquid metal-filled heat pipe radiators to reject waste heat to space. The candidate designs use static conversion devices like thermionic and thermoelectric converters which require no moving parts. Other designs use dynamic energy conversion systems which couple heat engines such as the Rankine, Brayton, and Stirling cycles to turbo-generators to produce electricity. Despite their lower conversion efficiencies, the static converters are currently preferred because of their inherent simplicity and dependability.

Figure 1. The SEHPTR Power Plant

Refractory metals are used for various high-temperature structural components in the different power plant designs. They are used in the heat pipe radiators and for the pipes which circulate the liquid metal coolant between the reactor core and the power converters. When heated above 675K, refractory metals undergo a ductile-to-brittle transition (embrittlement) which causes an increase in strength but a decrease in ductility [2]. Exposure to oxygen, carbon, or nitrogen at operating temperatures can increase embrittlement to the extent of promoting cracks and brittle failure. Such a failure would result in a loss of coolant which could be catastrophic to the power plant.

Some refractory metals are more sensitive than others when exposed to reactive impurities; therefore, the partial pressures of impurities should be minimized during high-temperature power tests. Current opinion dictates that niobium or its alloys, for example, should not be exposed to partial pressures of oxygen above $10\text{E}-8$ Torr for long periods at operating temperatures. This is based on data from creep tests performed in a high-vacuum furnace [2]. High-temperature components using molybdenum or its alloys, however, can tolerate partial pressures of oxygen up to $10\text{E}-6$ Torr [3]. However, the maximum partial pressure of oxygen at which the power tests can be performed without damage to the refractory metal components has not been established for operating conditions.

The manner in which heat is transferred from the reactor core to the power converters varies among the various reactor designs. The SP-100 design illustrated in Figure 2, for example, uses thermoelectric electromagnetic (TEM) pumps to circulate liquid lithium (at a peak temperature of 1375K) through closed-loop piping circuits between the reactor core and the thermoelectric converters. The piping used in these primary heat transport circuits is an alloy of niobium and zirconium which is particularly sensitive to oxygen-embrittlement. If these pipes developed leaks and lost their coolant there would be insufficient cooling to the reactor core and no power output from the converters. The excess heat due to the low converter efficiency is rejected from the converters through multiple heat pipe radiators into space. The SP-100 heat pipe radiators are constructed from a beryllium-titanium alloy and use potassium as the working fluid. The heat rejection temperature is approximately 800K.

The SEHPTR and STAR-C (Figure 3) power plants transfer heat directly from their reactor cores to their thermionic converters across a small gap. The emitter temperature of the thermionic converters is approximately 1850K. Heat is rejected at 1000K to space by multiple heat pipe radiators (seventy for SEHPTR) using sodium (SEHPTR) or potassium (STAR-C) as the working fluid. The SEHPTR heat pipes are molybdenum; the STAR-C heat pipes are a niobium-zirconium alloy. Both heat pipe materials are sensitive to high-temperature embrittlement in the presence of impurities like oxygen, carbon, and nitrogen.

Figure 2.. The SP-100 Power Plant

Figure 3. The STAR-C Power Plant

Because the SP-100 circulates a liquid metal in its primary heat transport system, that system requires more components than the STAR-C and SEHPTR designs, resulting in a greater chance of failure. A failure of the TEM pumps or a leak in the primary heat transport system would jeopardize the mission. Using redundant TEM pumps and coolant circuits adds yet more weight and expense to the design. The SP-100, the STAR-C, and the SEHPTR all incorporate liquid metal-filled heat pipes to radiate waste heat to space. The failure of a few of these heat pipes would not result in a mission failure.

Power Test Facilities

Most of the power tests are non-nuclear; an electrically heated core simulator is substituted for the reactor core. The power tests need to be performed in a vacuum environment in order to protect critical high-temperature components (coolant pipes and radiators) from embrittlement. Vacuum testing also allows the radiant transfer of waste heat between the heat pipe radiators and the cold walls of the vacuum chamber; however, the level of vacuum required ($10\text{E}-3$ Torr) for radiant heat transfer is not as critical as that necessary to protect the refractory metal components. Another reason for testing in vacuum is to simulate the space environment in which the power plant will be operating.

The vacuum chamber does not exactly simulate a space environment, however. The region of space between altitudes of 400 to 1000 km consists mainly of atomic nitrogen and atomic oxygen as well as ions of those species at pressures between $10\text{E}-8$ to $10\text{E}-10$ Torr [4]. Similar partial pressures of diatomic nitrogen and oxygen are attainable in the vacuum chamber. Hydrogen atoms and ions, electrons, and helium are the principal constituents beyond 1000 km where the pressure is very low ($10\text{E}-13$ Torr or less) [4]. Particles in space have higher energies than their counterparts inside the vacuum chamber. The effects of these high energy particles on the refractory metal pipes are not known.

There are a few fundamental requirements of the vacuum test chamber. Its vacuum pumps must reduce the partial pressures of oxygen and nitrogen in the chamber to levels which are not detrimental to the refractory metal pipes in the power plant. The vacuum pumps must also be able to accommodate the total outgassing from the chamber and everything inside it, including the power plant and test fixtures. The test chamber must be equipped with a cooling system to remove the heat rejected from the power plant while maintaining the chamber wall temperature at 300K or less. An emergency cooling system is also needed to protect the reactor core from overheating if its primary cooling system or its waste heat radiators should fail. A chamber heating system is required to bake out the vacuum chamber and power plant at temperatures up to 525K to remove as much gas and water vapor as possible before starting the high-temperature power tests.

Conductance

In high-vacuum technology, conductance is a measure of the ease with which molecules pass through a duct. Conductance has units of volume flowrate (liters/sec). Where maximum pumping speed is needed, as in this application, the vacuum system designer should strive for maximum conductance between the oxygen-sensitive components of the power plant and the high-vacuum pumps. The high-vacuum pumps should be mounted as close to the chamber as possible. No materials should be located between the test article and the vacuum pumps which could impede the molecular flow of gas to the pumps. Similarly, there should be as little impedance as possible within the test article's structure to obstruct the path of desorbed gas molecules.

Outgassing of Materials

Outgassing is a measure of the total efflux of gas and vapor from a material and includes surface desorption, bulk diffusion, material evaporation, and the release of trapped gas from small cracks, voids, and other virtual leaks. The standard unit of measure for outgassing is Torr-liters per second. The outgassing rate varies with temperature, material, surface finish, and prior material conditioning. Outgassing from the power plant materials and from the interior surfaces of the vacuum chamber itself represents the largest gas load to the vacuum pumps within a high-vacuum system if that system is assumed to be free from real leaks and permeation.

The largest source of gas which might influence the power plant's performance in space evolves from the outgassing of the power plant's materials. Gas desorbs from the surfaces of the power plant when those surfaces are exposed to the high-vacuum of space. The desorption rate increases sharply as the temperature increases. Increasing the temperature also increases the bulk diffusion rate of gases dissolved in the materials, which contributes to the increase in the outgassing rate at elevated temperatures. Whether the quantities of adsorbed and absorbed gas are sufficient to cause material degradation at high temperatures is not known. If the reactor can bake itself out in space at a temperature below the ductile-to-brittle transition temperature of its refractory metal pipes, much of the adsorbed gas can be released with minimal effects on the pipes.

The effects of outgassing on the power plant in space are somewhat different from the outgassing effects inside a vacuum chamber. Gas molecules released from a test article within a vacuum chamber have a high probability of condensing on the chamber walls and then being re-emitted to the power plant. The interior surfaces of the vacuum chamber also outgas molecules to the test article and to other parts of the chamber, as well as to the vacuum pumps. This cycle of emission, condensation, and re-emission may repeat itself many times before the gas molecules finally reach the vacuum pumps. In space there are no chamber walls to capture and re-emit desorbed gas; therefore, it is unlikely that gas emitted from the power plant could return

and recondense on the power plant. Gas loads which would be intolerable to the finite-capacity pumps in a vacuum chamber are easily accommodated by the infinite vacuum of space.

Although it is not possible to eliminate outgassing completely, there are ways to minimize its effects. The power plant should be designed in such a way to allow all surfaces to outgas freely without hindrance from other parts of the power plant. The design should use large, flat surfaces wherever possible and should provide generous spacing between components so that the desorbed gas can escape to space easily without first condensing on other components. All materials used should be characterized for their reactivity with common gas species, for their outgassing rates at operating temperatures, and for their vapor pressures at operating temperatures. Highly sorbent, porous materials such as the graphite endplates used in the SEHPTR, for example, should be avoided or preconditioned by a long, vacuum bakeout to minimize the initial outgassing rate [5]. The refractory metals pipes can also benefit from a vacuum bakeout by reducing the amount of adsorbed gases on the metals. The metal hydride reflectors and shield should be sealed within stainless steel canisters to contain the outgassing from their materials.

Materials like lead, cadmium, zinc, sulfur, selenium, plastics, and liquids exhibit relatively high vapor pressures at their operating temperatures. These materials should not be used in the power plant or in the vacuum system because they could evaporate and condense on sensitive components and they also represent large loads to the vacuum pumps. Alloys like brass and 303 stainless steel which use high vapor pressure materials should also be avoided inside a high-vacuum system. If a high vapor pressure material must be used, the amount of that material should be limited and it should be shielded to prevent the contamination of other components. Materials having high vapor pressures should not be used in thin-walled, high-temperature components because the long term evaporation of those materials could compromise the structural integrity of those components.

The shape of the power plant and its components can contribute to the amount of outgassing and to the ease with which gas can escape from the plant. Parts with intricate shapes have larger surface areas for outgassing to occur. A virtual leak is the gradual release of gas from a confined volume such as a blind-tapped hole or screw threads. Large amounts of gas can be trapped within such spaces and can be released abruptly and unexpectedly due to the long and tortuous escape paths encountered. Trapped gases may prevent the chamber from achieving its required operating pressure. Close fitting members or foil-wrapped pipes found in the SP-100 design can trap large quantities of gas, resulting in virtual leaks.

Shielding

Appropriate nuclear radiation shields are necessary to protect the test personnel and the containment facilities from harmful doses of neutron and gamma radiation generated by the reactor

during the nuclear power tests. If the shields are placed outside of a stainless steel vacuum chamber, the stainless steel would become activated by the neutron flux and would be difficult to use again. Personnel would not be able to service the chamber if the shields were removed; any maintenance or repairs would have to be performed by remote means.

Placing the neutron shields inside the chamber would increase the outgassing loads to the pumps and would reduce the conductance to the pumps, thereby requiring higher pumping speeds. If the shields were to surround the powerplant inside the chamber there would be no way to measure the actual pressure near the power plant.

The metal hydrides used for the neutron shields tend to have high initial outgassing rates and should be hermetically sealed inside metal skins to contain this source of outgassing. Some neutron shield materials are also sensitive to high temperatures and would require cooling if they were placed near the reactor core.

The neutron shields as well as the gamma shields can be placed outside a chamber made of aluminum, because aluminum is not as susceptible to neutron activation as stainless steel. Although aluminum is not as readily activated by neutrons and is lighter than stainless steel, it does have some disadvantages:

1. Aluminum has a higher outgassing rate than stainless steel.
2. Aluminum can not tolerate high temperatures as well as stainless steel can.
3. Hermetic welds are more difficult to achieve with aluminum.
4. Aluminum is difficult to bond to other materials.
5. Aluminum is very difficult to seal using knife-edge metal seals because of its inherent softness.
6. If liquid metal leaked from the power plant inside the chamber, the aluminum could be severely damaged.
7. Aluminum is not as strong as stainless steel and is subject to creep at moderately high temperatures.
8. Impurities within aluminum alloys can become activated.

The chief advantage of aluminum as the chamber material is its relative freedom from neutron activation. However, there are many expensive stainless steel components (the vacuum pumps and valves, for example) attached to the chamber which could become activated whether the shields were inside or outside the chamber. Since these stainless steel components represent a large part of the vacuum system, and because of the advantages of stainless steel as a chamber material, the chamber should be constructed of stainless steel.

If the vacuum pumps are doing their job, they will probably become activated. Attempting to shield the high-vacuum pumps completely from the neutron flux within the chamber would result in severely restricting the conductance from the test article to the pumps. If the pumps can pump gas molecules, they will certainly "pump" neutrons and gamma rays too. Decreasing the conductance to the high-vacuum pumps requires larger, more expensive pumps to produce an acceptable vacuum around the power plant. Therefore, in order to maximize the conductance to the pumps and to minimize the overall costs of the vacuum system, the neutron and gamma shields should be located outside the chamber.

Vacuum System Reusability

A frequently asked question is whether or not the vacuum system can be salvaged and reused after a nuclear power test has been performed within the vacuum chamber. The answer depends on the activation level of the chamber and its components, but it also depends on the costs of the remote-controlled tools and robotic manipulator, needed to work on activated equipment. Some expensive components will become activated despite elaborate shielding efforts, thereby necessitating the use of expensive robotic manipulators to perform even the simplest tasks. Although many of the activated components as well as the chamber itself could be reused with the aid of these remote manipulators, it would be very difficult and expensive to do so. Assembling and instrumenting a power plant for testing inside an unactivated vacuum chamber is a difficult enough task even when done by the hands of skilled technicians. Attempting to assemble and instrument a power plant inside an activated chamber by means of remote manipulators would be even more difficult and expensive.

A better question is how much would a new vacuum system cost to replace the activated vacuum system after a nuclear power test program has been completed. If the chamber design is simple and relatively inexpensive, it would be less costly to replace the activated vacuum system than attempting to reuse it. Personnel could then perform their "hands-on" assembly and instrumentation tasks without danger of radiation exposure from activated materials. Using a disposable vacuum system is easier and less costly than modifying a single, reusable system for each of the different power plant configurations. Another option would be to use two vacuum systems. One system would be used only for non-nuclear power tests and could be modified and reused for different power plants. The second system would be used for nuclear power tests of a particular reactor and would be disposable.

Alternatives to Vacuum Testing

One commonly suggested alternative to performing the power tests inside a vacuum chamber is to perform these tests inside a pressure vessel backfilled with an inert gas such as argon or helium. This plan might work if a rigorous high-vacuum, high-temperature bakeout of the

power plant and the pressure vessel were to precede the backfilling of the vessel with the inert gas. This procedure would remove much of the oxygen, water vapor, and nitrogen from the surfaces of the vessel and power plant that could outgas and cause problems during the high-temperature tests. There is really no advantage with this alternative, however, since the high-vacuum pumps and bakeout heaters would still be needed to remove the oxygen and other impurities outgassed from the materials. Power tests performed in an inert gas-filled vessel would also mask the effectiveness of the heat pipe radiators which rely only on radiant heat transfer when operating in the vacuum of space. The heat pipe radiators would be transferring heat primarily by convection through the inert gas to the chamber rather than by radiant heat transfer when operated inside the gas-filled pressure vessel.

Another option involves performing only the non-nuclear power tests on earth and reserving the nuclear power tests for an actual mission in space. This is a viable, cost-effective approach if the cost of the ground-based nuclear power tests exceeds the cost of putting the power plant into orbit. However, if the power plant should fail to function properly during a space test, the costs of that lost space mission and all of its hardware must be considered.

Liquid Metals

The heat pipe radiators in all of the proposed power plants use liquid metals as their working fluids. Additionally, the SP-100 design uses liquid lithium to transfer heat from the reactor core to the converters. The refractory metals pipes which contain these various liquid metal coolants are subjected to very high temperatures and can be quite sensitive to impurities within the liquid metals. Liquid metals are highly reactive with many substances. Reactions of the liquid metal with impurities inside the pipes could promote leaks.

Testing the SP-100 reactor is more difficult than testing the STAR-C, for the following reasons:

1. A reservoir of lithium must be provided as well as means for purifying the lithium and adding it to the system.
2. Helium gas must be separated from the liquid lithium during operation of the power plant.
3. The TEM pumps require a backup pump support system should the primary TEM pumps fail.
4. Complicated emergency core cooling systems are required in case the lithium coolant leaks.
5. The materials inside the vacuum chamber must be inert to hot lithium in case the core cooling system should leak its lithium inside the chamber.

6. A secondary liquid metal cooled heat exchanger must be used to remove heat from the primary lithium circuit if the large heat pipe radiators aren't used during tests. The secondary coolant in turn must reject its heat outside the chamber. Special precautions must be taken in case a leak develops in the secondary piping.

If an insufficient heat rejection rate occurs due to the failure of some of the heat pipe radiators, the reactor core could overheat with severe consequences. Therefore, emergency core cooling must be available for power plants which require their heat pipe radiators during power tests.

Part I Summary

The physical design of the power plant, the outgassing rates of the materials used, the high-temperature embrittlement rates of the refractory metals used, the method of core-to-converter heat transfer, and the type of power test performed are the salient cost drivers in testing space nuclear power plant designs on earth. There is insufficient information available to determine the operating pressure within the vacuum chamber at which to perform a power test, or whether a power test must be performed in a vacuum environment at all.

The operating pressure in the vacuum chamber directly influences the price of the vacuum test system. A higher vacuum (lower pressure) requires a higher pumping speed. If the vacuum requirements are less stringent, the vacuum system costs are significantly reduced. The physical design of the power plant and the outgassing rates of its materials influence the pumping system requirements for a specified chamber pressure. A power plant having a small total surface area which maximizes the exposure of its surfaces and which uses materials with low outgassing rates should be easier and less costly to test than a power plant with close-fitting parts or which uses materials with high outgassing rates.

The outgassing rates of the refractory metal components, the shield materials, and the reflector/moderator materials should be determined experimentally at their operating temperatures in accordance with AVS (American Vacuum Society) procedures. The operating pressure within the vacuum chamber must be established before a cost-effective vacuum system can be designed. The operating pressure should be based on that partial pressure of oxygen at which incipient damage occurs in the refractory metal pipes. That pressure should be established while the pipes are functioning at their operating temperatures and while transporting their liquid metal coolants.

The power plant designers should consult frequently with engineers experienced in vacuum system design during the design and construction of the power plant. An experienced vacuum engineer can recommend materials and layouts compatible with good vacuum design. This procedure should minimize pitfalls in the testing and operation of the power plant in vacuum environments.

PART II: VACUUM SYSTEM CONCEPT FOR SEHPTR

Introduction

A conceptual design for a vacuum system illustrates some of the points made in Part I of this report concerning the testing of small, space-based nuclear power plants. This vacuum system would be used to test a 40kW (electrical output) power plant concept being developed at the INEL. The name of this power plant is SEHPTR, which is an acronym for Small, Ex-core, Heat Pipe, Thermionic Reactor.

The SEHPTR Design

The SEHPTR (see Figure 1) is the conceptual design for a new space nuclear power plant and is somewhat similar to the STAR-C. The approximate dimensions of the SEHPTR power plant excluding the radiators and shield are 3 feet in diameter and 6 feet in length. The radiators and shield extend its overall dimensions to roughly 11 feet maximum diameter and 12 feet maximum length. The power plant uses thermionic converters located outside the reactor core to convert approximately 300 kW of thermal power into 40 kW of electrical power at an emitter temperature of 1850K. The SEHPTR rejects waste heat to space through seventy heat pipe radiators attached to the converters' collectors operating at 1000K. The radiators use sodium as their working fluid, and are constructed of molybdenum, a refractory metal.

The reactor uses an annular solid core consisting of uranium-dioxide fuel embedded in a tungsten matrix. The thermionic converters are mounted on the inside and outside diameters of the core. Reactor core heat is transferred across a small gap to the converters. The reactor's lithium-hydride neutron shield as well as its zirconium-hydride reflectors are hermetically sealed within stainless steel skins to limit the amount of outgassing. The gamma shield is tungsten and protects the payload from gamma radiation. The only questionable material is the graphite used for the reactor endplates. Unless the graphite is properly conditioned prior to vacuum testing of the power plant, it will have an unacceptable initial outgassing rate [5]. This would require much higher pumping speeds from the high-vacuum pumping system. The outgassing rate of the pre-conditioned graphite should gradually diminish to an acceptable level after a long, high-temperature bakeout in vacuum.

Two sliding reflectors and one axially loaded poison rod provide redundant power controls and emergency shutdown for the power plant. Vacuum-compatible electric motors actuate the power controls and operate only for short periods to avoid overheating. This control system does not require special linear or rotary vacuum feedthroughs during testing; only ordinary electrical feedthroughs are needed to operate the electric motors.

The power plant's construction is simple and open, permitting the unhindered release of outgassed matter to space with little interference from other power plant components. The power

plant's materials have very low vapor pressures and should have acceptable outgassing rates at their operating temperatures. The Table on page 17 lists the surface areas and outgassing rates of materials used in the power plant and the vacuum chamber. The outgassing rates in the Table correspond to the condition of the various materials after pre-conditioning and a long vacuum bakeout. The bulk outgassing rate of the graphite endplates limits the ultimate pressure achievable. If the outgassing rate for the graphite endplates is higher than anticipated following a thorough vacuum bakeout, then higher pumping speeds will be necessary to achieve the required operating pressure.

The Vacuum System

The vacuum system shown in Figure 4 consists of a stainless steel chamber, approximately thirty feedthroughs for power plant and vacuum instrumentation, high-vacuum pumps and gate valves, a viewport, a maintenance access port, and a roughing system of mechanical pumps, blowers, traps, a gate valve, and an inert gas purge line. The main seal for the two chamber sections is located about 4 feet above the bottom plate. An overhead hoist raises and lowers the upper "bell-jar" section on to the base section. This allows easy access to the power plant for instrumentation and checkout before sealing the chamber. A smaller port 2 feet in diameter permits access to the chamber and power plant before nuclear power tests begin without having to break the main chamber seal.

The best achievable vacuum depends upon the effective speed of the high-vacuum pumps at the chamber, and upon the total gas throughput. Throughput is the rate at which a volume of gas at a known pressure and temperature enters a system and is expressed in units of Torr-liters per second. Throughput is equal to the product of the chamber pressure and the effective pumping speed of the vacuum pumps. For this design, throughput is synonymous with the combined outgassing rates from all materials inside the chamber.

The ultimate pressure of this vacuum system is limited only by the outgassing rates of the vacuum chamber, its fixtures, and the power plant. A small total outgassing rate (throughput) is crucial for achieving a low base pressure with an economical pumping system. This vacuum system minimizes the throughput by minimizing the internal surface areas of the chamber and its fixtures. The SEHPTR's design as described is compatible with a high-vacuum environment.

Unfortunately, there is a lack of information relating the specific partial pressures of oxygen to leak failures in refractory metal pipes containing high temperature liquid metals. Such information is essential to selecting an acceptable operating pressure within the vacuum test chamber. An acceptable operating pressure provides a testing environment which will not harm the refractory metal components of the power plant and which can be achieved economically.

**TABLE
OUTGASSING RATES AFTER BAKEOUT**

VACUUM CHAMBER		
Material	Surface Area (sq. cm.)	Outgassing (Torr-liter/sec.)
Stainless Steel Chamber	1.35E+06	4.00E-06
OFHC Copper	Insignificant	-
Viton	Insignificant	-
Total		4.00E-06
SEHPTR		
Material	Surface Area (sq. cm.)	Outgassing (Torr-liter/sec.)
Molybdenum	2.00E+05	6.00E-07 (1)
Stainless Steel Components	2.00E+05	6.00E-07
OFHC Copper	1.00E+03 (1)	3.00E-06
Graphite (Pre-conditioned)	1.84E+04 (2)	1.20E-02 (1),[5]
Tungsten	5.00E+04	2.00E-07
S. S. Fixtures/Miscellaneous	2.40E+05	7.00E-07
Total		1.50E-02
Total Outgassing 1.50E-02 Torr-liter/sec.		
(1) - Estimated value		
(2) - Bulk volume, cubic cm.

Figure 4. The Vacuum System

An operating pressure of $10E-6$ Torr has been chosen for this vacuum system and should be sufficient to protect the molybdenum heat pipes from oxygen embrittlement [3]. A higher operating pressure might suffice for this test application, but there are no data to support this assumption.

The entire vacuum system and the external radiation shields are mounted on two modified flatcars joined side-by-side so that the assembly can be moved between the containment building (Figure 5) and the "warm" and "hot" shops via the four-rail system located at the INEL's Test Area North (TAN) complex. The power plant is loaded into the vacuum chamber, instrumented, and checked out in a portable clean room (class-100,000). This clean room assembles around the flatcars and provides a clean environment during the assembly and instrumenting of the power plant inside the vacuum chamber. Assembly tasks are performed in the containment building to eliminate unnecessary transit of the assembled test system. Both the non-nuclear and the nuclear power tests are conducted inside the containment building. After the nuclear power tests are completed, however, the entire test assembly is moved from the containment building to the "hot" shop for disassembly.

The Vacuum Chamber

The vacuum chamber represents the first containment for the reactor and is constructed in two sections of single-wall 304L stainless steel. The approximate dimensions of the chamber are 16 feet in diameter, 16 feet high, and 0.5 inch thick. The top and bottom endplates of the chamber are dished for strength. All structural joints, connections, and feedthrough penetrations are full-penetration, autogenous welds initiated from the vacuum side of the chamber. External cooling conduits remove waste heat from the chamber while maintaining the chamber walls and the high-vacuum pump ports at or below 300K. These cooling conduits also increase the stiffness of the chamber, thereby permitting a slightly thinner chamber wall thickness.

If certain construction codes for nuclear pressure vessels are invoked, the wall thickness of the chamber could increase significantly. One option would be to envelope a thin-walled, high-vacuum chamber within a thick-walled pressure vessel with a small gap between the two vessels. This gap would be evacuated by mechanical roughing pumps and would be maintained at low vacuum (0.05–0.01 Torr). The inner chamber would use 304L stainless steel and the thicker, outer vessel would use a less expensive steel, since it would not be exposed to a high-vacuum environment. By using this technique, the inner chamber's wall thickness could be greatly reduced because there would be no pressure difference across its walls. The cooling conduits would be welded to the exterior of the inner chamber to remove the waste heat from the power plant.

Figure 5. Test Concept

The power plant mounts vertically to fixturing attached to the baseplate of the chamber with its heat pipes extending upward. An optional arrangement would be to mount the power plant horizontally on rails within a horizontal vacuum chamber having one removable end. The reactor could then slide in and out of the chamber for access.

The Bakeout System

Heating the chamber and test article in vacuum prior to performing the power tests removes most of the gas from the chamber and the test article. The prevalent gases which are removed by a vacuum bakeout include water vapor, oxygen, and nitrogen. The remaining gases are hydrogen and small amounts of carbon monoxide and carbon dioxide which should not cause embrittlement problems.

The chamber manufacturer will have subjected the entire chamber to a rigorous cleaning followed by a two-hour bakeout at 400 C in air at atmospheric pressure. These procedures reduce significantly the vacuum bakeout time and temperature necessary to achieve minimum outgassing rates from the chamber during testing [6]. In order to reduce the outgassing from the test article as well, both the chamber and power plant are baked out at 250 C while under vacuum by enclosing the chamber in a forced-air oven heated by propane burners.

The oven is a well-insulated shell of stainless steel and assembles in sections around the chamber. The oven surrounds the chamber completely except for the high-vacuum pumps which cannot tolerate the high bakeout temperature. The bakeout consists of the following procedures to minimize the outgassing rates of the chamber and the power plant.

1. The chamber is evacuated and held at the best vacuum achievable for 24 hours.
2. The chamber's cooling circuits are drained and purged before assembling and starting the bakeout oven.
3. The bakeout oven's temperature is slowly increased to 250 C during a 24 hour period. If the outgassing rate increases beyond the high-vacuum pumps' capacity, the rough pumps and blowers will be used until the outgassing rate subsides to an acceptable level.
4. (Optional) The bakeout temperature is maintained at 250 C for 24 hours before backfilling the chamber with helium or argon to a pressure between $10E-2$ and $10E-1$ Torr. Backfilling the chamber with an inert gas increases the efficiency of baking out the power plant inside the vacuum chamber. The high-vacuum pumps are valved off from the chamber during this 8-hour convection bakeout. The amount of gas in the chamber is regulated by pressure-actuated valves so that the bakeout temperature can be maintained at a chamber pressure between $10E-2$ and $10E-1$ Torr.

5. (This step is deleted if procedure #4 is deleted.) The gas supply valve is closed and the chamber evacuated by the rough pump system. The high-vacuum valves are opened to continue the vacuum bakeout at 250C for 24 more hours or until the total outgassing rate is acceptable. Steps 4 and 5 may need to be repeated to achieve an acceptable outgassing rate.
6. The temperature is decreased slowly to room temperature before disassembling the bakeout oven and leak-checking the vacuum system.

An effective bakeout ensures that the lowest base pressure within the chamber is achieved in a reasonable time while using optimally sized vacuum pumps. A bakeout also guarantees minimal outgassing of water vapor, oxygen, and nitrogen from the chamber and from the power plant.

The power plant will actually bake itself out during the operational power tests as its temperature rises with increasing core power. It is important to increase the core's power and temperature slowly and then to maintain a temperature slightly below the ductile-to-brittle-transition temperature (675 K) of the molybdenum heat pipes until the outgassing rate subsides again. The temperature should not be increased until an acceptable partial pressure of oxygen is achieved. A residual gas analyzer (RGA) provides information about the types and amounts of gas species present within the vacuum chamber.

The High-Vacuum Pumping System

There are various types of high-vacuum pumps available from several suppliers. This conceptual design uses two-stage, gaseous helium cryopumps which capture gas molecules by condensing them on the cryogenic pump surfaces. Four 20-inch cryopumps are mounted on high-vacuum gate valves located on ducts at the top of the chamber. These ducts are actually 45-degree, water-cooled elbows that prevent radiant heat from reaching the cryogenic interiors of the pumps. Too much heat can reduce the effectiveness of a cryopump. The mounting angle also allows easy removal and replacement of the pumps by remote manipulator, if pump maintenance is ever needed. Having to replace a pump during a test is highly unlikely, however. Only two of the pumps are needed to achieve the operating pressure of $10\text{E}-6$ Torr. The other two pumps are redundant and would be used if the primary cryopumps should fail or require maintenance such as regeneration. These pumps are oil-free, have very high pumping speeds, and do not require backing pumps in order to operate.

A helium cryopump generally uses polymer seals in its displacer assembly. A major concern is the reliability of these seals in a radiation environment. Recent tests indicate that these seals can survive the gamma radiation absorbed during the nuclear power tests [7]. Mounting the pumps as shown in Figure 4 also permits some shielding from the power plant's neutron and gamma shields. Additional protection comes from the external neutron and gamma shields lo-

cated between the chamber and the pumps. The only way that gamma and neutron radiation can reach the pumps is through the pump ports.

Another type of cryopump which could be used circulates cryogenic helium through coils inside the chamber. The helium supply is stored in large dewars outside the chamber. To maintain the cryogenic helium temperatures, the helium coils must be surrounded by liquid nitrogen-cooled baffles. This system is more expensive than the proposed pumping system because it requires large quantities of cryogenic helium and liquid nitrogen and large dewars in which to store them. Shielding the liquid nitrogen-cooled baffles from the radiant heat of the power plant inside the chamber would also be difficult; an internal heat sink located between the power plant and the cryopump would be required to remove the waste heat from the power plant. This scheme would require yet another coolant to be circulated within the vacuum chamber and would create opportunities for coolant leaks inside the chamber near the high-temperature reactor core and heat pipes.

Other high-vacuum pumping systems were disregarded for the following reasons:

1. Turbomolecular pumps are not as cost effective as cryopumps; the price for a required pumping speed is high compared to cryopumps. Turbomolecular pumps also require backing pumps and risk backstreaming of pump oils if the pump breaks down suddenly. The lubricants for the high-speed turbine bearings may also break down when exposed to a radiation environment. The large pumps required for this application could only be mounted vertically.
2. Ion pumps have relatively low pumping speeds, are very heavy, and require a high-vacuum environment before they can be started. They also do not pump all gas species equally well. These pumps do not require backing pumps, however, are oil-free, and have no moving parts.
3. Diffusion pumps must be mounted in an upright position and require backing pumps. The pump oil may be damaged by the radiation environment. Backstreaming of pump oil is also a major problem unless the diffusion pump is properly trapped with liquid nitrogen-cooled traps. These traps usually decrease the effective pumping speed by one-half or more, due to the decrease in molecular conductance through the trap.

The Roughing System

The roughing system uses series-staged roots blowers backed by large mechanical roughing pumps to evacuate the chamber during its initial pumpdown, and may also be used during the bakeout if the outgassing rates become too large for the high-vacuum pumps to accommodate.

This roughing system can achieve a chamber pressure of $10E-3$ Torr in a reasonable time. The system mounts on the flatcars close to the vacuum chamber and connects to the vacuum chamber through a gate valve. A branch from the roughing system is used to evacuate the cryopumps before they are started. The roughing system is disconnected from the chamber at the gate valve after the bakeout oven is removed but before the radiation shielding is installed. In this way the entire roughing system may be reused since it will not be exposed to nuclear radiation during the nuclear power tests.

A purge gas is used during rough evacuation of the chamber to prevent the backstreaming of oil from the roughing pumps into the chamber. A pressure-regulated leak valve allows the purge gas to maintain a foreline pressure between $10E-2$ and $10E-3$ Torr during roughing operations. A foreline trap is also used between the mechanical pumps and the roots blowers.

Vacuum Seals

There is a variety of seals available for vacuum use. Each type has advantages and disadvantages which are outlined here.

1. Elastomer/polymer seals: Viton is usually used for high-vacuum work because it has a reasonably low outgassing rate and can be baked to 150°C without harm. It has relatively poor resistance to nuclear radiation damage, however. Polyimide is preferred for use in radiation environments and can withstand doses to $10E8$ rads [8]. All elastomers suffer from high permeation rates; this can be alleviated by using two concentric seals separated by an evacuated gap (also known as a guard vacuum). This type of double elastomer seal is known as a differentially pumped seal and requires a roughing pump to produce the guard vacuum.
2. Copper gasket/wire seals: The most familiar copper gasket seal is the Conflat (registered trademark of Varian Associates) knife-edge seal. An OFHC (oxygen-free, high-conductivity) copper gasket is restrained between the two mating stainless steel flanges to be sealed. Each flange has a sharp edge machined into its surface. When the connection is tightened, the sharp edges of the flanges penetrate the copper gasket forming a hermetic seal. This seal can be baked to 400°C without harm and is not damaged by radiation. Its only disadvantages are obtaining large diameter seals (larger than 16 inches diameter) and achieving uniform penetration to form and maintain a hermetic seal, especially following a high-temperature vacuum bakeout. Knife-edge seals perform well on small diameter connections (up to 16-in. diameter). This vacuum system would use the knife-edge seals for all joints less than 16 inches in diameter. Solid wire seals share the same advantages and problems as the flat copper gasket seals. Some wire seals require knife-edge penetrations while oth-

ers require compression within existing O-ring grooves. It is difficult to obtain large wire seals that fit O-ring grooves properly.

3. Helicoflex seals: Helicoflex is a brand name for specialty metal seals made by the Helicoflex Company from a variety of metals and is used in the Princeton Tokamak [9]. The Helicoflex seal applicable to this vacuum system would be small diameter aluminum tubing containing an Inconel coil spring inside the tubing. This design combines the advantages of an elastomer seal with the advantages of a metal seal. This vacuum system would use a Helicoflex seal for the 16-ft. diameter chamber seal, the 2-ft. diameter access port seal, the 20-in. diameter pump and gate valve seals, and any flanged port larger than 16 inches in outside diameter.
4. Welded seals: All permanent joints, seams, and connections in this vacuum system are welded. Strong consideration was given to sealing the main chamber halves by welding them shut [10]. This is still a viable option. Disassembly following a nuclear power test would require cutting through the welded seal by remote manipulators, however.

Radiation Shields

Many of the activated parts of the vacuum system must be discarded or replaced following nuclear power tests. Depending on their levels of activation, some components may be reused. The roughing system, for example, can be reused because it is never exposed to activation. The entire vacuum system could be reused if remotely operated equipment were used for assembly and maintenance tasks on the test apparatus. Such equipment is expensive when compared to the cost of replacing the activated parts. Furthermore, working on an activated system by remote means is quite difficult and cumbersome. The strategy for this test system is to discard activated parts after a nuclear test. This vacuum system is highly efficient using four small cryopumps and a simple chamber which can be replaced rather inexpensively.

The shielding used to protect personnel consists of neutron and gamma shields and is located outside the vacuum chamber as depicted in Figure 6. SEHPTR uses its own neutron and gamma shields to protect the mission's payload from the power plant's nuclear radiation. Since these shields are part of the power plant, they can be used advantageously during nuclear power tests inside the vacuum chamber. In fact, SEHPTR's internal shields limit the neutron and gamma radiation reaching the high-vacuum pumps. This arrangement decreases the activation rate of the high-vacuum pumps. These pumps receive additional protection from the external shields located between the chamber and the pumps.

Figure 6. Shielding Configuration

The external shielding consists of neutron and gamma shields. The neutron shield is adjacent to the chamber and is made of borated polyethylene several inches thick. The gamma shield is constructed from a high-density material such as lead, depleted uranium, or tungsten. The exact thicknesses needed for the neutron and gamma shields have not been determined. These shields are designed for ease in assembly and disassembly. Each gamma and neutron shield section can be matched and assembled as a unit section. The unit sections are then assembled to form a complete shield around the test chamber on the flatcars.

The Chamber Cooling System

As much as 300 kW of excess heat must be rejected by the power plant's heat pipe radiators to space. This large amount of waste heat is a result of the thermionic converters' low efficiency (13 percent) in changing thermal energy from the reactor into electrical energy. The entire quantity of waste heat must be radiated to space. This waste heat must also be removed from the power plant during earth-based power tests to prevent the reactor from overheating.

The proposed vacuum chamber removes waste heat by circulating a mixture of chilled water and anti-freeze through stainless steel conduits welded to the outside of the chamber. The power plant's heat pipes radiate the waste heat to the vacuum chamber walls which then conduct it to the coolant circulating through the conduits. The cooling system consists of four independent cooling circuits; each circuit has its own chiller and pump system capable of removing 100 kW at a flow rate of 15 gal/min. Each chiller/recirculator has excess capacity so that if one system should fail, the others could continue to supply adequate coolant to the chamber. The operating temperature of the coolant can be varied from 250K to 300K.

An option would be to use the water cooling system already available at the existing containment building. Since a much larger reactor has already been tested there, the existing cooling system is adequate for this application.

Emergency Core Cooling System

An emergency cooling system is necessary to prevent the reactor from overheating should its cooling system fail. The SEHPTR conducts heat from the core directly to the converters. The converters reject excess heat through heat pipe radiators to space. If enough of these radiators should fail at once, the core could overheat because the core lacks sufficient surface area to radiate excess heat to space effectively.

This situation can be alleviated during testing. If the radiators fail while the power plant is inside the vacuum chamber, the vacuum chamber can be slightly pressurized (to approximately atmospheric pressure) by introducing a high-purity inert gas such as helium or argon into the chamber after the vacuum pump valves are closed. The reactor power would be shut down just

prior to backfilling the chamber with the inert gas. This technique increases the heat transfer efficiency between the power plant and the chamber walls while the reactor core is cooling.

Instrumentation

A variety of sensors and instrumentation is necessary to operate and test a nuclear power plant inside a vacuum chamber. All of the instrumentation and sensors that are not exposed to or activated by the nuclear radiation may be reused. The following is a list of necessary instruments:

1. Residual gas analyzers (RGA) determine the types and amounts of gas species present inside the chamber.
2. High-vacuum ionization gauges determine chamber pressures less than $10\text{E}-3$ Torr and are located near the high-vacuum pump ports and at chamber locations close to the power plant.
3. Low-vacuum gauges measure chamber pressures greater than $10\text{E}-3$ Torr and are located near the roughing pump port and at another chamber location far from the roughing pump port.
4. A closed circuit video camera system outside a special radiation-resistant viewport on the chamber observes events within the chamber. By adjusting a pair of mirrors mounted inside the viewport a large portion of the chamber can be observed with the video camera.
5. A control system uses signals from the vacuum gauges and thermocouples to operate various valves and solenoids for the vacuum pumps, gate valves, bakeout system, and emergency cooling system according to pre-programmed procedures.
6. A variable load uses the 40 kW generated by the thermionic converters. This load is located in the containment building outside the chamber. The 40 kW electrical power output produced by the thermionic converters has a high current (about 3000 amps, D.C., total) and a low voltage (about 14 volts, D.C.). By using multiple-lead current feedthroughs, the outputs from the individual converters (about 40 amps each) or from small clusters of converters can be monitored.
7. An assortment of voltmeters, ammeters, and power meters monitor the outputs from the converters to the variable load.
8. Thermocouples are used extensively to monitor and control the temperatures of the power plant's components, the vacuum chamber, the chamber coolant, the radiation shields, and the bakeout oven.

9. Continuous air monitors and radiation air monitors are used to determine nuclear radiation levels at various locations within the containment building and between the biological shielding and the chamber.
10. Reactor power instruments monitor the thermal power level of the reactor (or the reactor simulator) and are used in the reactor power controls.
11. The reactor power control system provides automatic emergency shutdown control of the power plant as well as manual power adjustment control during normal operation of the power plant.
12. A data acquisition system stores the information gathered from the various sensors and instruments used in the power tests.

Part II Summary

The conceptual design of the vacuum system for testing the space nuclear power plant, SEHPTR, employs the principles inherent in good, high-vacuum design. The vacuum chamber uses autogenous welds for permanent seals, Helicoflex O-rings for large diameter seals, and copper gasket, knife-edge seals for small diameter seals. The chamber uses external cooling circuits to remove waste heat from the system while maintaining a chamber wall temperature of 300K or less. The total gas load for the high-vacuum pumps is limited to the outgassing of the materials inside the chamber. The materials selected for the vacuum system and SEHPTR are compatible with a high-vacuum environment and have low outgassing rates when properly conditioned. A thorough bakeout using a removable propane-powered oven minimizes the outgassing from the materials inside the chamber. An inert gas system shortens the bakeout time by providing convective heat transfer via a non-reactive gas. This gas system also serves as an emergency core coolant and acts as a purge gas during rough pumping operations to prevent the backstreaming of pump oil into the chamber.

The initial evacuation of the chamber is accomplished by a pumping system consisting of roots blowers backed by mechanical roughing pumps. A branch from this system also evacuates the high-vacuum pumps before they are started. This rough-pumping system may also be employed during the bakeout. The entire rough-pumping system is disconnected from the main chamber before assembling the external nuclear shielding to prevent its exposure to radiation. In this way the entire rough-pumping system can be reused.

Although the pressure in the vacuum chamber at which SEHPTR must be tested has not been established experimentally, a partial pressure for oxygen of $10\text{E}-6$ Torr has been assumed adequate. An operating pressure of $10\text{E}-6$ Torr should provide sufficient protection of its molybde-

num heat pipes against oxygen embrittlement within the vacuum chamber. The selected high-vacuum pumps can produce this operating pressure.

Helium cryopumps are used for high-vacuum operation because of their simplicity and high pumping speeds. The cryopumps are shielded from thermal radiation by mounting them on short, water-cooled elbows so that they don't "see" a thermal source. The power plant's own nuclear radiation shields reduce the neutron and gamma dosage to the pumps by their placement between the reactor and the pumps. The neutron and gamma shields surrounding the chamber protect the test personnel from harmful radiation.

No attempt is made to protect the chamber and pumps from neutron activation by using internal shields; doing so would increase the gas load to the pumps and would severely reduce the conductance to the pumps. Internal shields would demand much higher pumping speeds to achieve the same ultimate pressure. Maximizing the conductance between the test article and the high-vacuum pumps minimizes the pumping speed requirements, thereby lowering the cost of the system.

The vacuum system can withstand any number of non-nuclear power tests of SFHPTR. Because of its simplicity, the vacuum system can be produced at a reasonable cost; therefore, any activated parts of the vacuum system can be discarded after a nuclear power test and replaced with new parts.

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