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ENGINEERING SERVICES FOR THE NEXT GENERATION NUCLEAR PLANT (NGNP) WITH HYDROGEN PRODUCTION

Test Plan for Helium Circulators (PHTS, SCS, SHTS)

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ACRONYMS AND ABBREVIATIONS

AGR	Advanced Gas Reactor
AMB	Active Magnetic Bearing
CB	Catcher Bearing
CTF	Component Test Facility
DV&S	Design Verification & Support
EMCPM	Electric Motor Control and Power Module
ESC	Emergency Shut Down Circulator
GA	General Atomics
GT-MHR	Gas Turbine – Modular Helium Reactor
HTGR	High Temperature Gas cooled Reactor
HTS	Heat Transfer System
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
LSV	Loop Shut-off Valve
MBCPM	Magnetic Bearing Control and Power Module
MBI	Magnetic Bearings Inc.
MC	Main Circulator
MHTGR	Modular High Temperature Gas cooled Reactor
MSLV	Main Shut-off Loop Valve
NGNP	Next Generation Nuclear Power
NP-MHTGR	New Production – Modular High Temperature Gas cooled Reactor
PHTS	Primary Heat Transfer System
RPM	Rotations Per Minute
S2M	Societe de Mecanique Magnetique
SCHE	Shut down Cooling Heat Exchanger
SCS	Shut down Cooling System
SG	Steam Generator
SHTS	Secondary Heat Transfer System
TRL	Technology Readiness Level

1 INTRODUCTION

Gas cooled nuclear reactor circulators have been used for several decades to circulate primary coolant CO_2 and helium through various types of high temperature gas cooled reactor cores. Both centrifugal types and axial flow types of circulator compressors have been used depending on primary coolant flow requirements and on the type of driving method being used, i.e. slower speed electric motor or higher speed steam turbine. Electric motor driven CO_2 circulators predominantly use oil-lubricated bearings for support of circulator-motor rotor assembly. Water lubricated bearings have been used predominantly for support of high-speed steam turbine driven circulators.

Active Magnetic Bearings (AMB) have been used in the last two decades for support of variety of natural gas compressor rotors and other high speed rotating machine rotors. Advancements in the AMB technology have opened an improved way to support primary coolant helium circulator rotors as well as support for the large rotor used in Gas Turbine – Modular Helium Reactor (GT-MHR) design. Huge advantage of the AMB concept is that there is no lubricant to potentially contaminate primary coolant flow. There are also rotor dynamics stability advantages with AMBs, in their ability to continuously "tune-up" bearings stiffness and damping coefficients to produce minimum shaft orbits at different operating speeds.

Aerodynamic experience with CO_2 and helium compressor designs is huge, allowing for highly predictable aerodynamic performance. One of the key differences between CO_2 and helium compressors is the high helium sonic velocity, which virtually eliminates the Mach number affect in helium circulators, while still present in CO_2 circulators.

This test plan addresses the design considerations for the helium circulator for the Next Generation Nuclear Plant (NGNP). The NGNP circulator is a variable speed, electric motor-driven axial flow helium compressor that facilitates thermal energy transfer from the reactor core to the steam generator; or Intermediate Heat Exchanger (IHX) and, hence, to the external turbo-generator set. It is therefore a key component in the primary system of the nuclear plant with the impeller being the focal point of the system where electro-mechanical energy is converted to overcome resistance and create helium flow in the reactor primary coolant circuit.

A circulator with a power of higher than 5 MW, with such design features as submerged electric motor compressor drive, axial impeller, and AMBs is regarded as state-of-the-art technology. The above-mentioned design features have been down selected to simplify the machine arrangement and to ensure that high availability goals are met.

The Main Circulator (MC) will be heavier duty than any other secondary circulator in the plant. Therefore, the developmental needs or Design Verification and Support (DV&S) of prototypal components will only be discussed for the MC or those components of the shutdown cooling circulator that are not present in the MC. The test results and analyses will be applicable to the secondary helium circulator as well as the components of the shutdown cooling circulator.

1.1 Background

The NGNP helium circulator development builds on earlier studies carried out by circulator vendors for GA. The design proposed by Howden for the MHTGR program in 1989 was a two-stage axial flow machine running at 4500 rpm, with a maximum power rating of 4 MWe. It featured an induction motor and an AMB system. Further to this, in 1993, Howden also designed the helium circulator for the New Production-Modular High Temperature Gas-cooled Reactor (NP-MHTGR) program. The selected design had radial flow impeller, oil-bath lubricated bearings, submerged motor drive, rotational speed of about 3000 rpm and a maximum power level of approximately 6 MWe. The James Howden Company has designed and built 112 machines for the commercial Advanced Gas Reactor (AGR) plants. Howden has designed a 4 MWe helium circulator to the concept stage for GA.

1.2 Circulator Description

Under the NGNP scope, helium circulators are placed in two major systems of the plant. In the NGNP configuration preferred by GA, the MC is mounted in the cold leg of the primary loop following the heat removal stage in the Steam Generator (SG), and is part of the Heat Transfer System (HTS) (see Figure 1-1). In case of a single-loop configuration, the entire helium flow is circulated by a single MC.

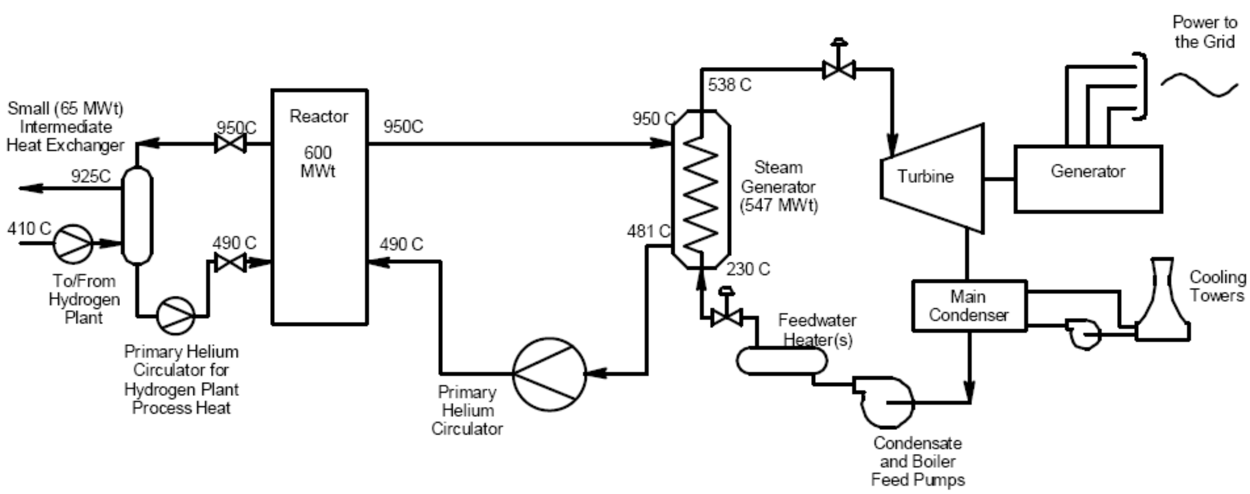

Figure 1-1. NGNP Single Loop Configuration

There is an option to replace the MC in the above configuration with two smaller-capacity circulators in case the MC power requirement exceeds the maximum that can be achieved with a reasonable development effort. In such case, the helium flow is split into parallel loops utilizing two circulators with the total helium flow capacity distributed equally among each circulator (Figure 1-2).

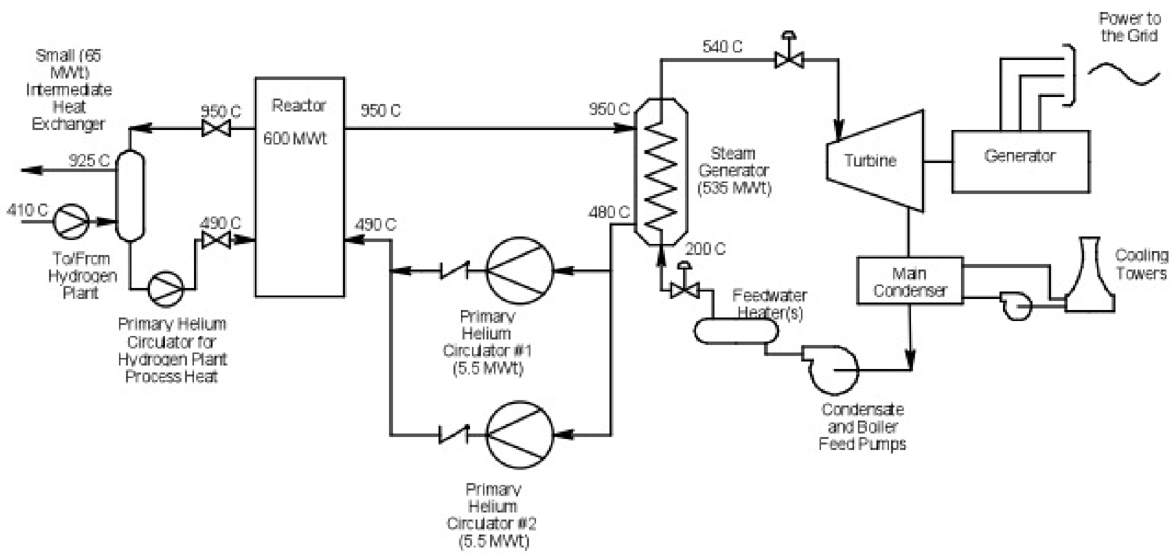

Figure 1-2. NGNP Configuration with Two Parallel Main Helium Circulators

In the case of an indirect power conversion cycle with an IHX in the primary loop, the MC is mounted above and in line with the IHX and a secondary helium circulator is mounted above the SG (see Figure 1-3). The shutdown cooling circulator, which is a part of the shutdown cooling system, is located in the lower position of the reactor vessel.

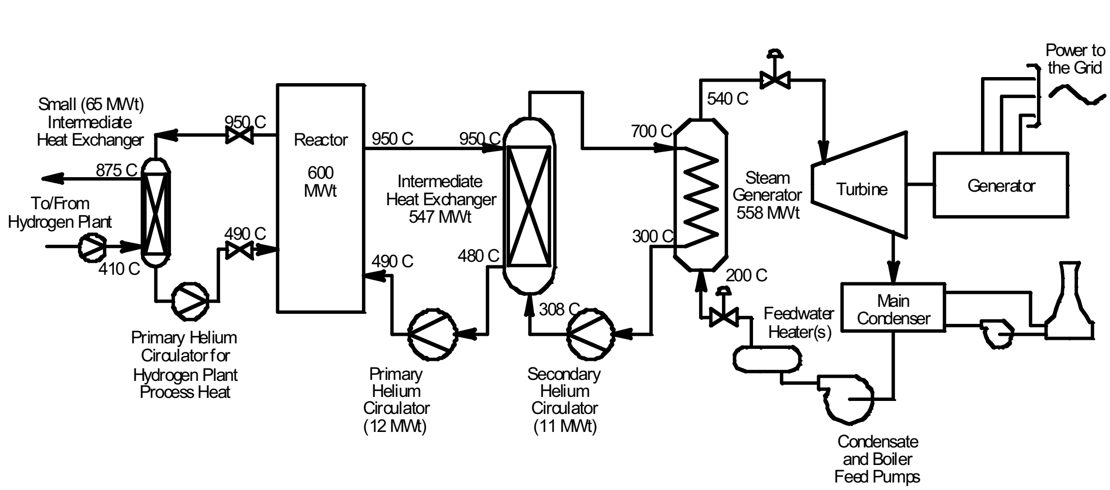

Figure 1-3. NGNP Indirect Cycle Configuration

The Shutdown Cooling System (SCS) provides an independent means of cooling the reactor core if the primary cooling system becomes inoperable. It consists of Shutdown Cooling Heat Exchanger (SCHE), Emergency Shutdown Circulator (ESC), loop isolation valve and motor controls. The SCS circulator design being an order of magnitude lower in power can possibly utilize some of the MC test data, such as motor windings performance in helium, cooling, instrumentation and loop isolation valve.

The helium circulator design requirements for a loop configuration with a single MC and a loop configuration with two MCs in parallel are listed in Table 1-1.

Table 1-1. NGNP Circulator Design Requirements

	Single MC	Two MCs in Parallel
Helium Mass Flow Rate, kg/s	223.8	111.9
Compressor Inlet Pressure, MPa	6.996	6.996
Compressor Inlet Temperature, °C	480	480
Compressor Pressure Rise, KPa	175.66	175.66

Preliminary design optimization indicates that a three stage axial compressor is the best choice for the single loop requirements and a single stage centrifugal type compressor is the best choice for the dual loops requirements. Table 1-2 lists the optimized individual circulator parameters.

Table 1-2. NGNP Circulator Optimized Parameters

	Single MC	Two MCs in Parallel
Compressor type	3 Stage Axial	Centrifugal
Compressor wheel diameter, m	1.128	1.284
Compressor speed, rpm	3440	3961
Compressor wheel tip speed, m/s	203	266
Compressor adiabatic efficiency, %	82	78
Compressor power, MW	10.636	5.591
Estimated electric motor efficiency, %	96	96
Motor power input, MW	11.080	5.824

Typical design arrangement of a vertical shaft helium circulator utilizing centrifugal compressor is shown in Figure 1-4. This preliminary design was developed in 1990, by Howden Company, for General Atomics Modular High Temperature Gas cooled Reactor – New Production Reactor (MHTGR-NPR) Project. This design concept is based on standard CO_2 circulator designs that were produced in great numbers by Howden and successfully used in many British CO_2 cooled reactors.

The key difference between the design shown in Figure 1-4 and the proposed NGNP circulator design is in circulator bearings. At that time, the highly reliable and proven oil lubricated bearings were chosen over potentially new and unproven AMB type bearings for several reasons. AMB technology at that time was not nearly at the advanced stage it is today. Also, longer development schedule of relatively new AMB bearing technology at that time was another factor.

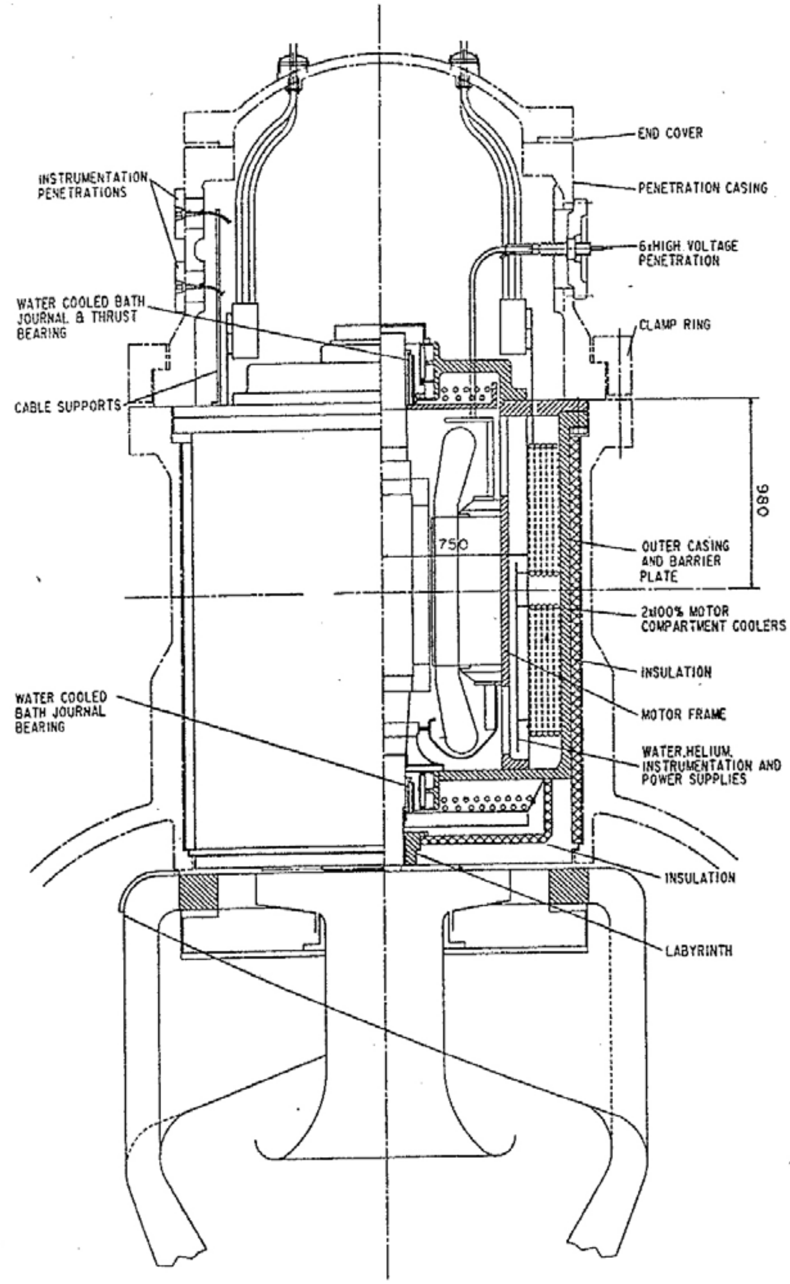

Figure 1-4. General Atomics MHTGR NPR Helium Circulator Drawing

The 5 MW helium circulator conceptual design shown in Figure 1-4 fits closely the circulator requirements for the NGNP configuration shown in Figure 1-2, with the exception that the oil lubricated bearings would be replaced with a combination of AMB and catcher bearings (CB). There may be other changes, such as increased bearings diameters because of elimination of the high oil film sliding velocity limit that existed in the NPR helium circulator design. This would stiffen the NGNP circulator shaft and improve its rotor dynamic characteristics.

A reverse flow actuated twin plate check valve, similar to the Ft. St. Vrain helium circulator check valve concept (not shown), is installed in the inlet duct to the centrifugal compressor shown at the bottom of Figure 1-4 drawing. The isolation valve is installed in series with the circulator to prevent reverse flow through a non-operating loop. The conceptual design of the twin plate check valve is counter-weighted to close by gravity and reverse flow. The design includes a manual jet override actuator for closing assist and a fiber optics position monitoring system.

The entire circulator assembly is submerged in helium at approximately helium circulator discharge pressure, which is also the core inlet pressure. The shaft labyrinth seal, shown in Figure 1-4, combined with small purified helium bleed flow, prevents the primary coolant from entering and contaminating the electric motor cavity.

The electric motor is of a variable speed induction type. Electric power to the motor is supplied via externally located variable frequency static inverter. This allows for accurate control of circulator speed and helium flow rate at all reactor thermal loads and helium pressures all the way down to depressurized reactor shutdown.

Two radial and one double acting axial AMBs support the rotor. Externally located AMB computers control the individual AMB stiffness and damping characteristics. Two angular contact (radial-axial) catcher bearings serve as the back up if there is failure of AMBs.

The electric motor is cooled by two redundant motor compartment water coolers shown in Figure 1-4, each sized for 100% heat load. Operating experience with AGRs has shown that if there is a problem with one of the motor cooling loops, the circulator can still continue operating with one cooling loop and the reactor does not need to shut down.

Figure 1-5 shows the three-stage 13 MW, 3200 RPM helium circulator design, developed for large commercial General Atomics (GA) High Temperature Gas Reactors (HTGR). This design is close to a single loop NGNP main helium circulator configuration with the exception of oil lubricated bearings that are replaced with AMBs as described above in the Figure 1-4 circulator.

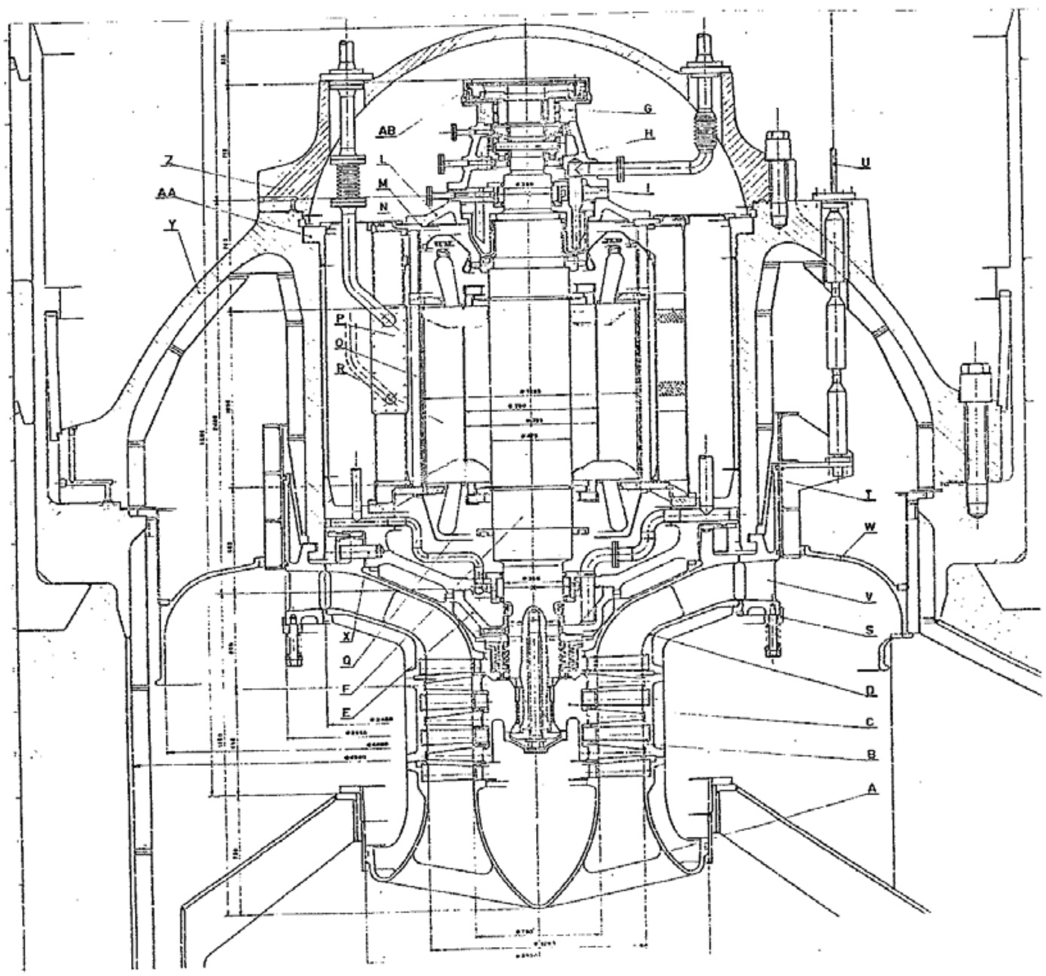

Figure 1-5. General Atomics HTGR Helium Circulator Drawing

The SCS provides an independent means of cooling the reactor core if the primary cooling system becomes inoperable. It consists of SCHE, ESC, loop shutdown valve and motor controls. The SCS has capability to cool down the reactor in 24 hours, thereby maintaining the temperature of all components in the reactor confinement within safe limits with the primary coolant system either pressurized or depressurized. The SCS circulator design being an order of magnitude lower in power can possibly utilize some of the Main Circulator test data, such as motor windings, cooling, instrumentation and loop isolation valve.

1.3 Scope

The Helium Circulators Test Plan outlines the critical test areas requiring performance verification needed prior to NGNP Main Helium Circulator final design and operation. Major development effort is focused on dynamic performance of the MC AMBs supporting the full-scale "dummy rotor" operating over the full speed range in helium. CBs are included in the design of this test rig, verifying the CB performance during the rotor coast-down following simulated failure of AMBs.

A 1/3-scale model aerodynamic test will include a three stage axial or a single stage centrifugal compressor combined with the compressor wheel inlet duct geometry that will include loop isolation valve.

A full scale, full power Main Circulator Test Facility will include a prototype MC mounted inside a helium pressure vessel. The closed loop test vessel system is designed to fully simulate thermal and flow conditions of the NGNP reactor steady state and transient operation at all operating pressures.

A full-scale, full power Shutdown Circulator Test Facility will include a prototype shutdown circulator mounted inside a helium pressure vessel. The closed loop test vessel is designed to allow testing of shutdown circulator at all steady state and transient pressurized and depressurized NGNP shutdown conditions.

The following tests are planned for the helium circulator subsystem to reach from Technology Readiness Level (TRL) 6 to TRL 7.

1. Active Magnetic Bearings Verification Tests
2. Catcher Bearings Verification Tests
3. Scaled Model Circulator Aerodynamic Flow Tests
4. Motor Cooling Design and Insulation Dielectric Strength Verification Tests
5. Main Circulator Motor Cooling Design Verification

An integrated full-scale prototype circulator performance test in helium is planned for the main circulator subsystem to reach from TRL 7 to TRL 8.

The basic approach in the testing program is to repeat the steps used to achieve high reliability for previously built circulators. The approach is to test all subcomponents where any change exists from pervious experience and progress through various stages until an entire prototype assembly is tested.

1.4 Purpose

Purpose of the tests outlined in this plan is to verify the overall main circulator performance at all steady state, transient pressurized and depressurized operating conditions.

Any change in the circulator design from previous experiences requires requalification of the design including insulation system and satisfactory operation of the impeller, bearings and seals under high temperature, pressurized as well as non-pressurized helium environment.

The overall program objective is to increase the reliability/availability and operability of the MC subsystem under pressurized helium as primary working medium, higher reactor system pressure and temperature, and size/speed effects using variable speed drive and magnetic bearings with assurance of rotor stability over a wide speed range.

The development of a testing program will be design dependent; therefore this test plan document is prepared for guidance only. Following are the key performance parameters to be evaluated:

- Dynamics and stability of full scale vertical circulator rotor supported in helium by two radial and one double acting axial AMBs.
- Capability of CBs to support the full-scale vertical circulator rotor with failed AMBs during the coast down at all steady state, transient pressurized and depressurized operating conditions, in helium.
- Durability of CBs in helium.
- Aerodynamic performance of the circulator compressor stage or stages including the compressor efficiency, helium flow rate vs. helium pressure rise speed lines including compressor surge limit at all pressurized and depressurized helium operating conditions.
- Electric motor high voltage insulation performance at pressurized and depressurized helium conditions.
- Electric motor cooling system performance at all operating conditions, using two redundant water-cooled heat exchanger systems.
- Performance of circulator shaft sealing system during steady state and transient pressurized and depressurized circulator operation.
- Aerodynamic and mechanical performance of the loop isolation valve at all pressurized and depressurized operating conditions.

1.5 Prior MC Test Activities and Applicable Experience

Considerable operating experience with magnetic bearings in various industrial applications has been accumulated, and covers the size and load range of a circulator of 4 to 5 MWe. Societe de Mecanique Magnetique (S2M), the world's leading manufacturer of magnetic bearings, has some proprietary data under various non-representative conditions. Data on characteristics and performance of AMBs operating in conditions representative of the NGNP MC environment have not been established. There are several large (5000 to 10,000 hp) commercial gas compressors on the market that employ magnetic bearings. Magnetic Bearings Inc. (MBI), a licensee of S2M, had a catcher bearing test program in late 80s with a 1000-lb rotor rotating at up to 12,000 rpm (NGNP MC is likely to have < 6500-lb rotor rotating at up to ~4000 rpm). There is a lack of data on the reliability of backup "catcher" bearings for vertical rotors to repeatedly support the turning rotor for a limited time when the active magnetic field supporting the rotor is lost. Around the same time as MBI, BBC/HRB had a test program of a proprietary catcher bearing design for the HTR-500 concept in Germany. There is also experience with magnetic bearings for use in centrifuge enrichment equipment as part of some classified government programs. Part of this work has recently been declassified.

No experimental data is available for the cooling of a motor configuration submerged in helium.

Data on helium circulators are primarily available from component testing performed for Fort St. Vrain and the proposed Delmarva plant. The database has applicability limited to the design of axial compressors and shutoff valves. Data on active magnetic and catcher bearings, and submerged motor cooling should be available prior to design verification of the entire MC system. There is no data available on the performance characteristics of the current MC design and its interactions with the associated external systems and controls.

1.6 Significant Changes in Main Circulator Design Requirements

Magnetic bearings (with catcher bearings) have different design requirements than the previously used water bearings. They utilize variable strength magnetic fields that suspend the high speed/ large mass rotor in position. In the event of a failure in the magnetic suspension system, catcher bearings are used to support the rotor and are required to withstand at least 20 drops without the need for replacement. Although an advantage of magnetic bearings is that they can be designed to eliminate critical speed vibrations, it is intended to design the rotor and support housing with no resonant frequencies throughout the full speed range.

The electric motor drive submerged in helium has different cooling requirements than previous designs. Submerged motor and bearing cooling is provided by shaft mounted fans circulating helium through passages into a collection cavity that feeds the helium flow into a water-cooled heat exchanger.

The capability of the NGNP MC subsystem to provide adequate primary coolant circulation for various plant operating requirements needs to be verified. The utilization of the magnetic bearings and the vertical submerged electric motor drive, with the associated new design requirements, will be verified in conjunction with the entire MC subsystem. This includes MC, ducting, Main Loop Shut-off Valve (MLSV), service modules, instrumentation, motor and control, and interfaces.

The MC assembly including compressor impeller, bearing systems, MLSV, drive motor, instrumentation and controls must be capable of performing its function during all normal operating conditions and transients with a failure probability of 7×10^{-5} / h.

Figure 1-6 shows the layout of a typical submerged gas circulator.

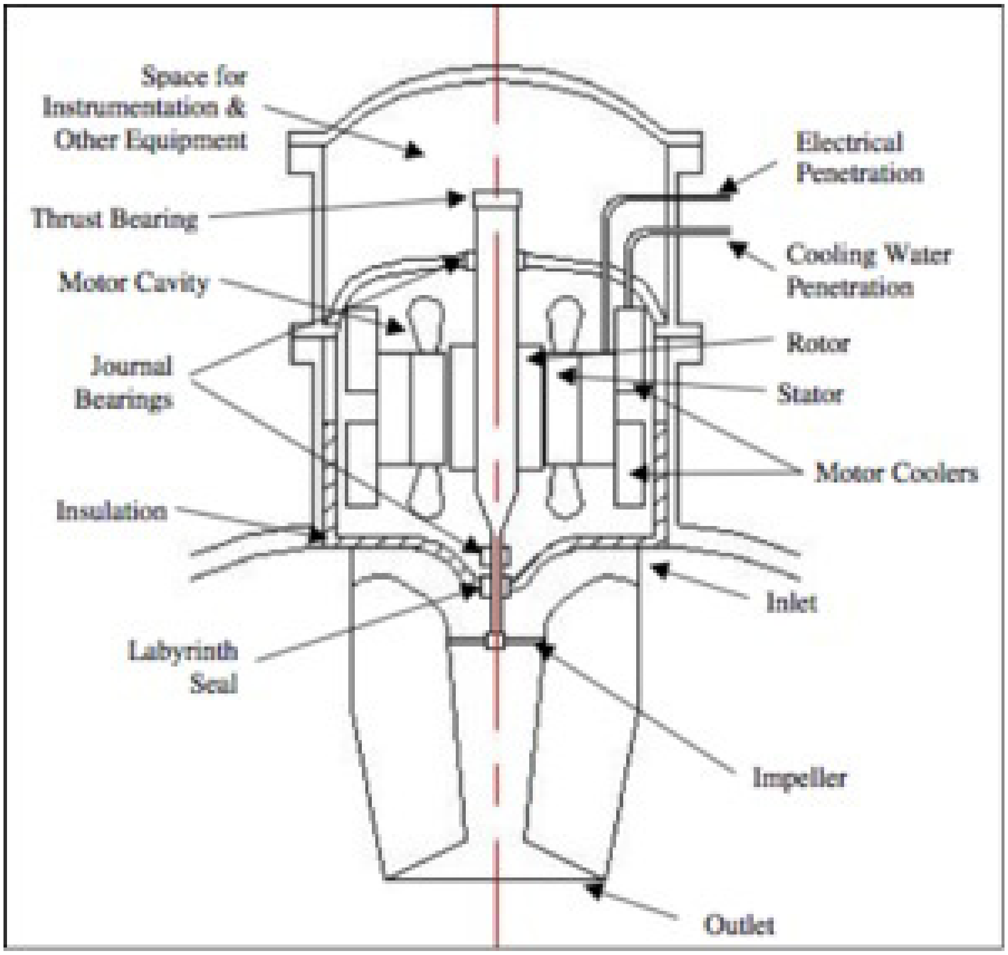

Figure 1-6. Simplified Sketch of a Typical Submerged Gas Circulator Layout

2 APPLICABLE DOCUMENTS

Table 2-1. Applicable Documents

Document Number	Title
DOE-GT-MHR-100217/Rev. 0	600 MW(t) Gas Turbine-Modular Helium Reactor Design Data Needs
DOE-HTGR-86025/Rev. 4	Design Data Needs Modular High–Temperature Gas-Cooled Reactor
CEGA-002712/Rev. 1	The Engineering Development Plan for The New Production – Modular High–Temperature Gas–Cooled Reactor Program
DOE-HTGR-88279/Rev. 0	Main Circulator Design Status
PC-000255/Rev. 0	Test Plan – MHTGR Main Circulator

3 TRL 6 TO 7 – HELIUM CIRCULATOR SUB COMPONENT VERIFICATION TESTING

The NGNP Helium circulator is assumed to be at a TRL rating of 6 because the technological choices for the components of the circulator have already been demonstrated in a relevant environment for other applications. In order to promote the NGNP circulator technology to a TRL of 7, these components need to be integrated for an engineering scale demonstration in a relevant environment. The required tests for such engineering scale demonstration are discussed in the current section.

3.1 Test: Active Magnetic Bearings Verification

3.1.1 Test Objective

The objective of this test is to provide a demonstration and verification of the magnetic bearings capability. The application of magnetic bearings to the MC design is within the state-of-the-art in terms of rotational speed, rotor mass, rotor diameter, axial and radial loading and rotor horsepower, and therefore few problems are expected. Testing will be based on simulation of actual conditions of magnetic bearing configuration, loading, environment and operation, as much as is practical. When it is impractical to conduct certain developmental aspects of the testing because, for example, several design changes are necessary for screening purposes, small-scale supplementary testing can be done.

3.1.2 Test Description

Active Magnetic Bearings are designed to provide stiffness and damping forces required to support the circulator electric motor and compressor rotor at all steady state and transient operating conditions.

Bearings stiffness is defined as the force due to displacement. Bearing damping is defined as the force due to velocity and is 90 degrees out of phase with stiffness force.

Combined individual bearing force is controlled by individual computers located externally to the helium pressure vessel. Rotor dynamics and bearings stability characteristics are “tuned” by external computers providing optimum bearings stiffness to damping ratio at all circulator operating speeds.

Testing is conducted through the full circulator speed range, in helium with the full-scale “dummy rotor” with dynamic properties of the complete rotor but without compressor blades. Test rig rotor is driven by the electric motor requiring only relatively low power level.

Test rig includes the Catcher Bearings, which are not to be intentionally tested in these tests, but in the next phase of tests.

Test rig bearings are fully instrumented with shaft displacement and velocity probes and the rotor speed probes. All the parameters will be recorded on real time basis.

3.1.3 Test Configuration

The selected approach is to test a full-size rotor. Since the motor, compressor blading and disc will not be included, appropriate masses will be added in such a way that rotor dynamics are simulated; the first bending mode natural frequency should be correct. The details of the catcher and magnetic bearings will duplicate the expected reference design.

The vertical load includes the rotor weight (6500 lb downward) and the aerodynamic thrust load, which ranges from 4500 lb upward during pressurized reactor operation to 100 lb during depressurized reactor operation. Radial loading (3550 lb) is due to centrifugal force when the 0.010-in, radial displacement limit to catcher bearing engagement is reached. An upward load of one "g" is included in the design basis.

The magnetic bearings must withstand and operate through the loads imposed by an operating basis earthquake (Ref. 1). These loads need to be developed, based on a maximum ground acceleration of 0.15 g, and will be included during supplemental testing by the bearing vendor.

3.1.4 Test Conditions

Ideally the test environment should be at the design condition for the magnetic bearings. From a tribological point of view it is important to test in pure dry helium because the lack of surface contamination can promote interface welding and the lack of oxidation can lead to adhesion of contacting metal parts. In the temperature range of interest only water and particulates are expected to play a role in wear and adhesion processes. Testing should therefore cover the full range between expected and design values for these impurities. When testing with lubricants, the test environment would be altered. The need for control of other impurities should be determined during the course of testing. High standards of cleanliness will be necessary during assembly of the test rig, since residual contamination can improve tribological behavior. Atmospheric air will have to be excluded.

3.1.4.1 Test Operating Cycle

It is expected that operational testing of the magnetic bearings will be accomplished in the course of conducting the rotor drop tests, while supporting the rotor, bringing it up to speed, and dropping it onto the catcher bearings. The number of operating events and operating time need to be established.

3.1.5 Measured Parameters

Magnetic bearing operational testing should include, as a minimum:

- Determination of static and dynamic axial thrust load capacities, stiffness, and damping coefficients over the operating speed range. For example, preliminary calculations indicate that thrust ranges from 6500 lb downward at zero speed to 2000 lb downward at full speed. These loads, and the capability of the bearing control system to operate over the range, must be verified.
- Sensitivity of the associated electronic control system to external disturbances.
- Rotor dynamic response to externally induced unbalance loads occurring in the impeller plane of rotation.
- Switching off the redundant control circuit and simulating performance of repair of the out-of-service circuit.
- Magnitude of drag losses.

3.1.6 Magnetic Bearings Supplementary Tests

Some supplementary testing will be required as part of the magnetic bearing tests. These will include the following:

- Development testing of alternate bearings, operating procedures, lubricants, and/or materials, if the reference design is unsatisfactory.
- Development testing of a helium injection cooling system, if it is required to provide proper simulation of pressurized operation, or to provide supplementary bearing cooling as part of the design of an actual bearing system.
- Evaluation of aerodynamic load simulation, including decay, in the test rig.

Only minimal supplementary testing of the magnetic bearings should be necessary. The magnetic bearings are a standard product, which are not required, in the MC application, to operate beyond the range of speed, power, loading, temperature, or pressure for which they have been designed.

The effect of out gassing of helium, during a rapid depressurization, on the magnetic bearing insulation system, is the only potential problem area, which has been identified. This problem needs to be evaluated by the magnetic bearing manufacturer and appropriate design modifications and/or testing should be proposed. One possible design modification would be encapsulation of the insulation. Important testing parameters would be soak time at pressure, helium environment, and depressurization rate.

Corona discharge in the insulation system is not expected to be a problem in the low-pressure helium environment, because the voltage requirement for the magnetic bearings is low (less than 200 V).

3.1.7 Data Requirements

Data are required to establish for the magnetic bearings:

- Static and dynamic load capacities, stiffness and damping coefficients of the radial and axial bearings for the entire operating speed range,
- Sensitivity of the associated electronic control system to outside disturbances, and
- Rotor dynamic response to externally induced unbalance loads occurring in the impeller plane of rotation.

3.1.8 Test Evaluation Criteria

AMB test evaluation criteria include the following:

- The rotor and support housing have no resonant frequencies throughout the full speed range operation.
- Active magnetic bearings system designed can adequately perform its function under the NGNP full spectrum range of helium (flow, temperature, pressure, pressure rise) under pressurized and depressurized, steady state and transient operating conditions.
- The thrust bearing has adequate margin of overload capacity to react all gravitational (including seismic) and aerodynamic axial loads.

3.2 Test: Catcher Bearings Verification

3.2.1 Test Objective

Requirements for testing catcher bearings are described in detail in Refs. 2 and 3. This part of the test program is primarily for development of the catcher bearings design. It will also provide a demonstration and verification of the final catcher bearings design.

Testing will be based on simulation of actual conditions of catcher bearing configuration, loading, environment and operation, as much as is practical.

3.2.2 Test Description

Testing of Catcher Bearings will be conducted with the test rig used to conduct tests of Active Magnetic Bearings following successful completion of the AMB verification series tests.

Catcher Bearings must demonstrate capability to withstand multiple simulated failures of the Active Magnetic Bearings function, causing trip of the electric motor and the rotor coast down.

In addition to the instrumentation used in section 2 series tests, temperature probes will be installed to monitor temperature of the upper and the lower radial catcher bearings including the double acting thrust catcher bearing.

After each drop test a static torque measurement of the catcher bearings will be conducted to indicate the degree of catcher bearings wear. Test will be conducted using electric motor and measuring previously calibrated motor voltage required to move the rotor.

3.2.3 Test Configuration

The test configuration for catcher bearing verification testing is pretty much the same as that for magnetic bearings verification testing. The details of the catcher bearings will duplicate the expected reference design.

A means will be necessary to simulate aerodynamic force and its decay during rundown. Braking of the rotor will also be required to shorten rundown time as required during testing. The rundown cycle must be determined as it relates to the catcher bearing.

It is not considered appropriate to add seismic loads to catcher bearing requirements. The likelihood of rundown on the catcher bearing coincident with an operating basis earthquake (estimated duration of 30 s) is negligible and not appropriate as a design basis for non-safety related equipment.

3.2.4 Test Conditions

The test environment for catcher bearing design verification should be at the design condition and almost the same as that for the magnetic bearings.

It is possible that rundown during depressurized conditions will result in catcher bearing overheating. This is because there may be insufficient mass of helium to help provide adequate cooling. Because the depressurized rundown is the more severe, initial testing should be at this condition to determine the extent of any overheating problem. Designing the test rig for operation at pressure will be difficult and it needs to be planned for, however, depending upon the extent of the overheating problem, it may be possible to test only depressurized.

3.2.4.1 Test Operating Cycle

The worst case loading condition for the catcher bearings is depressurized reactor operation. The catcher bearing must withstand the impact of the full rotor weight since the aerodynamic lift force is negligible. Spin down time will be long because aerodynamic drag is negligible, and heat dissipation will be diminished in the absence of a pressurized helium environment.

Catcher bearing testing should include the full 20 rotor drop events (18 pressurized and two depressurized). To simplify the design of the test rig, testing should initially be in the depressurized operating condition. If the catcher bearings are not able to survive the 20 rotor drop events depressurized, consideration should be given to either modifying the test rig for pressurized operation, providing simulated helium injection cooling, or postponing pressurized testing into the "Prototype Circulator Test." Development testing of modified catcher bearings could also be undertaken. This would include evaluation of "soft landing" concepts such as a spring-loaded catcher bearing or the use of braking to slow the rotor.

3.2.5 Measured Parameters

Catcher bearing testing must demonstrate the capability of catcher bearings to support the full scale vertical circulator rotor with failed AMBs during the coast down at all steady state, transient pressurized and depressurized operating conditions in helium.

3.2.6 Catcher Bearings Supplementary Tests

Some supplementary testing will be required as part of the catcher bearing tests. This will include development testing of the reference design angular contact 4400 steel MoS_2 lubricated bearing by the bearing vendor.

3.2.7 Data Requirements

Data are required to establish for the Catcher Bearings,

- Useful life of catcher bearings versus number of drops from full rpm in the helium environment.

3.2.8 Test Evaluation Criteria

Testing should be done at full speed, full load conditions in the controlled helium environment. If damage is observed, then subsequent testing should be conducted to determine the cause. This would include several evaluations including:

- Damage during touchdown or rundown phase
- Slippage between balls and races, or at thrust ring
- Role of contamination or moisture
- Role of lubrication
- Helium inventory for cooling.

3.3 Test: Scale Model Circulator Aerodynamic Flow

3.3.1 Test Objective

The objective of this test is to evaluate and verify the overall aerodynamic performance of the configuration. Design features of the loop isolation valve will be tested to ensure its reliability and integrity. Life cycle of the isolation valve in helium will be determined.

3.3.2 Test Description

A 1/3-scale model of the main circulator compressor inlet, impeller, and diffuser along with a model of the loop isolation valve will be constructed and tested using air as the working fluid.

Because of large difference in sonic velocities between air and helium, test will be conducted in air with the compressor blades Mach number approximately equivalent to the full scale compressor blades Mach number operating in helium.

Drive motor will be power calibrated at five speeds with bladeless bearings/rotor configuration allowing for determining later the compressor aerodynamic shaft power at the same rotating speeds.

Compressor stage will be fully instrumented with pressure/temperature probes including a flow/pressure rake in the compressor inlet duct containing the loop shutoff valve. Flow/pressure rake will determine the degree of compressor inlet flow disturbance by the loop isolation valve. Effects of loop isolation valve flow disturbance will be evaluated by removing the isolation valve from the inlet duct and repeating the flow test.

3.3.3 Test Conditions

The scale-model aerodynamic test will require the following conditions:

- Air flow of 19,000 cubic feet per minute (cfm) at 38ºC
- Drive power - 105 KW

3.3.3.1 Test Operating Cycle

This test will be conducted to obtain complete performance maps of the MC compressor and diffuser, and will include:

- Pressure rise across the compressor as a function of speed and helium flow through the compressor.
- Overall efficiency including impeller and diffuser efficiency.

3.3.4 Measured Parameters

Measured will be airflow rate vs. air pressure rise across the compressor and compressor power for five rotating speeds. Flow tests will include operation establishing the compressor surge line at five rotating speeds.

3.3.5 Data Requirements

Data are required to verify the aerodynamic performance of the inlet, MLSV, compressor impeller, and diffuser.

3.3.6 Test Evaluation Criteria

The circulator compressor aerodynamic flow tests results are evaluated based on the following criteria:

- It is feasible to design a circulator with an axial flow compressor with conservative aerodynamic and structural loading being driven by submerged electric motor under vertical orientation.
- The helium flow can be stably controlled between 5% and 110% speed
- A technically sound and defensible compressor design definition is established
- MLSV assembly performance is validated and verified under expected environmental conditions for all anticipated operating modes. Leakage through the MLSV is be maintained within the specified rate whereas any operating torque increase has been assessed and taken into account in the design of the actuation system provided.
- The reliability and integrity of the MLSV is verified by accelerated testing to represent the characteristic life of the valve.

3.4 Test: Motor Cooling Design and Insulation Dielectric Strength Verification

3.4.1 Test Objective

The electric motor drive submerged in helium has some different cooling requirements than previous designs. Submerged motor and bearing cooling is provided by shaft mounted fans circulating helium through passages into a collection cavity that feeds the helium flow into a water-cooled heat exchanger. The circulator motor cooling system test will determine the performance of the motor cooling heat exchanger and the shaft-mounted motor cooling fans. Flow resistances through the rotor/stator cooling passages will be compared with estimated values.

Other supplemental testing is also required to assure that the insulation and diodes will operate satisfactorily in the helium environment (Ref. 5). The helium at approximately 1014 psia is significantly higher in density as compared to atmospheric air that is the normal cooling medium for electric machinery. This higher density allows for higher thermal storage as compared to the cooling medium normally used in this kind of equipment. An estimate of the helium drag losses indicated the same order of magnitude as the total electromagnetic losses in the motor, and circulation of helium for cooling would further increase the losses. Test data is needed to assure adequate motor cooling in conjunction with minimum drag losses.

3.4.2 Test Description

This part of the test program is primarily for development of the submerged motor cooling flow path in terms of helium pressure drop and flow distribution. Testing will be based on simulation of actual conditions of motor, heat exchanger and housing configuration, loading, environment, and operation as much as is practical. This will reduce the uncertainty in test results. When it is impractical to conduct certain aspects of the testing because, for example, numerous design changes are necessary for screening purposes, small-scale supplementary testing can be done.

Testing of examples of electric motor windings and high voltage electric penetrations and wires at representative voltages down to depressurized helium operating conditions is required to verify that the dielectric strength of insulation has sufficient voltage margin capability.

3.4.3 Measured Parameters

The buffer gas flow necessary to prevent the leakage of radioactive helium into the motor cavity will be measured.

3.4.4 Electric Motor Supplementary Tests

The following tests are required to assure satisfactory operation of the motor insulation and diodes in the helium environment.

Flashover as a Function of Helium Pressure: Helium has demonstrated lower dielectric strength than air at equal pressures, thus flashover is a concern. The dielectric breakdown strength of air and helium over a gap improves with increasing pressure (increasing density of the gas), and at some pressurized helium level its breakdown strength will be equal to that of air at atmospheric pressure. Flashover tests should be performed on samples in air at atmospheric pressure and in helium at three pressures: atmospheric, operating pressure, and an intermediate pressure to obtain flashover data as a function of helium pressure for the various insulation and rectifier components

Corona Start Tests: Corona starting voltage is of more concern in the design of the motor stator insulation because its operating voltage is high relative to the rotor and brushless exciter and rectifier. This concern exists for machines operating in air, but is increased for operation in helium because corona will start at lower voltages due to the lower dielectric strength of helium versus air. The corona starting voltage will be a function of helium pressure due to the effects on dielectric strength with changing density of the gas. Corona has a detrimental effect on the life of the insulation and the corona start data for the stator insulation versus helium pressure is needed for design. To prevent the detrimental effects of corona on the stator insulation, three design options are available.

1. Construct the insulation system so that the voltage stress across the insulation for the 2300-V machine is low enough to prevent corona start from occurring at helium pressures from atmospheric to the operating pressure of 1014 psia.
2. Operate in the corona range and qualify the insulation life by test.
3. Design the insulation system to prevent corona start at operating helium pressure and for the motor to be used at reduced voltages and loads at reduced helium pressure to prevent operation in corona. As the motor load is reduced due to reduced speed the motor losses will reduce faster than the motor cooling capability, making it possible to operate with reduced voltage on the motor and a corresponding higher current for the load.

Pressurization and Depressurization Effects: The insulation systems and the diodes must be capable of surviving the pressurization and depressurization of the helium. There is concern that some enclosed voids may exist that may become filled by pressurized helium if it permeates the insulation or diodes, and about the effect on the insulation if the helium pressure surrounding the machine were to change rapidly.

While the initial assessment indicates that both the insulation and diodes should prove satisfactory, it is important to confirm this assessment by test.

The results of these three supplementary tests will be used to select an insulation system design that is compatible with other design objectives, and to assess the voltage endurance under the most severe of the helium operating conditions.

3.4.5 Data Requirements

Distribution of internal cooling flow and the associated pressure losses through the motor, bearings, rotor, stator, and windings needs verification.

Data on cooling flows, pressures and temperatures throughout the motor cavity are required to validate the thermal/hydraulic performance of the submerged motor cooling system.

3.4.6 Test Evaluation Criteria

The dielectric insulation is reliability and life span is adequate to meet the NGNP operating condition requirements.

Non-radioactive helium is maintained in the motor cavity at all NGNP operating steady state and transient conditions.

4 TRL 7 TO 8 – FULL SCALE HELIUM CIRCULATOR PROTOTYPE TESTING

Successful completion of tests discussed in section 3 above would lead to an integrated sub system demonstrated at engineering scale. A full-scale prototype circulator test in helium with the appropriate duration of test, would demonstrate the main circulator in its operational environment at the required levels of test rigor and quality assurance. This full-scale prototype testing would conclude the resolution of any technology issues pending qualification of the circulator design and would demonstrate its readiness for hot startup. Successful completion of the full-scale prototype circulator performance test in helium would elevate the NGNP helium circulator design to a TRL of 8.

4.1 Test: Full Scale Prototype Circulator Performance in Helium

4.1.1 Test Objective

This part of the test program will demonstrate the operation and compatibility of the various prototype components at full pressure and temperature in helium. Reactor conditions and transients will be simulated to verify performance of the complete MC system including the compressor, magnetic bearing assembly, ducting, MLSV, motor, control, and the MC service modules.

Testing is designed to lower the risk of delaying the plant commissioning date by verifying MC performance under the full range of operating conditions, prior to delivery to the plant site. It is planned to conduct part of the testing under various transient and faulted conditions. Extensive testing of the MC and its service systems under those conditions will either verify the capability of the system or provide the necessary data for solution of problems discovered during the tests. In either case, it is planned that the problems, as they may arise, will be resolved well in advance of the MC and service modules' installation into the plant.

4.1.2 Test Description

The complete prototype MC unit will incorporate components that have been tested as described in preceding sections. The prototype will be constructed and tested ahead of the production MCs so that any changes indicated by the test program may be incorporated into the production units with a minimum delay.

4.1.3 Test Configuration

Main Circulator test facility will have capability to fully simulate Main Circulator operating conditions as installed in the NGNP reactor.

The full scale, full power main circulator test facility will include a prototype main circulator mounted inside a helium pressure vessel. The closed loop test vessel system is designed to fully simulate thermal and flow conditions of the NGNP reactor steady state and transient operation at all operating conditions.

Circulator instrumentation will include:

- Pressure and temperature measurements required to monitor circulator aerodynamic
- Performance, electric motor power, performance of the electric motor cooling system and the amount of heat rejected in the water cooled main helium flow cooling system.
- Displacement probes in two planes 90 degrees apart located at upper and lower AMB bearings. Axial displacement probes located at AMB thrust bearing location.
- Measurement of circulator inlet and discharge noise intensity and frequency spectrum.
- Redundant circulator shaft speed indicating probes.
- Isolation valve position indicator probes
- Moisture monitor, that is not a part of the MC subsystem, will be installed in the MC discharge for testing.

Power supply to the electric motor will be at voltage and power level as in NGNP reactor installation. Prototype variable frequency power converter will include prototype speed control system to supply power to the Main Circulator electric motor as in the NGNP reactor installation.

Helium pressure vessel will include features such as high voltage electric penetrations, electric motor cooling lines penetrations; magnetic bearings control lines penetrations and instrument lines penetration.

Electric motor cooling system will include two redundant water-cooling loops providing cooling water service to two redundant electric motor coolers mounted in the electric motor frame inside the pressurized helium cavity.

The entire circulator assembly is submerged in helium at approximately helium circulator compressor discharge pressure. Prototype circulator includes the shaft labyrinth seal, which is combined with small purified helium bleed flow out of the electric motor cavity. Circulator performance test will verify that the primary coolant will not enter the electric motor cavity under all steady state and transient operating conditions.

4.1.4 Test Conditions

Testing will be in helium throughout the range of NGNP design operating temperatures and pressures. Helium impurity levels will be within the range specified for plant operation.

Service modules will operate in an environment as specified for NGNP plant operation.

4.1.5 Measured Parameters

Prototype testing will verify the operation and interaction of all MC components and service modules. In addition, the following separate test phases will be performed.

4.1.5.1 Buffer Helium System Transient Test

This series of tests will be conducted to verify the MC buffer helium system and to ensure that the MC service module operation is compatible with the MC capabilities. The limitation of flows and pressures that may be utilized in the buffer helium system will also be determined.

4.1.5.2 Shaft Brake Tests

These tests are required to verify performance of the shaft brake. The following will be determined:

- The proper position of the shaft brake, which requires that the brake retract from the brake disc.
- The actuation of the brake on shutdown, which requires that the brake move at low shaft speed and contact the brake disc and thus stop rotation.

For these tests, it will be necessary that design temperatures are attained but not necessarily that design speed be attained. During any cycle of testing, 1000 rpm will be sufficient for maximum speed. Tests will be carried out at a range of pressures from approximately 200 to 1014 psia.

4.1.5.3 Low Speed Test

The objective of this test is to verify that the MC can operate down to 5% speed level. Furthermore, it is planned to verify the low speed performance as predicted by analytical methods. Shaft orbit will also be recorded.

4.1.5.4 Hot Restart Test

The objective of the hot restart test is to simulate the startup of the MC. The MC will be brought up to normal 100% load operating speed and temperature. After system temperatures have been allowed to stabilize, the MC speed will be reduced to zero, buffer helium flow will be stopped, and the shaft brake will be actuated. Temperatures within the MC will be monitored and when the thermocouple sensing the lower bearing reaches a peak temperature, the machine will be restarted and slowly brought up to full speed.

4.1.5.5 Rapid Depressurization Test

These tests will be conducted to evaluate the capability of the MC to operate during an accidental depressurization of the helium systems. These tests will include:

- A test in which the MC is run at the design point and shutdown is initiated.
- Tests to simulate the effects on the MC of a design basis depressurization accident. These tests will determine the MC and buffer helium response to the changing conditions during the accident within the capacity of the test equipment and will demonstrate the speed deceleration from 4000 to 1000 rpm in 10 s, and back up to 4000 rpm in approximately 1 min.

4.1.5.6 Endurance Tests

These tests will consist of simulating MC startup and shutdown operating conditions for a minimum of 200 h of cumulative running time to fulfill the design requirements for endurance testing of the first production MC unit. The test plan requires that the MC be brought up to design speed (4000 rpm) at 500 rpm/min with the helium temperature and the outlet pressure at NGNP plant operating values. These conditions will be held for 60 min and then the power supply will be cut off. The shaft brake will be actuated below 500 rpm. This procedure will be repeated until 200 h of operating time has been accumulated.

Any performance or design deficiencies will be noted and steps will be taken to make the necessary modifications to the MC designs for the demonstration plant.

4.1.5.7 Acoustic and Vibration Tests

The purpose of these tests is to establish the acoustic noise levels of the compressor and vibration levels of components at various critical locations within the MC and test loop. The noise levels and vibration levels will be measured as a function of frequency while the MC is operating at 100% speed, and at full operating pressure and temperature. The resulting frequency spectrum and noise levels will then approximate the reactor operating conditions.

The vibration level of panels, tubing, and other component structures will be measured as a function of frequency for the same operating conditions specified for the noise level tests.

These tests will be part of the overall development plan for identifying and resolving critical flow-induced and acoustically induced vibrations

4.1.5.8 Spin Test

To meet the MC design objectives, it is necessary to establish and verify that stresses due to dynamic loading are within the operating life expectancy limits. This will be accomplished by conducting a spin test of the compressor wheel in a special test rig in ambient air to 150% of normal operating speed.

4.1.6 Data Requirements

Prototype testing will verify the operation and interaction of all main circulator components and service modules.

Data on the functional capability of the entire main circulator system including motor/control/main circulator compatibility are required to verify the reference design. Data needed on the main circulator prototype include:

- Aerodynamic performance of the inlet, MLSV, compressor impeller, and diffuser;
- Motor thrust bearing performance
- Over speed capability
- Structural integrity of rotating parts and supports
- Noise levels and frequencies
- Vibration characteristics and critical speeds
- Transient, shutdown, and hot restart capability including hot soak, and
- Extended duration operation

4.1.7 Test Evaluation Criteria

The Prototype Main and Shut down Circulator test evaluation criteria include the following:

- The performance and reliability of the main circulator prototype to provide adequate primary coolant circulation are validated and verified under the NGNP full spectrum range of helium (flow, temperature, pressure, pressure rise) conditions, including part load and startup, for a test duration of 200 hours and hot soak simulation for duration of 6 hours under both pressurized and depressurized, steady state and transient operating conditions with a failure probability <= 7×10^{-5}/hr.
- The circulator can perform reliably and adequately for an operating life of 40 years (from receipt of operating license)
- Quality assurance QAL II requirements are satisfied.
- Circulator meets plant availability requirements of greater than or equal to 90% full power time per year.
- Circulator assembly design is feasible for shop fabrication and assembly

5 TEST EQUIPMENT

In addition to the ones already discussed in the preceding sections, other major test equipment and facility items needed for these tests are described below.

Brake System - A brake will be provided to simulate the reduction in aerodynamic drag as the rotor spins down, and to stop or slow down the rotor.

Helium cooling system - The system may need to be developed to simulate the effect of pressurized helium cooling, if unacceptable bearing overheating occurs during testing at atmospheric pressure. This system will cool the catcher bearings during rotor rundown.

Lubrication system - The system may need to be developed if lubricant injection becomes a viable design option. This system will inject lubricant to the catcher bearings during rotor rundown.

Load simulation system - This system will simulate the aerodynamic thrust load including its decay during rundown.

Building - An enclosure for the test facility will be required having ample floor space and headroom to handle the test rotor. An overhead crane will be required which will be capable of lifting the test rotor. Testing will be with the rotor vertical. Additional floor space will be needed for work platforms around the rotor, and for electrical control, data acquisition equipment, and environmental control equipment.

Power - The design power requirement for the MC is 11.080 MW. For the test program, however, the power requirement will be considerably less, since there will be no blading on the rotor. Drag forces due to the magnetic bearings and the depressurized helium environment are expected to be negligible.

Since the drive motor for testing will be small, consideration should be given to installing it within the helium environment to avoid helium seal requirements. Such a motor would have to be reliable without requiring contaminating lubricants. The capability to heat the helium inventory to a maximum of 490 °C will be required.

Environmental maintenance - Equipment will be required to maintain a controlled helium environment in the test vessel enclosing the rotor. Pressure in this vessel will be slightly above atmospheric in the temperature range of 60 to 260 °C. Moisture and other impurity levels will be in the range between design and expected values.

Data acquisition - A data acquisition system including signal conditioning, data storage, printout, recording, monitoring, and dynamic analysis will be required. The system will have sufficient channels for measuring and recording the following:

- Helium temperature
- Helium pressure
- Impurities in the helium
- Bearing loads including dynamic analysis
- Rotor displacements and vibration frequencies
- Rotor speed
- Rundown time
- Magnetic bearing recovery time
- Bearing clearances

For the full-scale prototype verification tests, the major equipment and facility items required are:

Test article - A complete prototype MC subsystem with service modules will be tested. The following will be included:

1. MC assembly
2. MLSV assembly and MLSV service module
3. MBCPM
4. EMCPM

Cooling loop and pressure vessel - This loop will provide a circulation path for MC testing. It will include the following:

1. MC test vessel and large diameter external piping
2. Control and shutoff valves
3. Heat exchanger to cool helium
4. Internal flow ducting
5. Special valving to simulate depressurization of the reactor. This valve would have a controllable opening rate and feed large diameter piping which would exhaust to atmosphere

Supporting services - These will include:

1. Electrical power to drive the MC motor and other auxiliary requirements
2. Purified helium of up to 0.014 kg/s for buffer helium and 112 kg/s for activation of the MLSV

3. Purified water for motor cooling of up to 160 gpm at 540°C
4. Cooling system to reject heat from circulating helium
5. Compressed air and nitrogen for general valve and instrumentation requirements

Building - An enclosure for the test facility will be required having ample floor space and headroom to handle the largest component. This will be the test vessel whose dimensions will depend upon the factors, which are currently undetermined for the NGNP program.

Instrumentation and data acquisition - This system will be required to monitor and record the following:

1. Stator phase winding temperature.
2. MC Shaft vibration frequency and amplitude.
3. MC shaft speed, position, and eccentricity.
4. Motor and exciter voltage and current.
5. Buffer helium flow and pressure differential.
6. Cooling water flow and temperature rise.
7. MC compressor pressure rise and inlet AP.
8. Magnetic and catcher bearing loads and load direction.
9. Helium depressurization rate.
10. MC rundown time.
11. MLSV position.
12. MLSV override actuator flow rate.

6 PROPOSED TEST LOCATION

The prototype performance and qualification tests will require a test facility that could accommodate the prototypal assembly and simulate the pressures, temperatures, flows, power, and speed requirements identical to reactor operating conditions. A pressure vessel will be required to enclose the circulator assembly, including the compressor inlet, diffuser, and loop isolation valve. Individual components will be tested in the designer/vendor's test facility. However, for any integrated testing, Idaho National Laboratory's (INL) proposed Component Test Facility (CTF) could be used for conducting these performance and qualification tests.

A seismic test facility and shaker table will be required that can accommodate large assemblies and produce the required excitation range.

A high temperature high-pressure helium test facility currently operating in South Africa could be a near term prospect to perform the proposed tests. Although the specifications of this facility have not been acquired at the moment, the contact details of this facility are as follows:

Facility Name
Pebble Bed Modular Reactor (Proprietary) Limited
Helium Test Facility

Physical Address
Republic of South Africa
1279 Mike Crawford Ave
Centurion 0046

c/o Nesca
Church Street West
Gate 2 P1900
Pelindaba 9992
Republic of South Africa

Contact Details
Tel: +27 (0)12 641 1000
Fax: +27 (0)12 205 8036
communications@pbmr.co.za

7 TEST DELIVERABLES

- Preliminary rotor dynamic analysis.
- Preliminary electromagnetic bearing analysis and design of bearing and sensors.
- Environmental test plan for bearing and sensor winding insulation (Pressure, Temperature and Coolant)
- Shutdown Cooling Circulator Component Test Development Plan
- Main circulator Component Test Development Plan
- Test specifications
- Test reports
- An optimized circulator design with acceptable aero thermal and structural loadings

8 COST, SCHEDULE, AND RISK

8.1 Cost

The development test program for the MC must be integrated with the design and fabrication effort for the MHTGR program to assure that conceptual design, final design, production hardware, etc., are available in a timely fashion. This document assumes a test program, with adequate design and development funding, for completion of development testing prior to the start of fabrication. However, all work is subject to DOE contract award and may be supplied or performed by other selected vendors. Completing the test program, described herein, will provide greater confidence in the design prior to the release for fabrication. The estimated cost for testing of circulators is presented Table 8-1.

Table 8-1. Estimated Cost for Testing NGNP Helium Circulators

Test Title	Estimated Cost (000's) 2008$
Active Magnetic and Catcher Bearings Tests	
Hardware and instrumentation – main circulator	$ 2,500
Test – labor	$ 400
Scale Model Flow Tests	
Hardware and instrumentation – main circulator	$ 800
Test – labor	$ 300
Motor Cooling and Insulation Dielectric Strength Test	
Hardware and instrumentation	$ 400
Test – labor	$ 150
Full Scale – Full Power Circulator Tests	
Hardware – prototype main circulator	$ 6,000
Hardware – main circulator test facility	$ 10,000
Test – labor – main circulator	$ 3,500
Hardware – prototype shutdown circulator	$ 2,500
Hardware – shutdown circulator test facility	$ 1,500
Test – labor – shutdown circulator	$ 1,500
Total	**$ 29,550**

These costs are best guess estimates based on engineer's awareness of past circulators' testing programs and should be considered approximate since facility, equipment, and test article drawings and specifications for NGNP are not yet available. These costs do not include any supplementary testing required at vendor facilities.

8.2 Schedule

To satisfy the NGNP plant start-up schedule of 2018, completion of each event must correspond to the schedule presented in Figure 8-1.

8.3 Risk

The technology required to produce high-temperature helium circulators is well understood and relatively easily available for circulators of up to 5 MWe. Development risks increase with circulator power. Such risks should be mitigated by implementation of an early test program, developed to check feasible limits of operation. An expert organization, such as a circulator vendor, should be engaged by the NGNP Project at an early date in order to develop a circulator design and a demonstration/qualification program for the design. Fall back options for state-of-the-art prototypal components should be identified in parallel. There is potential to reduce development costs by utilizing an existing circulator design of around 4 MWe developed by James Howden Company for GA's MHTGR program.

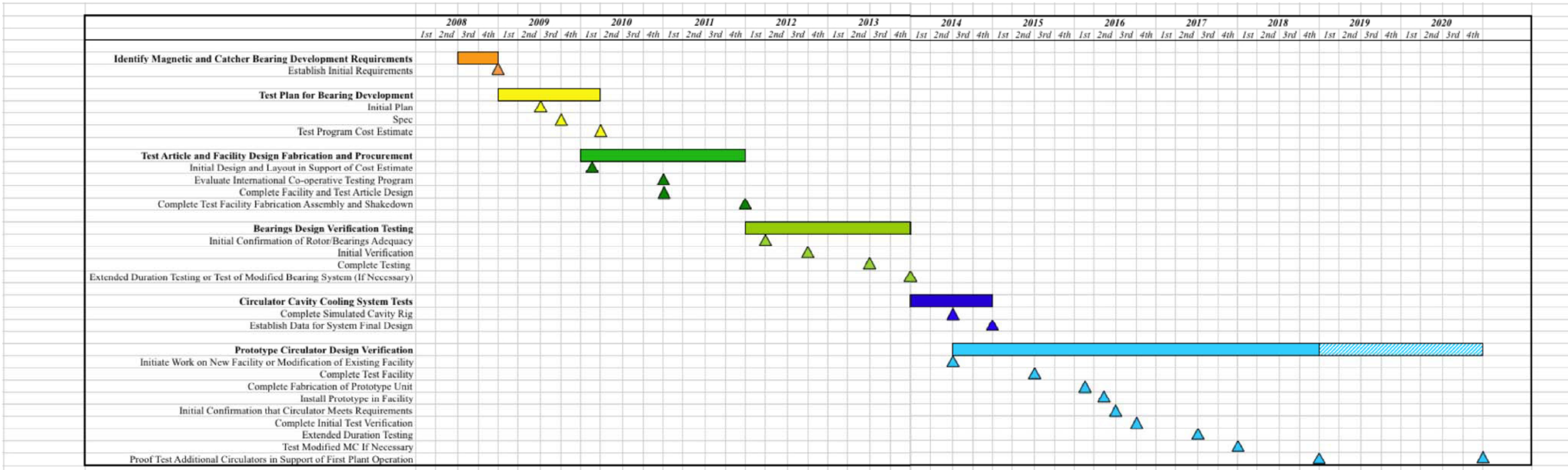

Figure 8-1. NGNP Helium Circulator Test Schedule

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