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

Test Plan - Steam Generator for 750°C Reactor Outlet Helium Temperature

Prepared by General Atomics
For the Battelle Energy Alliance, LLC

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ACRONYMS

ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CTF	Component Test Facility
DDN	Design Data Need
DOE	U.S. Department of Energy
FSH	Finishing Superheater
FSV	Fort Saint Vrain
GA	General Atomics
GT-MHR	Gas Turbine Modular Helium Reactor
HTGR	High-Temperature, Gas-Cooled Reactor
HTTR	High Temperature Test Reactor
INL	Idaho National Laboratory
NGNP	Next Generation Nuclear Plant
MHR	Modular Helium Reactor
MHTGR	Modular HTGR
MTS	Material Testing Solutions
NP-MHTGR	New Production Modular HTGR
ORNL	Oak Ridge National Laboratory
SG	Steam Generator
THTR	Thorium High-Temperature Reactor
TRD	Tube Retention and Wear Protection Device
TRL	Technology Readiness Level

1 INTRODUCTION

1.1 Scope

This Test Plan provides a high-level description of a test program to support design, fabrication, and deployment of a steam generator (SG) for the Next Generation Nuclear Plant (NGNP). Startup of the NGNP is currently scheduled for 2021. The described activities are those that are seen at this time as necessary to advance the Technology Readiness Level (TRL) of the SG from its current level to the level required prior to hot startup of the NGNP.

This Test Plan is applicable to an SG for the plant configuration shown in Figure 1, which General Atomics (GA) selected as its preferred configuration for the NGNP following the decision by the NGNP Project in October 2008 to lower the reactor outlet helium temperature from 900°C - 950°C to 750°C - 800°C.

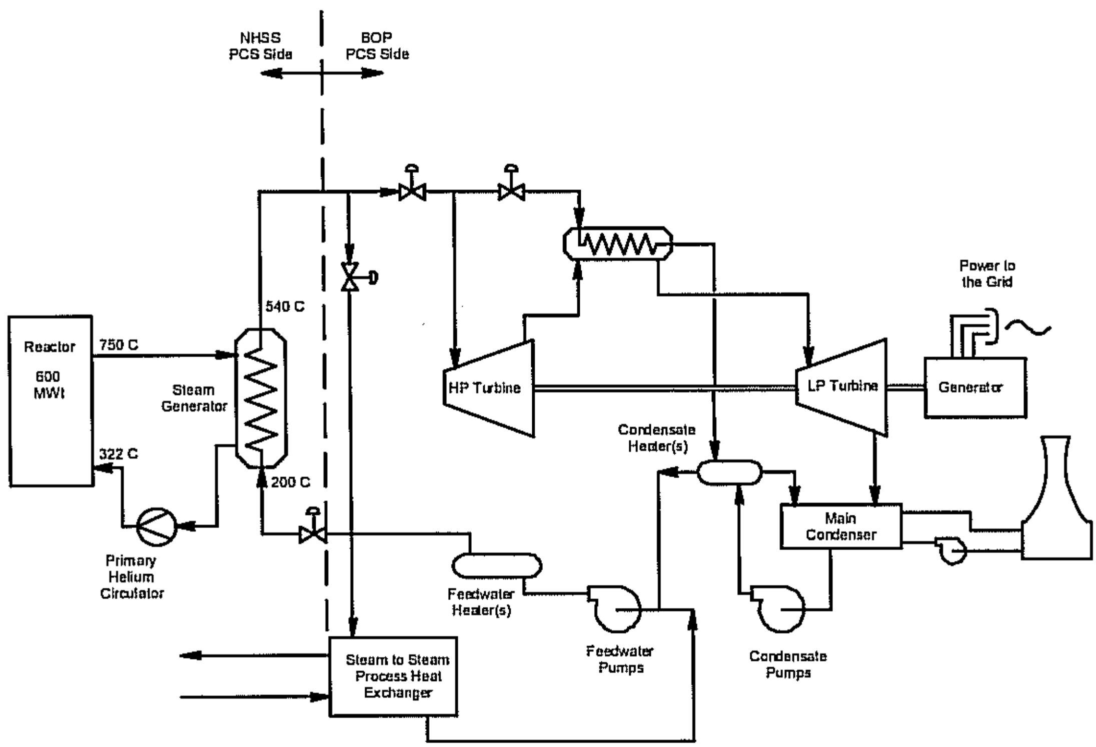

Figure 1. NGNP Configuration for Technology Development Roadmapping

GA has assigned a TRL of 4 [TDRM 2009] to the 750°C SG primarily because (1) the Fort St. Vrain (FSV) reactor experience has demonstrated the basic helical-coil SG thermal and hydraulic design and the SG material selections, and (2) the level of SG design definition already available from the MHTGR Program. As previous presented in GA Test Plan 911142 [Test Plan 2008], the technology development activities to advance the TRL from 4 to 8 are essentially the same for the 750°C and 950°C SG designs, although the specifics of the design support and verification tests would be somewhat different. In this test plan, the design support tests described for the SG are specific to the 750°C SG and are based on the SG design support plan presented in document DOE-HTGR-88131 [DS Plan 1990].

1.2 Background

1.2.1 Steam Generator Design Description

Helical tube SG designs have been used for several decades and have exhibited satisfactory performance in FSV and the Thorium High-Temperature Reactor (THTR). It is expected that the design of the SG(s) for the NGNP will be similar to the SG design for the MHTGR. This SG was designed as a single once-through unit as opposed to a series of individual modules operating in parallel. Figure 2 shows a cross section of the MHTGR SG.

In this design, steam is generated by passing the hot primary helium coolant over a system of helically-coiled tubes contained in a vertically-oriented enclosure vessel. The helium is circulated through the system by an electric motor-driven, single-stage circulator. Hot helium leaving the reactor vessel flows into the central duct of a coaxial cross duct that connects the reactor vessel to the SG vessel. This center duct, which is called the hot duct, connects directly to the inlet of the SG. Helium discharged from the SG flows upward through an annular space between the tube bundle shroud and the SG vessel wall back to the inlet of the primary helium circulator located at the top of the vessel. Helium discharged from the circulator is ducted back to the reactor inlet through the annular outer region of the cross duct.

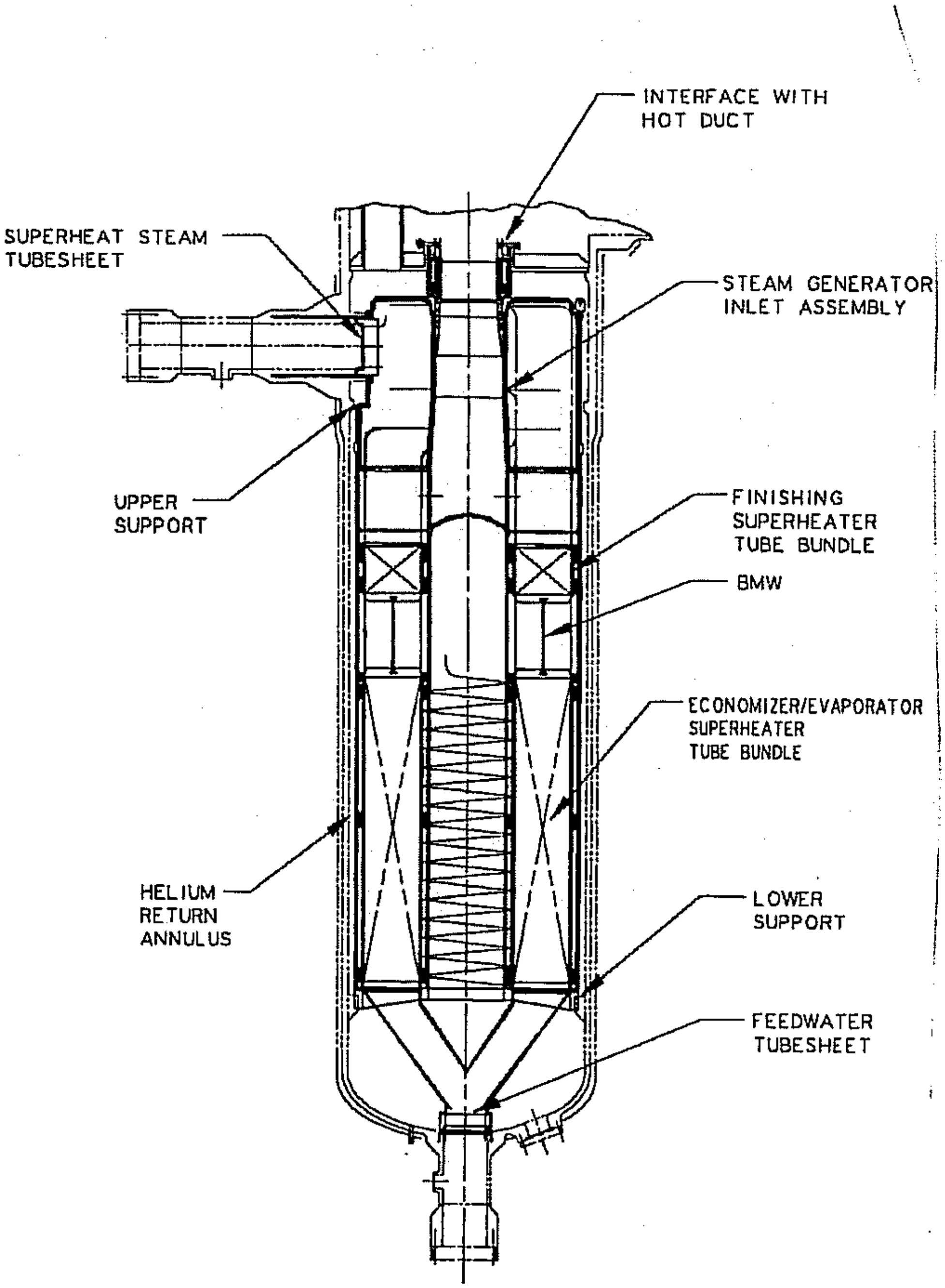

Figure 2. MHTGR Steam Generator Design

Table 1 lists the principal design conditions for the 350-MWt version of the MHTGR SG.

Table 1. Design Conditions for the MHTGR Steam Generator

Helium Flow Rate (kg/sec)	157.2	Main Steam Flow Rate (kg/sec)	121
Primary Coolant Delta-P (kPa)	34.5	Main Steam Pressure (Mpa)	17.3
Primary Coolant Pressure (MPa)	6.4	Feedwater Temperature (°C)	193
Thermal Capacity (MWt)	350	Main Steam Temperature (°C)	541
Helium Inlet Temperature (°C)	687	Reheat Steam Pressure (MPa)	None
Helium Outlet Temperature (°C)	259	Reheat Steam Temperature (°C)	None

The MHTGR steam generator assembly is approximately 4.1 meters (13.45 ft.) in diameter and 10.3 meters (33.78 feet) in length.

The heat transfer surfaces of the SG include an evaporator-economizer section in the lower portion of the enclosure vessel, and a finishing superheater section in the upper portion. There is no provision for a reheater section. In the short space between the evaporator-economizer section and the finishing superheater section, the steam tubes are oriented vertically. The bimetallic weld between the two heat-transfer sections is located in these vertical tubes. The specified materials of fabrication are Alloy 800H for the superheater section and 2¼Cr-1Mo steel for the evaporator-economizer section. In both sections, the steam is designed to flow counter-current with respect to the primary helium coolant, thus resulting in "uphill" boiling.

As with the FSV SGs, provision is made in the system design to allow for a rapid steam-water dump of the steam generator contents to minimize water ingress to the primary coolant in the event of a large tube leak. Simultaneously, the feedwater and steam lines are also immediately isolated during such an event.

1.2.2 Design Data Needs

The design data needs (DDNs) for the MHTGR SG are provided in [DS Plan 1990], which also provides a plan that outlines design support tasks to satisfy the DDNs. Table 2 summarizes the DDNs and the proposed design support tasks. It was intended that all of these tasks would be completed by the end of MHTGR preliminary design.

Table 2. MHTGR Steam Generator DDNs and Design Support Tasks

DDN No.	Title	Required Data	Design Support Task
M.13.02.01	Corrosion Testing	Assess secondary side corrosion characteristics of the bimetallic weld and Alloy 800H base metal	Corrosion testing of bimetallic weld and Alloy 800H tube material in a test loop with prototypical MHTGR environment
M.13.02.02	Testing of 2¼Cr – 1Mo Material	Testing of mechanical properties of 2¼Cr – 1Mo in a prototypical MHTGR environment	Testing of material in an MHTGR type environment to generate mechanical properties data in a format comparable to ASME Code Case N47 data
M.13.02.03	Testing of Alloy 800H Material	Testing of mechanical properties of Alloy 800H in a prototypical MHTGR environment	Testing of material in an MHTGR type environment to generate mechanical properties data in a format comparable to ASME Code Case N47 data
M.13.02.04	Tube Bundle Acoustic Test	Frequency spectra and sound pressure levels generated by tube bundle	Scale acoustic mockup of SG
M.13.02.08	Airflow Test	Helium inlet flow distribution as a function of inlet distribution device configuration. Thermal mixing characteristics of inlet region	Wind tunnel/airflow test of ¼ scale model of inlet region
M.13.02.10	Insulation Verification Test	Frequency response of selected insulation attachment and cover plate designs to acoustic and flow induced loads	Specialized testing and/or incorporate with acoustic test
M.13.02.11	Vibration Fretting Wear and Sliding Wear Protection Tests	Wear data for candidate wear protection material/support material combinations to be used for the tube wear protection devices	Bench testing in autoclave to simulate vibration, fretting, and sliding wear under prototypical loads and environment
M.13.02.12	Tube Wear Protection Device Tests	Verification of loading capability of the tube retention device under prototypical loading and thermal environment	Fabricate samples of tube retention devices, install on tubes, and perform load tests
M.13.02.07	Large Helical Coil Test	Tolerance characteristics of as-bent and as-installed helical coils: preliminary definition of installation procedures	Fabricate prototypical helical coils and install in simulated support structure
M.13.02.14	Lead-in, Lead-out, Expansion Loop Mockup Test	Determine space envelope requirements, support configurations, and natural frequency ranges	Fabricate prototypical lead-ins, lead-outs, expansion loops and install in a mockup
M.13.02.15	Flow Induced Vibration Test	Fluid-elastic response characteristics of helical tube bundle and lead-out tubes	Scale wind tunnel/airflow test of helical bundle with appropriately scaled geometry

2 APPLICABLE DOCUMENTS

Table 3. Applicable Documents

Document Number	Title
DOE-HTGR-88131, Rev. 2	MHTGR Steam Generator Design Support Plan
CEGA-002712	NP-MHTGR Engineering Development Plan
GA-D15443	Criteria for the Design and Operation of Steam Generators for High-Temperature Gas-Cooled Reactors
ANL/EXT-06/46	Preliminary Issues Associated with the Next Generation Nuclear Plant Intermediate Heat Exchanger Design, ANL Nuclear Engineering Division, September 2006
NUREG/CR-6816	Review and Assessment of Codes and Procedures for HTGR Components, ANL, US NRC, July 2003.
INL/EXT-06-11701	Next Generation Nuclear Plant Materials Research and Development Program Plan, INL, September 2007.
911120/0	NGNP Steam Generator Alternatives Study, General Atomics Document 911120, April 2008
INEEL/EXT-05-00758	Next Generation Nuclear Plant Materials Research and Development Program Plan, September 2005
INL/EXT-06-11750	Summary of Studies of Aging and Environmental Effects on Inconel 617 and Haynes 230, September 2006
INL PLN-2804	Next Generation Nuclear Plant Intermediate Heat Exchanger Materials Research and Development Plan, April 2008
911142/0	Test Plan-Steam Generator Helical-Coil Design
PC-000586/0	Technology Development Road Mapping Report for NGNP with 750°C Reactor Outlet Helium Temperature

3 TRL 4 TO 5 – STEAM GENERATOR DESIGN AND ANALYSIS

3.1 Activity Description

As discussed in Section 1.2, it is expected that the design of the SG(s) for the NGNP will be similar to the SG design for the MHTGR. However, the NGNP reactor power level and operating conditions will likely be different than those for the MHTGR, and the impact of these differences on the MHTGR SG design must be assessed. The steam generator analysis effort includes (but is not limited) to the following:

- Thermal sizing for design operating conditions at 100% power
- Evaluation of the steady state pressure drop
- Structural evaluation of the various components including the tubes, and the tube support method

Also, a review of the DDNs defined for the MHTGR SG (and assumed herein to be applicable to the NGNP SG) must be performed to determine their applicability in view of any SG design changes and advances in SG technology that have occurred since the MHTGR SC design and DDNs were developed in the late 1980's.

3.2 Deliverables

The SG design and analysis activity will result in the following deliverables

- A conceptual design for the NGNP SG
- A revised set of DDNs for the NGNP SG
- A design support and verification plan that is responsive to the NGNP SG DDNs

3.3 Cost and Schedule

This activity will start early in NGNP conceptual design and will take about two years to complete. The cost is estimated to be about $3M.

4 TRL 5 TO 6 – DESIGN SUPPORT TESTING

With the NGNP reactor outlet helium temperature of 750°C the materials used in past HTGR SG designs (see Section 1.2.1) can be used for the NGNP SG. The materials-related testing described in this section is specific to a maximum temperature of 750°C.

4.1 Materials Properties Testing including Bimetallic Weld

4.1.1 Test Objective

Generate the test data needed to satisfy DDNs M.13.02.01, M.13.02.02, and M.13.02.03 (see Table 2 in Section 1.2.2). Specifically, data is needed to confirm the mechanical properties of 2¼Cr-1Mo and Alloy 800H base metals and their weldments in a format comparable to the *ASME BPVC-III NH - 2007 BPVC Section III Rules for Construction of Nuclear Facility Components-Division 1 Subsection NH Class 1 Components in Elevated Temperature Service* (Formerly Code Case N-47) data. Corrosion test data is also needed to assess the secondary-side corrosion characteristics of the bimetallic weld and Alloy 800H base metal.

4.1.2 Test Description

For the candidate materials, studies to be conducted include:

- Conduct literature search and compile data to compare to the *ASME BPVC-III NH - 2007 BPVC Section III Rules for Construction of Nuclear Facility Components-Division 1 Subsection NH Class 1 Components in Elevated Temperature Service* (Formerly ASME Code Case N-47) values.
- Identify the limitations of the existing material data and develop the details of the necessary test program.

The testing program will depend on the extent of the existing materials data; however, it is anticipated that the necessary testing will include:

- Testing to determine fatigue strength for tensile and bending loading conditions
- Testing of joining techniques for the tubing material
- Testing to determine creep rupture, low-cycle fatigue, fracture toughness, and stress corrosion cracking. Corrosion properties should be considered for exposure to helium and exposure to water/steam.

A more complete listing of the required materials property data are given in Section 1.4 of DDNs M13.02.01, M.13.02.02, and M13.02.03.

4.1.3 Test Conditions

The required data and test conditions are given in Section 1.4 of DDNs M.13.02.01, M.13.02.02, and M.13.02.03, which are subject to revision based on the results of the current data base evaluation. These DDNs are available in [DS Plan 1990]. The mechanical properties of 2¼Cr-1Mo and Alloy 800H should be obtained in helium with impurity levels of 2 ppmv H_2O, 7 ppmv $CO+CO_2$, 10 ppmv H_2, 2 ppmv CH_4, and 10 ppmv N_2 (subject to confirmation as being appropriate for NGNP). The corrosion testing per DDN M.13.02.01 must be performed under conditions that are representative of NGNP operating conditions and feedwater chemistry.

4.1.4 Test Configuration

Pull-test servo-hydraulic devices, such as an MTS, with test specimen in heated chamber or with heater blanket will be used to determine strain, tensile strengths, fracture toughness, 3-point bending behavior, fatigue crack growth, and crack arrest measurements in accordance with the procedures of [ASTM STP 1210]. A Tinius-Olsen Charpy impact machine will be used to determine crack propagation. The test configurations will be further defined by the test facility in order to fully characterize the candidate materials at operating conditions.

4.1.5 Test Duration

Approximately 3 years

4.1.6 Test Location

Test facilities as well as material manufacturers are listed below.

FACILITY:	**ARGONNE NATIONAL LABORATORY, Nuclear Engineering Division** **Engineering Development & Applications Department** http://www.ne.anl.gov/activ/cap_mt.html
ADDRESS:	9700 South Cass Ave. Argonne, IL 60439-4814
CONTACT:	Section Manager: K. Natesan Fax: +1 630-252-3604 natesan@anl.gov
CAPABILITIES:	• Environmentally Assisted Cracking (EAC) of Reactor Materials • Corrosion Performance/Metal Dusting • Irradiated Materials • Steam Generator Tube Integrity

FACILITY:	**HAYNES INTERNATIONAL, INC., manufacturer of Haynes 230** **Research and Technology Group** **Haynes International Processing Laboratory** http://www.haynesintl.com/ http://www.haynesintl.com/RTGLabEquipment.htm
ADDRESS:	1020 West park Avenue PO Box 9013 Kokomo, Indiana 46904-9013 USA
CONTACT:	Roger Cash, Process Lab Supervisor 765-456-6246 Fax: 765-456-6905 rcash@haynesintl.com
CAPABILITIES:	Services of the Research & Development Laboratories within the Technology Department include: • Metallographic Lab • Scanning Electron Microscopy Lab • Mechanical Test and Wear Lab • Corrosion and High Temperature Test Labs • Welding Lab.

FACILITY:	**SPECIAL METALS, manufacturer of INCONEL 617 and INCOLOY ALLOY 800H** http://www.specialmetals.com/index.php
ADDRESS:	3200 Riverside Drive Huntington, West Virginia 25705
CONTACT:	Phone 1.304.526.5447 Fax 1.304.526.5973
CAPABILITIES:	IncoTest®, a division of Special Metals, offers independent and confidential contract analysis and metals testing programs. The laboratory facilities offer a comprehensive range of analytical, mechanical, physical, corrosion, NDT and metallographic testing and sample preparation services. Mechanical testing includes: • Creep and stress rupture • Fatigue and fracture toughness • Tensile and compression testing up to 1200°C Metallography Testing Physical Testing includes: • Thermal expansion up to 1000°C • Dynamic Young's and shear modulus • Magnetic Permeability • Foil emission and absorbtivity • Bash and Harsch accelerated life testing • Thermoelectric EMF • Electrical resistivity and resistance Corrosion Testing

FACILITY:	**ASTON METALLURGICAL LABORATORIES** http://www.astonmet.com/
ADDRESS:	200 Larkin Drive Wheeling, IL 60090-6498
CONTACT:	Alan Stone Phone 888-ASTON10 (888-278-6610) Fax 847-353-8204
CAPABILITIES:	Microstructural analysis capabilities and digital image analysis capabilities are extensive. Metallurgical testing capabilities include: • Microhardness Testing Knoop and Vickers down to 1 gram loads • Case Depth • Decarburization • Effective Case Depth • Nitride Case Depth • Corrosion Testing • Photomicrography • Macro Etching and Macro Ratings Corrosion testing capabilities include: • Stress Corrosion Cracking • Pitting • Galvanic Reactions • Intergranular • Erosion • Microbiological Attack • Electric Current Loops • Hydrogen Embrittlement • Oxidation • Dezincification • Sensitization • Metal dusting • Stray current fields

FACILITY:	**CC TECHNOLOGIES, a DVN Company** http://www.cctechnologies.com/labs/index.htm
ADDRESS:	5777 Frantz Road Dublin, Ohio 43017-1386
CONTACT:	Luis Garfias Luis.Garfias@dvn.com Phone 614-761-1214 • Fax 614-761-1633
CAPABILITIES:	• Corrosion Testing • Failure Analysis • Metallurgy & Materials Science • SEM Services • TEM Services • DC Techniques Electrochemical Testing • AC Techniques Electrochemical Testing • Environmentally Assisted Cracking • Fatigue & Fracture Assessment • Coating Testing • Inhibitor Testing & Monitoring • Elastomer Selection & Testing • Non-Metallic Materials • H2S Corrosion Testing • Autoclave Testing • High Temperature Materials Evaluation • Multiphase Flow & Corrosion System • Generator Winding Insulation and Electrical Lead-Out Measured Parameters

4.1.7 Required Data

See Sections 4.1.2 and 4.1.3.

4.1.8 Test Evaluation Criteria

The material test data gathered from previous test programs and the testing performed per DDN M.13.02.02 and M.13.02.03 in this program must be sufficient to provide confirmation that exposure to the primary loop helium coolant will not degrade the mechanical properties of the 2¼Cr-1Mo and Alloy 800H materials and weldments below the ASME CC N-47 values. The data obtained from the testing performed per DDN M.13.02.01 must be sufficient to quantify the secondary side (tube side) corrosion characteristics of the bimetallic weld and Alloy 800H material under representative NGNP operating conditions and feedwater chemistry.

4.1.9 Test Deliverables

A final Test Report shall be provided. The Test Report should include:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

4.1.10 Cost, Schedule, and Risk

The estimated overall cost and schedule data is shown in Table 6 and Figure 5 in Section 7. The SG material properties testing is included in the "Materials Testing" activity.

4.2 Flow-Induced Vibration Test (DDN M.13.02.15)

4.2.1 Test Objective

The objectives of the flow-induced vibration testing are:

- Determine frequency spectra and sound pressure levels generated by tube bundle as a function of flow velocities and geometry.
- Determine that the helium flowing across the tube bundle will not cause dynamic instabilities.
- Confirm that unacceptable flow induced vibrations that can cause severe damage to the tubes will not occur in the helical bundle and lead-out tubes.
- Determine flow-induced vibration characteristics of the helical tube bundle and the lead-out tubes.

4.2.2 Test Description

The flow-induced vibration test should represent geometric similitude to the full-scale SG. The helical tube bundle is obviously important to determine turbulent buffeting, vortex shedding, fluid elastic instability, and acoustic resonance emission. The lead-in and lead-out tube array and support plates are also important to model in the test.

4.2.3 Test Conditions

An SG ¼-scale model should be built including tube bundle, shrouds, flow baffles or shields. The model will simulate the specific array characteristics, geometry, and shell-side fluid flow conditions. The model only needs to simulate the conditions at the hot end of the helical tube bundle which are considered to be the most susceptible to the flow-induced vibration. The shell side should be simulated as:

- Temperature: 260°C to 700°C
- Pressure: 918 psia
- Gap velocities: 25 ft/sec to 42 ft/sec
- Reynolds number: 20,000 to 31,000
- Speed of sound: 4450 ft/sec to 6000 ft/sec

4.2.4 Test Configuration

A wind tunnel with flowing air at ¼-scale may be used. The speed of sound in air is about one-fourth the speed of sound in helium, so the model may be ¼-scale to match sound wave velocity. The details of the test configuration will be determined by the testing organization to best represent the SG geometries, including the lead-in and lead-out tubes and support plates.

4.2.5 Test Duration

Approximately one year

4.2.6 Test Location

The Flow-Induced Vibration Test Facility (FIVTF) at Argonne National Laboratory (ANL), Components Technology Division, had water-flow facilities including pump capacities of 500, 1000, 2500, and 4000 gpm [ANL FIVTF]. For the air flow tests outlined here, it is recommended to contact ANL to inquire about what air flow test facilities exist at ANL. As with other national laboratory and private industry test facilities, the capabilities may have been reduced or eliminated during the last decade(s). Other potential test facilities include, but are not limited to NTS and Wyle Laboratories (see Section 4.4.6).

4.2.7 Required Data

Temperature, pressure, test frequency spectra, measured resonant frequencies, and sound pressure levels as a function of flow velocities and geometry variations should be recorded. Specifically, the input air flow velocities and sensor output data measuring frequency response spectra of internal SG structures are needed. Visual data may also be needed to witness vortex shedding behavior. Pressure measurements may be needed to determine buffeting response.

All of this information is needed to verify lack of destructive acoustic energy, thus requiring the need for geometry modifications or baffling.

4.2.8 Test Evaluation Criteria

The data should verify that operational frequencies are not close to the resonance frequencies predicted by analysis.

4.2.9 Test Deliverables

A final Test Report shall be prepared. The Test Report should include:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing.

4.2.10 Cost, Schedule, and Risk

The estimated overall cost and schedule data is shown in Table 6 and Figure 5 in Section 7. The cost and schedule considerations for flow-induced vibration are included in the "Air Flow Testing" activity.

If the testing is not performed, it will be necessary to rely on computer modeling; however, this involves a higher level of risk. If a modeling-only approach is taken, the modeling effort should verify that large sheet metal plates have been properly supported or gusseted as determined by modeling and subsequent vibration analysis.

4.3 Air Flow Test (DDN M.13.02.08)

4.3.1 Test Objective

The objectives of the air-flow testing are:

- To determine if the primary coolant flow entering tube bundle will have hot/cold streaking and/or velocity non-uniformities. Velocity and temperature profiles of primary coolant flow as it enters the finishing superheater (FSH) should be experimentally observed.
- Approximate elevation in tube bundle where velocity profile becomes uniform.

- Measure stagnation pressure losses from the cross duct exit to the entrance of the FSH tube bundle.
- Develop flow distribution device(s) in the SG inlet region which establishes acceptable flow distribution into the FSH tube bundle. Verify that the selected flow distribution device(s) satisfies design requirements and/or assumptions.
- Determine flow mixing characteristics at SG inlet and FSH tube bundle.

4.3.2 Test Description

The flow velocity and temperature entering the SG are specified at the inlet. Performance calculations have demonstrated the sensitivity of the SG to non-uniform velocity and temperature conditions and have shown the need for correction of the inlet flow to achieve more uniform conditions at the FSH tube bundle. Correction of inlet flow will allow for the SG to operate within design limits.

The SG inlet region consists of an entrance interface with the hot duct elbow followed by a conical duct which leads into the top end of the FSH tube bundle. The incoming temperature distribution may be unacceptable relative to design limits/assumptions. The temperature and flow data will provide the velocity and temperature distribution and the mixing characteristics of the SG inlet region and FSH bundle. The test data will confirm the need for a mixing device to assure SG flow distribution.

The test model will simulate a SG inlet region with a full-scale airflow test model.

4.3.3 Test Conditions

Flowing air for cross duct Reynolds Number in the range $1.25x10^6$ (25% power) < Re < $3.65x10^6$ (100% power) in similar physical configurations.

4.3.4 Test Configuration

Air flow thermal testing should model the SG inlet and FSH with instrumented hardware for test post-processing. A concept of the test configuration is shown in Figure 3. The air flow test stand shall have the ability to inject uneven inlet flow. Flow mixing devices should be removable such that different configurations may be tested.

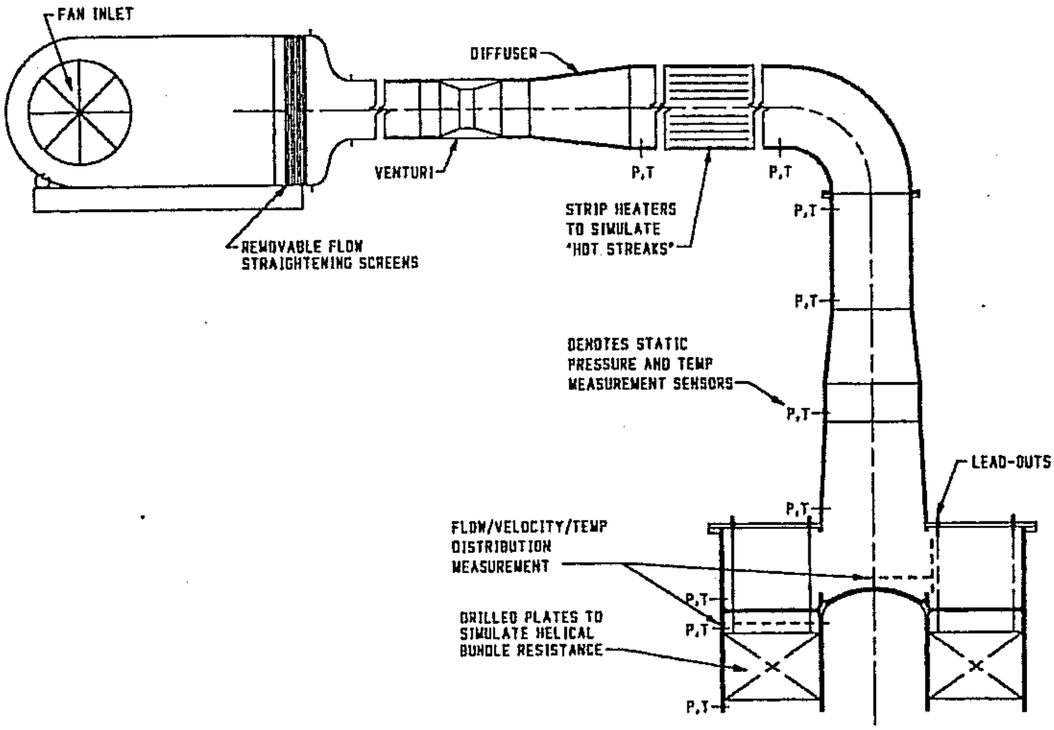

Figure 3. Air Flow Test Section Concept

4.3.5 Test Duration

Approximately one year

4.3.6 Test Location

It is assumed that the air-flow testing can be performed at the same test facility as the flow-induced vibration testing (see Section 4.2.6).

4.3.7 Required Data

Primary coolant velocity, temperature, and stagnation pressure at inlets and outlets of the eccentric duct and the FSH tube bundle. The temperature, velocity/pressure distributions, and flow visualization information will be gathered with and without flow distribution devices over a range of bulk flow rates. The mixing characteristics of the inlet region and FSH will be determined.

4.3.8 Test Evaluation Criteria

The test data will be compared against predicted values to determine if temperatures, pressures, and flow rates are comparable. The test results should confirm the SG thermal/hydraulic analysis, or be used to correct the analytical model.

4.3.9 Test Deliverables

A final Test Report shall be prepared. The Test Report should include:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

4.3.10 Cost and Schedule

The overall estimated cost and schedule is shown in Table 6 and Figure 5 in Section 7. The air flow tests are included in the "Air Flow Testing" activity.

4.4 Insulation Verification Testing (DDN M.13.02.10)

Thermal insulation will blanket the SG to minimize heat losses and to limit structural temperatures to design values. Typically, the insulation is a ceramic fiber contained by metallic cover plates. The general test approach is to fabricate prototypical sections of the thermal barrier and subject the sections to acoustic and other vibratory input to determine frequency response to verify fatigue life assumptions as well as thermal and structural performance. Insulation verification is proposed in this test plan as an independent test. As test planning advances, insulation verification may be incorporated into acoustic test or air flow testing.

4.4.1 Test Objectives

The objectives of the insulation verification testing are:

- Verify the thermal and mechanical performance of insulation installed in the SG primary loop subjected to thermal, structural, vibration, acoustic, and helium flow environments.

- Determine if thermal cycling or flow/thermal gradients will affect the life span of the chosen fibrous insulation, which is expected to last the 60-year lifetime of the plant. A breakdown in insulation would lead to greater heat load to insulated component.

4.4.2 Test Description

Testing will be performed to determine the frequency response of selected insulation attachment and cover plate designs to acoustic and flow induced loads. The insulation shall be installed in a helium test loop, possibly while other components are helium tested. Insulation material samples will be taken from the test setup for thermal, wear, and lifespan analysis.

4.4.3 Test Conditions

Insulation will be installed in a helium environment for the entire plant lifespan and be subject to thermal cycling. The service conditions for the insulation are:

- He temperatures: 260°C to 750°C helium temperatures
- Duration: 450,000 hours (~60 years) expected service life

Vibration frequencies, acoustic sound pressure, sliding contact forces, and flow velocities should be evaluated, if expected to have an impact on insulation performance. The test conditions for an accelerated life-cycle test that simulates the NGNP service conditions will be defined by the reactor designer working with the testing organization.

4.4.4 Test Configuration

The test configuration will be defined by the testing organization working with the reactor designer and the insulation vendor.

4.4.5 Test Duration

Approximately one year has been assumed in the schedule in Figure 5 in Section 8; however, this is highly uncertain (see Section 5.4.3)

4.4.6 Test Location

A large, diverse environmental testing facility is recommended to perform the insulation testing. NTS offers many facility locations throughout the United States, with their nuclear power division in Massachusetts. Wyle Laboratories is another possible test location. Information for NTS and Wyle Laboratories is presented below.

FACILITY:	**NATIONAL TECHNICAL SYSTEMS** **NTS Power Products Group** http://www.ntscorp.com/about/locations/acton/
ADDRESS:	533 Main Street Acton, MA 01720
CONTACT:	Phone 978-263-2933 Fax 978-263-5734
CAPABILITIES:	NTS provides integrated engineering services and technical solutions, product testing and design for compliance, regulatory standards compliance testing and evaluation, project management, technical resources, engineering solutions and managed services. NTS is globally accredited by many leading regulatory agencies. NTS has testing laboratories and engineering services offices located in North America, Europe and Asia. NTS is the largest independent testing laboratory in the world. NTS offers nuclear utilities and suppliers worldwide superior customer service in the provision of a full range of engineered services. Testing, equipment qualification, commercial grade dedication, engineering, component supply and field services are provided under our NUPIC and NIAC audited 10CFR50 Appendix B quality program. As the largest independent test laboratory in the U.S., NTS offers the broadest range of nuclear environmental testing. State-of-the-art facilities and capabilities for safety-related qualification and dedication including: • Equipment Qualification to IEEE-323 (Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations) • Seismic simulation to 35,000 lbf, single axis, dependent biaxial, and independent triaxial to IEEE-344 (Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations) • Vibration aging and fatigue studies, up to 40,000 lbf • EMI/EMC testing and analysis to EPRI TR-102323 (Guidelines for Electromagnetic Interference Testing in Power Plants) and Regulatory Guide 1.180 (Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems) • Software V & V to IEEE Standard 7-4.3.2 (Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations) • Materials identification and testing • Mechanical aging • Normal or accident radiation exposure • Reliability simulation, and evaluation (MTBF) • Thermal aging testing and analysis • Vacuum testing, leak detection • Climatics: temperature, humidity, salt, sand, dust, solar radiation and fungus • Finite Element Analysis, ANSYS, NASTRAN, Super Sap • Nuclear steam accident, LOCA, HELB to 600°F (315°C) / 300 psi

FACILITY:	**WYLE LABORATORIES**
ADDRESS:	128 Maryland St. El Segundo, Ca 90245
CONTACT:	Phone: 310-563-6662 E-mail: john.shimada@wylelabs.com
CAPABILITIES:	Wyle Laboratories is headquartered in El Segundo, Calif. and employs approximately 4,200 employees at more than 40 facilities nationwide. Wyle is one of the nation's leading providers of specialized engineering, scientific, and technical services to the Department of Defense, NASA, and a variety of commercial customers. Wyle has been designing and building unique test fixtures, equipment and entire test facilities for industry and government use for more than 50 years. These facilities include centrifugal and linear accelerators, vibration systems with up to six axes of motion, high intensity acoustic chambers, dynamic shock devices like crash barriers, plus rail dynamics test facilities and numerous combined-environment test systems. In the nuclear sector, Wyle has qualified more equipment than anyone else in the industry.

4.4.7 Required Data

'Reflective' value for insulation thermal performance should be measured and incorporated into designers' thermal calculations (perhaps 'R' value is transient dependent upon insulation lifetime). Insulation degradation due to helium and wear should be measured as percent lost in either material thickness or density.

4.4.8 Test Evaluation Criteria

Determine if insulation will perform as expected when thermally insulating external areas from zones of greatest temperature. Determine if insulation 'R' values are maintained and, if not, it is sufficient for SG lifespan.

4.4.9 Test Deliverables

A final Test Report shall be prepared. The Test Report should include:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data

- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

4.4.10 Insulation Verification Test Cost, Schedule, and Risk

The overall estimated cost and schedule is shown in Table 6 and Figure 5 in Section 7. The insulation test is included in the "Insulation Testing" activity.

If testing is not completed, it will be necessary to rely only on analytical results; however, this will entail a higher level of risk. This would require the design effort to include additional insulation to be conservative. However, the critical thickness of insulation, R_o, may be exceeded with too much insulation [Heat Transfer].

4.5 Tube Coil/Threading Fabrication (DDN M.13.02.07)

4.5.1 Test Objective

The test objective is to determine the feasibility of coiling and treading multiple tubes in concentric coils through holes in support plates to make the SG helical coil. Clearances between tubes and sheet metal, wear protection hardware, fabrication time, tube coil rejection rate due to tolerance selection shall be determined.

4.5.2 Test Description

Full-scale SG tubing will be coiled and threaded through the drilled plate support structures to determine ease of fabrication and assembly.

4.5.3 Test Conditions

This test is to verify the ability to fabricate, within tolerance, and assemble the SG internals. The drilled plate support structure must also satisfy thermal expansion limits and seismic design, which are verified through analysis and other testing.

4.5.4 Test Configuration

Full-scale hardware components of tubing and drilled plate support system are needed to be fabricated and installed according to design.

4.5.5 Test Duration

Approximately one year

4.5.6 Test Location

The tube coiler's facility and/or the drilled support structure fabrication facility would be sufficient for such testing. When tube coilers are identified, pursue in parallel the accompanying facilities to perform the integration of the coiled tubing and the support structures. Note that tube bending and tube coiling are different fabrication techniques. There are tube benders in most cities that have an industrial machine shop base. However, a search for a tube coiler may be nationwide. One such tube coil fabricator is Azusa Pipe and Tube Bending in Azusa, California.

FACILITY:	**AZUSA PIPE AND TUBE BENDING** http://www.azusabending.com/azusa_pages/capabilities_equipment.html
ADDRESS:	766 N. Todd Ave. Azusa, CA 91702
CONTACT:	Phone 626-334-2941
CAPABILITIES:	Equipment and capabilities: • (1ea.) #4 Pines (can bend up to 4" pipe & 4" tube) • (3ea.) #2 Pines (can bend up to 2" pipe & 2-1/2" tube) • (1ea.) Pines Press Bender (press bends up to 1-1/4") • (1ea.) 1400 Pines • (1ea.) Bend Tech Hydraulic Bender • Standard & specialized tool room machinery and equipment • Pipe threading up to 6" pipe • Complete certified welding capabilities

4.5.7 Required Data

Detailed fabrication procedures for handling, coiling; and tube threading should be witnessed. Verify tooling design. Verify tolerances, including tube cross section ellipticity (flattening).

4.5.8 Test Evaluation Criteria

If tubes can be threaded through drilled support structures successfully within tolerances, then the fabrication test is successful. The wear protection hardware should be tested under operating conditions (at temperature in helium environment).

4.5.9 Test Deliverables

Finished fabricated sections of SG such that the ability to fabricate and assemble the overall SG is proven.

4.5.10 Cost, Schedule, and Risk

The estimated cost and schedule data is shown in Table 6 and Figure 5 in Section 7 under the "Fabrication Testing" activity.

The risk of not performing this test is that fabrication time spans may increase to accommodate fabrication technique unknowns. It may be necessary to adopt other support system designs involving simpler manufacturing methods.

4.6 Additional Steam Generator Fabrication Methods Tests

Table 4 includes the individual design support tests grouped in the Additional Fabrication Tests Category and the applicable DDNs.

Table 4. Individual Tests Included with Fabrication Testing

Fabrication-Specific Area	Fabrication Testing
Vibration fretting wear and sliding wear protection (DDN M.13.02.11)	Verify wear protection method for SG tubes that are in direct contact with drilled support plates, including other metal to metal contact areas.
Tube wear protection devices (DDN M.13.02.12)	Verify installation of tube wear protection devices. Verify that devices can survive hot end of tube bundle.
Lead-in, lead-out, expansion loop mock-up (DDN M.13.02.14)	Verify for portions of tubing not included in the tube bundle the spatial envelope, support configurations, thermal movement, and assembly sequence.

4.6.1 Test Objectives

The objectives of the tests are as follows:

Vibration fretting wear and sliding wear tests

- Provide wear data to be used for the tube retention and wear protection devices (TRDs) for candidate wear protection material/support material combinations using prototypical configuration under representative service conditions
- Provide high cycle wear data for selected material combinations and wear coatings for the TRDs using prototypical configuration under representative service conditions
- Based on the test data and analytical predictive model, confirm that the TRD will protect the tubes for the design life of the plant

TRD tests

Test several TRD designs with respect to:

- Ease of installation, installation time, and repeatability
- Magnitude and repeatability of pre-load achieved during installation of candidate TRDs
- Forces required to dislodge the TRDs after creep relaxation at elevated temperature
- Develop necessary tooling

Lead-in and lead-out expansion loop mock-up test

- Develop specific routing and support configurations
- Determine spatial envelope, characteristic thermal movements and interactions of tubes and supports, and the adequacy of clearances to avoid multiple tube interactions

4.6.2 Test Description

The scope of each of the tests is outlined below.

Vibration fretting wear and sliding wear tests

- Preparation of detailed test plan and specification.
- Design and fabrication of test article.
- Design and fabrication of bench test rig.
- Performance of tests.
- Test data analysis and report preparation.

TRD tests

- Prepare detailed test plan and specification
- Design and fabrication of test articles
- Design and fabrication of bench test rig
- Design and fabrication of installation tooling
- Analysis of test articles to predict results
- Performance of tests
- Test data analysis and report preparation

Lead-in and lead-out expansion loop mock-up test

- Prepare detailed test plan and specification

- Design and fabrication of the mockup
- Performance of tests
- Test data analysis and report preparation

4.6.3 Test Conditions

The test conditions for each of the tests will be defined in the detailed test plan and test specification that will be prepared as the first activity in each of the test programs.

4.6.4 Test Configuration

The test rigs required for the various tests will be designed as an early activity in each of the test program. A conceptual design of a test rig for the vibration fretting wear test is shown in Figure 4.

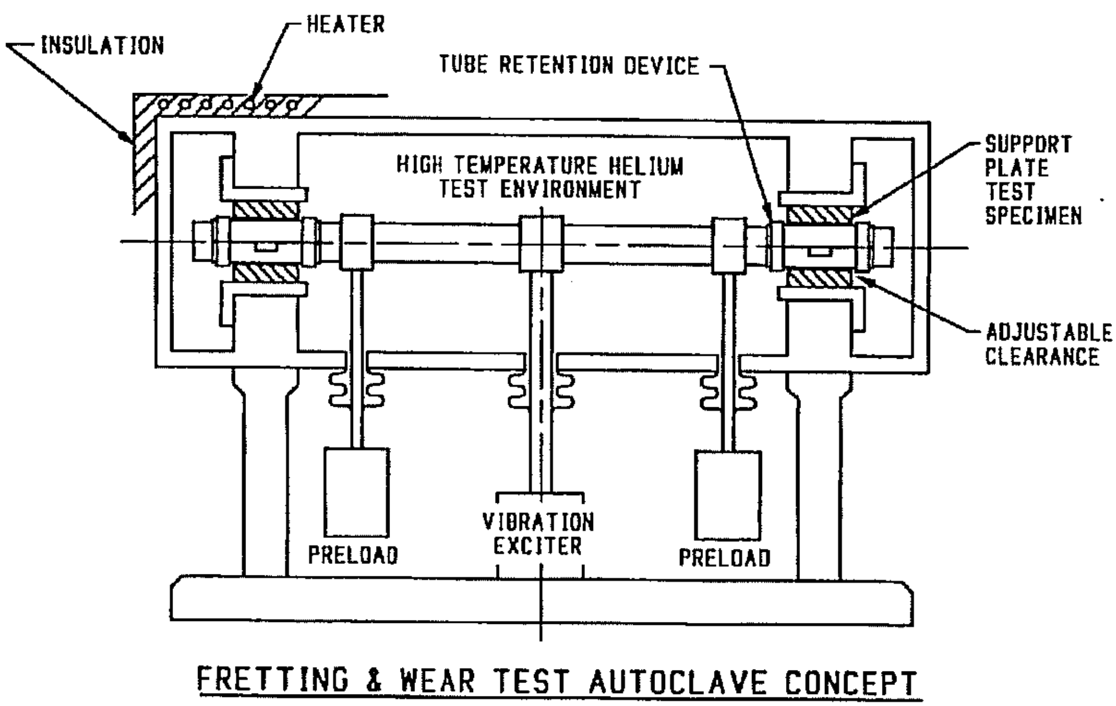

Figure 4. Conceptual design of test rig for vibration fretting wear test

4.6.5 Test Duration

Approximately two years

4.6.6 Test Location

The testing could be conducted at the SG manufacturer's facility and/or at any number of commercial testing laboratories, including the laboratories identified in Section 4.4.6. Various SG fabricators are available to the nuclear industry.

FACILITY:	**FOSTER WHEELER** Global Power Group http://www.fwc.com/publications/pdf/PowerGroupQualificationDocument.pdf http://www.fwc.com/publications/pdf/GlobalPowerGroupBrochure.pdf
ADDRESS:	Perrysville Corporate Park Clinton, NJ 08809
CONTACT:	Phone 908-730-4000
CAPABILITIES:	World-leader in combustion technology that designs, manufactures and installs steam generating and auxiliary equipment for power stations and industrial facilities world-wide

FACILITY:	**BABCOCK AND WILCOX Canada** Nuclear Power Generation Group Construction Operations http://www.babcock.com/products/commercial_nuclear_plant_components/
ADDRESS:	581 Coronation Blvd. Cambridge, ON Canada N1R 5V3
CONTACT:	Phone 519-621-2130
CAPABILITIES:	Have engineered and manufactured more than 1,100 thermal boilers and more than 297 nuclear steam generators, producing in excess of 270,000 megawatts of power for industrial and utility markets around the world.

4.6.7 Required Data

The required data for each of the tests is outlined below.

Vibration fretting wear and sliding wear tests

Data as needed for a data base for analysis to verify that the selected TRDs will meet the following requirements:

- Selected wear protection materials shall withstand prototypical vibration and/or sliding loads for the 60-year design life of the steam generator given the imposed thermal and helium environment
- Unacceptable wear of the interfacing materials shall not occur

TRD tests

Data is needed to verify that the TRD satisfactorily meets the following requirements:

- Ease of mechanical attachment to the tubes
- Repeatable attachment to the tubes
- Satisfactory and repeatable pre-load which does not unacceptably relax at operating temperature
- Seismic load capacity

The data gathered will have an influence on the final selection of the TRD design.

Lead-in and lead-out expansion loop mock-up test

Test data are required to confirm the adequacy of the overall spatial envelope for the assembly as well as the adequacy of the structural support configurations. The test results are expected to provide the designer with information on the SG assembly sequence.

4.6.8 Test Evaluation Criteria

The testing will be successfully completed when the required test data identified in Section 5.6.7 has been obtained and the test objectives as identified in Section 4.6.1 have been met.

4.6.9 SG Fabrication Test Deliverables

A final Test Report shall be prepared fore each of the tests. The Test Report should include:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data

- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

4.6.10 Cost, Schedule, and Risk

The estimated cost and schedule data is shown in Table 6 and Figure 5 in Section 7 under the "Fabrication Testing" activity.

It has been speculated that sliding wear may have caused tube leaks in the FSV steam generator tubes. Testing is the only sure way to assure that sliding wear will not cause SG leaks.

The lead tubes require a unique space envelope and bend pattern. Either testing or computer models are required to assure that the lead tubes will not cause a fabrication problem.

4.7 Inlet Orifice Testing

4.7.1 Test Objective

Steam generator tube inlet orifices are required to assure flow stability. These orifices can be sized via computational methods, but, their pressure drop characteristics must be verified by test.

4.7.2 Test Description

A length of SG tubing with a stability orifice installed will be flow tested to establish the pressure drop loss coefficient for the orifice.

4.7.3 Test Conditions

The test will be performed using water at the design inlet temperature and pressure.

4.7.4 Test Configuration

The test configuration would consist of a length of SG tubing with a stability orifice installed. The test would require a source of water at the design inlet temperature and pressure.

4.7.5 Test Duration

Approximately 2 months

4.7.6 Proposed Test Location

This test could be performed at the General Atomics Test Tower or at any number of testing facilities including those identified in Section 4.4.6.

3550 General Atomics Court
San Diego, CA 92121-1122
(858) 455-3000

4.7.7 Required Data

The following measurements must be made.

- Water Flow Rate
- Water Temperature
- Water Pressure
- Pressure Drop across the orifice

4.7.8 Test Deliverables

A final Test Report shall be provided which includes:

- Detailed discussion of Test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results observations and calculations that were completed throughout the course of testing

4.7.9 Costs, Schedule and Risks

The cost and schedule are shown in Table 6 and Figure 5 in Section 7.

Inlet orifices are required to assure flow stability. If the orifice does not meet the pressure drop requirements as established by analysis, it is possible for an unstable flow condition to exist. Flow instability can lead to tube dry-out and tube failure.

5 TRL 6 TO 7 – STEAM GENERATOR FABRICATION AND TESTING IN AIR

TRL 6 is achieved when all the design support testing described in Section 4 has been successfully completed. TRL 7 is achieved by building and operating the full-scale SG as described in below. It is assumed that the full-scale SG subjected to the testing described herein will be the SG installed in the NGNP; however, this will depend on the available funding and the rigor of testing required for the SG.

5.1 Test Objective

Testing will be performed to observe the following characteristics of the SG:

- Stability
- Pressure Drop
- Vibration and Wear Protection of Tubing
- Handling and Shipping
- Helium Drag Loads
- Hydrostatic Testing
- Gas Seals
- Drainability
- Removability
- Instrumentation
- Secondary Coolant Leakage Limits
- Thermal Barrier
- Thermal Losses
- Inspection Accessibility
- Piping Reaction Loads
- Purge Connections
- Chemical Cleaning Connections
- Steam Temperature Control
- Feedwater Screens
- Weld Testing

5.2 Test Description

A buildup of the entire SG assembly is required. SG components will be manufactured at many facilities and shipped to one central assembly location. In order to test the SG at operating conditions, a natural gas fired combustion turbine will likely supply the required amount of heat. The SG and all of its subsystems shall be operated, first as start-up cold testing.

Instrumentation data will be recorded and reviewed for proper operation. Testing of the SG will start at 50% load and gradually increase to 100% load at steady state.

Tests of specific features, which are included within the testing of the overall SG, are listed in Table 5.

Table 5. Individual Tests within Operational Testing

Fabrication-Specific Area	Fabrication Testing
Instrumentation Attachment Test	Verify that the instrumentation will remain adhered and functional.
Orifice Qualification Test	Verify that no choked flow, excessive acoustic response, or excessive pressure drop occur as a result of orificed tubing.
Inlet Flow Distribution Test	Verify earlier conducted computational fluid dynamics modeling that no excessive thermal striping is occurring during operation or no excessive pressure drop.

5.3 Test Conditions

The test conditions will be defined in the Test Specification that will be prepared as the initial activity in the test program. To the extent practical, test conditions will be selected to simulate the SG operating environment in the NGNP

5.4 Test Configuration

The full-scale SG will be mounted in a test rig with all subsystems made operational, such as air supply, water supply, coolant supply, power, etc. A natural gas fired combustion turbine will likely supply the required heat.

5.5 Test Duration

Approximately six years to build the prototype SG and complete the testing

5.6 Test Location

The operational testing may be conducted at the SG manufacturer's facility if the facility can reasonable simulate the NGNP operating environment, such as high temperature and flowing air. However, it is expected that, beyond manufacturer functional/checkout/acceptance testing, the operational testing will take place on the NGNP site in a test facility built for this testing purpose.

5.7 Required Data

To be defined in the Test Specification

5.8 Test Evaluation Criteria

To be defined in the Test Specification and Test Plan that will be prepared specifically for this test.

5.9 Test Deliverables

A final Test Report shall be prepared fore each of the tests. The Test Report should include:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

5.10 Cost, Schedule, and Risk

Cost and schedule data is shown in Table 6 and Figure 5 in Section 7.

Although testing of the full-size SG prior to installation in the NGNP is desirable, the practicality of this is questionable. Testing of the full-size SG in helium in the CTF is not possible because of its size, and testing of a scale-model of the SG is not considered cost effective or technically defensible. The cost/benefit of the testing outlined in this section is also questionable and the need for it should be further evaluated. If the results of the design support testing outlined in Section 5 and of computer modeling of the SG provide a reasonably high level of confidence that the SG will perform satisfactorily, then this test can potentially be eliminated. This would be consistent with the experience with the intermediate heat exchanger (IHX) in the HTTR. Testing of the full-size heat exchanger was not performed prior to installation and operation in the HTTR

6 TRL 7 TO 8 – STEAM GENERATOR FULL SCALE TESTING IN HELIUM

As noted in Section 5.1.10, testing of the full-size SG under NGNP operating conditions is not considered to be possible (or at least practical) prior to installation in NGNP. Cold-testing of the SG can be performed as part of the NGNP startup testing program; however, hot-testing of the SG at NGNP operating temperatures can only be performed once the NGNP has gone hot. Thus, it is believed that a TRL rating of 8 for the SG cannot be achieved before hot startup of the NGNP and that demonstration of the SG during NGNP power operation will be necessary to achieve a TRL 8 rating.

6.1 Test Objective

Conduct the appropriate number and duration of tests in the actual operating environment (i.e., in the NGNP) to verify that the SG meets all operational requirements under normal operation operating and transient conditions as defined in the NGNP technical specifications.

6.2 Test Description

TRL 8 will be achieved for the SG by performing cold-testing during the NGNP startup program and by demonstration of acceptable performance during NGNP operation. Some elevated-temperature testing of the SG prior to hot startup of the reactor can be performed by heating the primary coolant via operation of the primary helium circulator(s), as was done in the HTTR. The first part of this activity will be to prepare the Test Specification (or alternately to define the SG testing in the NGNP startup plan).

6.3 Test Conditions

The test conditions will be defined in the Test Specification or the NGNP startup plan.

6.4 Test Configuration

The tests will be performed in the NGNP.

6.5 Measurements

The NGNP will include the necessary instrumentation to monitor SG performance.

6.6 Test Location

The tests will ne performed in the NGNP.

6.7 Test Evaluation Criteria

The test evaluation and acceptance criteria will be defined in the Test Specification or in the NGNP startup plan.

6.8 Test Deliverables

It is assumed that the test results will be included in the NGNP startup testing report. The information to be provided for the test includes:

- Detailed discussion of test method
- Equipment employed
- Equipment calibration verification
- Detailed test procedures
- Original test data
- Summarized and reduced test data
- A detailed discussion of test results, observations, and calculations that were completed throughout the course of testing

6.9 Schedule, Cost, and Risks

6.9.1 Schedule

The SG testing will be performed as part of NGNP startup testing and during initial NGNP operation.

6.9.2 Cost

The incremental cost of this test on the overall cost of the NGNP startup program and NGNP operation cannot be reasonably estimated at this time.

6.9.3 Risks

Not applicable

7 COST ESTIMATE SUMMARY AND SCHEDULE

A summary of the estimated costs and a schedule for SG technology maturation testing are given below in Table 6 and Figure 5, respectively.

Table 6. Costs Estimates for Steam Generator Testing

Test Category	Test	Test Costs (000's)
Design (TRL 4 to 5)	Design the Steam Generator	$3,000
Materials (TRL 5 to 6)	Verify Alloy 800H and 2-1/4Cr-1Mo, Bimetallic Weld	$15,000
Air Flow (TRL 5 to 6)	Flow-Induced Vibration (Acoustics)	$780
	Air Flow Testing	$890
Stability Orifice (TRL 5 to 6)	Stability Orifice Testing	$200
Insulation (TRL 5 to 6)	Insulation Verification	$700
Fabrication Testing (TRL 5 to 6)	Tube Coil/Treading Verification	$1,260
	Wear Protection Tests	$2,450
	Lead Tube Test	$600
Operation Tests	Steam Generator Fabrication (TRL 6 to 7)	TBD
	SG Steady State Operation in Air (TRL 6 to 7)	$6,000
	SG Testing in Helium(TRL 7 to 8)	TBD
	Total	$30,880
	Total for Testing Only	$27,880

All costs are based on 2008 dollars.

<table>
<tr><th rowspan="2">Activity</th><th colspan="14">Year (FY 20xx)</th></tr>
<tr><th>09</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th></tr>
<tr><td rowspan="3">NGNP Schedule</td><td colspan="2">CD</td><td colspan="3">Prelim. Design</td><td colspan="9">NGNP Final Design</td></tr>
<tr><td colspan="7"></td><td colspan="2">Site Work</td><td colspan="5">Construction</td></tr>
<tr><td colspan="12"></td><td colspan="2">Startup/ Testing</td></tr>
<tr><td>SG Design & Analysis</td><td colspan="14">=======></td></tr>
<tr><td>Base Material and bimetallic weld testing</td><td colspan="14">===========></td></tr>
<tr><td>Air Flow Testing and orifice testing</td><td colspan="2"></td><td colspan="12"><===></td></tr>
<tr><td>Fabrication Testing</td><td colspan="2"></td><td colspan="12"><========></td></tr>
<tr><td>Tube Support System Testing</td><td colspan="2"></td><td colspan="12"><===></td></tr>
<tr><td>Insulation Testing</td><td colspan="4"></td><td colspan="10"><===></td></tr>
<tr><td>SG final design and fabrication</td><td colspan="4"></td><td colspan="10">< ================></td></tr>
<tr><td>Air Flow Testing</td><td colspan="9"></td><td colspan="5"><========></td></tr>
<tr><td>Testing in Helium</td><td colspan="12"></td><td colspan="2"><====></td></tr>
</table>

Figure 5. Steam Generator Testing Schedule by Test Category

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