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Technical and Functional Requirements

Heat Transport Small Scale Testing Loop

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ABBREVIATIONS AND ACRONYMS

Abbreviation or Acronym	Definition
ASME	American Society of Mechanical Engineers
BEA	Battelle Energy Alliance
C	Carbon
CH_4	Methane
CIRC	Circulator
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CTC	Component Test Capability
CTF	Component Test Facility
DDN	Design Data Need
dP	Delta Pressure
ECC	Engineering, Commissioning and Construction
EMB	Electromagnetic Bearing
H_2	Hydrogen
HPAS	Hydrogen Plant Alternative Study
HTGR	High Temperature Gas-Cooled Reactor
HTS	Heat Transport System
HTSST	Heat Transport Small Scale Testing
HX	Heat Exchanger
IHX	Intermediate Heat Exchangers
kg/s	Kilogram per second
kPa	Kilopascal
LAB	Laboratory
m	meter
mm	millimeter
MC	Mixing Chamber
MHTGR	Modular High Temperature Gas-Cooled Reactor
MPa	Megapascal
MW	Megawatt
MWt	Megawatt thermal
N	No
NGNP	Next Generation Nuclear Reactor
OD	Outer Diameter
PCDR	Preconceptual Design Report
PCS	Power Conversion System
PFHE	Plate Fin Heat Exchanger

Abbreviation or Acronym	Definition
PIP	Piping
PHTS	Primary Heat Transport System
Ref.	Reference
ROT	Reactor Outlet Temperature
SG	Steam Generator
SHTS	Secondary Heat Transport System
SOW	Statement of Work
SSCs	Systems, Structures and Components
T&FR	Technical and Functional Requirements
TBD	To Be Determined
TDL	Technology Development Loop
TDRM	Technology Development Roadmapping
TRL	Technology Readiness Level
TS	Test Specification
UUT	Unit Under Test
WEC	Westinghouse Electric Company
Y	Yes

1. INTRODUCTION

1.1 Purpose of the Document

The purpose of this Requirements Document is to establish an original source baseline reference for the HTSST loop's Technical and Functional Requirements (T&FR) based on the relevant Technology Maturation Plans and Test Specifications as indentified in [1] and [2].

Correspondingly, all the requirements reflected in this Requirements Document are subject to reviews with all stakeholders partaking in its elicitation so that each requirement remains necessary, attainable and verifiable.

The approved Technical and Functional Requirements Document will be used as the baseline for the HTSST Loop Conceptual Design.

1.2 Scope of the HTSST Loop

The scope as per SOW-7342 [3] constitutes the vision for having an HTSST loop, which is broken down into needs, goals and objectives in the subsections that follow.

1.2.1 NEED

The need for developing a high temperature HTSST loop is:

"To provide a small-scale testing loop capability for heat transport system components thereby making provision to advance the technology maturation of these components in an environment representative of High Temperature Reactors at minimum schedule and cost."

1.2.2 GOALS

The goals of the HTSST loop are:

- To further technology development of High Temperature Reactor (HTR) components or parts thereof within a testing environment similar to the NGNP environment (with regard to temperature, pressure and relative flow rate where applicable) to which they would be exposed in actual service.

- To promote the mission need of the Component Test Capability (CTC) (previously known as the Component Test Facility (CTF)).

1.2.3 OBJECTIVES

The objectives of the HTSST loop are listed below.

- The HTSST loop shall be capable of performing all selected tests as per Table 2 through Table 11 of this Technical and Functional Requirements Document, thus advancing the TRL of NGNP Heat Transfer components within a budget that meets Congressional approval.

- The HTSST loop helium mass flow rate shall be sufficient to enable testing of a single module of IHX A, together with a module of IHX B connected in series; thus, delivering flow rates equal to what is envisaged per module in the NGNP plant.

- The design shall be driven by the heat transfer capability of a single IHX A.

- Where applicable, the IHX B module shall be sized so that its inlet and outlet temperatures correspond to the design temperatures of IHX B.

- The HTSST loop's heating capacity shall be adequate to maintain the test sections at temperatures required by the test specifications.

- The HTSST loop is to serve as a test bench in which smaller blower development may be supported.

2. GENERAL DESCRIPTION / OVERVIEW

2.1 User Needs

The HTSST loop will be used to address NGNP requirements in terms of testing and examining heat transfer components as well as to calibrate instrumentation under NGNP process conditions.

The HTSST loop will also be used to address NGNP requirements in terms of qualifying materials, fluids, components and component integration.

These tests will lead as input to ensure Nuclear Regulatory Commission (NRC) acceptability for use in the NGNP.

2.2 System Description

The need for an HTSST loop has surfaced from the CTC Preconceptual Design that addressed the CTC Mission Need. The HTSST loop will be used to facilitate High Temperature Reactor (HTR) heat transfer technology development as a forerunner to larger-scale heat transfer testing loops.

The HTSST loop will provide the necessary equipment and furnishings to meet the suited test cases, as screened from both the 950 °C [1] and 750°C-800°C [2] Technology Development Road Mapping (TDRM) Reports.

The HTSST loop shall have a testing space through which helium shall enter. An interface shall be provided that allows helium to enter the testing space from one end and

exit it at another end. A maximum helium temperature of 950°C at a maximum pressure of 9 MPa shall be attainable and shall be used as entrance temperature and pressure to the IHX A modules placed within the testing space.

The capability of the proposed HTSST loop to support the Hydrogen Production System (HPS) i.e. testing of subsections or component related thereto cannot presently be determined because of the incomplete design of the candidate HPS technologies at this point in their development. Consequently, no detailed test specifications currently exist for HPS systems and components. Advancement of their designs and representative sizing of testable units first needs to be completed.

However, an indication of the potential use of the HTSST loop in development of the HPS can be attained from review of the NGNP Hydrogen Plant Alternatives Study [5], which establishes the most complete pre-conceptual design for the HPS that has been done thus far. The Hydrogen Study is based on the NGNP with reactor outlet temperature of 950 °C, but sensitivity analysis in that report touches on the feasibility of hydrogen production at lower temperatures.

Assumptions that underlie these indications are the following: 1) The technology evaluations and resulting process simulation, equipment selection and process flow design of the Hydrogen Study constitute the HPS conceptual design, 2) The technology development roadmapping based on the evaluations and the conceptual design are followed, and 3) The timing of the roadmap is compatible with the HTSST deployment.

The tests identified in the Hydrogen Study that are potentially compatible with the HTSST appear to be the following:

- Sulfuric Acid Decomposition Reactor.
- Hydrogen Iodide Distillation Column.
- High-Temperature Steam Electrolyzer.
- High-Temperature Helium Valves.

More information regarding hydrogen production and high temperature helium valves is given in Appendix A along with discussion of other process heat applications.

2.2.1 NEEDS JUSTIFICATION

The HTSST loop will provide testing capability to enable prototype testing and qualification of heat transfer and -transport components. This forms part of the overall CTC Mission Need i.e. to enhance Technology Development of NGNP heat transport components.

2.3 General Constraints

General Constraints concerning the HTSST loop are categorized under the following:

2.3.1 FUNDING, MILESTONES AND TIMELINES

The HTSST loop Conceptual Design stage is to follow upon the requirements elicitation in Fiscal Year 2010.

The HTSST loop will be designed for an operational lifespan of [TBD][1] years.

Funding to initiate and complete the entire design lifecycle of the HTSST loop needs to be available as a complete package to ensure continuity of design teams and optimized efficiency.

2.3.2 COMPATIBILITY AND SUPPORT

The HTSST loop's mission is to support the NGNP testing and licensing programs at the Idaho National Laboratory (INL).

2.3.3 AVAILABILITY

The HTSST loop will be made available to all end-users contributing to the overall NGNP program. NGNP-driven schedules shall be given first priority.

2.3.4 PROCEDURAL CONSTRAINTS

The following procedural constraints are applicable:

- The HTSST loop will be treated as a high hazard, non-radiological facility.
- The HTSST loop will be subject to the National Environmental Policy Act (NEPA).
- The HTSST loop will be a government-owned, contractor-operated facility.
- The HTSST loop will provide the capability to test NGNP heat transport system components or prototypes thereof to demonstrate and advance their TRL maturity.

[1] BEA to specify HTSST loop operational lifespan.

3. REQUIREMENTS

Note that all TBDs in this Requirements Section are to be addressed during the follow-up phase. Later revisions of this Technical and Functional Requirements Document thus forms part of the Verification process within the whole requirements elicitation process.

3.1 Functional Requirements

3.1.1 PROGRAM ADMINISTRATIVE AND SUPPORT FUNCTIONS

Concerning the HTSST loop program administrative and support functions, the following necessary dedicated workspace shall be provided:

- Storage areas for all supplies related to the HTSST loop.
- Services related to the HTSST loop.
- Conferencing facilities.
- Maintenance areas for HTSST loop equipment (Mechanical, Electrical and Instrumentation and Control)
- Access to parking areas, rest rooms, locker rooms and break rooms for HTSST loop personnel.

The HTSST loop may need to include other program administrative and support functions that may be derived during future design activities.

3.1.2 PROGRAM TRAINING FUNCTIONS

Training shall be done in dedicated training areas reserved for electrical, maintenance and I&C disciplines. Maintenance mockup capabilities shall be implemented to ensure compatibility of HTSST loop trainees' skills with real plant maintenance.

A training simulator shall be used to ensure that operators become and remain knowledgeable and thus shall be adequately skilled for their job.

The training simulator shall also serve as an engineering simulator by predicting and simulating plant behavior to enable vendors to adequately do pre-preparation of their test specifications and plans.

3.1.3 PROGRAM RESEARCH FUNCTIONS

Program research functions entail the following:

- Access shall be given to authorized HTSST personnel to make use of laboratories and researcher workspaces.

3.1.4 HTSST LOOP OPERATIONAL, TESTING AND QUALIFICATION FUNCTIONS

Representative NGNP heat transfer components, parts thereof or proto-typical components shall be tested in environments comparable to NGNP conditions, i.e., temperature, relative flow rate, fluids and pressure level. General testing and qualification functions are described in the following paragraphs.

3.1.4.1 Test Conditions

The test conditions deal with high level HTSST loop requirements, which are listed below:

- The thermal heat duty of the HTSST loop to be applied for *heat exchanging purposes* in the testing of heat transfer components shall not exceed 2 MW.
- The maximum steady-state operating temperature of the HTSST loop shall be 950°C.
- The maximum steady-state operating pressure of the HTSST loop shall be 9 MPa.
- The HTSST loop shall have a mass flow rate of 0.8 to 1.4 kg/s.
- Provisions shall be made for temperature and pressure control within the HTSST loop to maintain both a temperature demand up to a maximum of 950°C and a pressure demand up to a maximum of 9 MPa within the testing space.
- A minimum temperature gain in the HTSST loop shall be 1.5°C/min.
- The heat transport medium that shall interface with heat transport components identified for testing shall be helium.
- Provisions shall be made for parameter measurement within the HTSST loop testing space – refer to paragraph 3.1.4.2.
- Provision shall be made for the injection, control, measurement and removal of the following impurities:
  - CO
  - CO_2
  - H_2
  - H_2O
  - CH_4
  - O_2
- Interfacing equipment shall be subject to the following requirements:
  - Surface finishing (tolerances [TBD]).
  - Gasket material (material [TBD]).
  - Flange torque (tolerances [TBD]).
- The HTSST loop interface with auxiliary equipment shall include the following:
  - Cooling Water (Purity [TBD]).
  - Instrument Air (Quality [TBD]).
  - Electricity Supply (Voltage [TBD]).

  - Heating, Ventilation and Air Conditioning (HVAC) (Process Conditions [TBD]).
  - Lifting Capacity (Maximum Weight [TBD]).
  - Helium Inventory Control System (HICS).
- Provision shall be made to allow application of cyclic loading on identified test specimens. Amplitude, frequency and number of cycles are [TBD].
- The HTSST loop shall provide a means to measure mass flow rate with an accuracy of within 1 percent, in order to calibrate other helium mass flow meters. It shall do so at a maximum temperature of 85°C.

3.1.4.2 Parameter Measurements

Provision shall be made to measure the following list of parameters within the HTSST loop testing space:

- Temperature;
- Pressure;
- He impurity levels as a function of time;
- Duration of exposure of tested component(s), part(s) or both;
- Thermal conductivity;
- Leak rates of test components and the HTSST loop;
- Differential pressures;
- Flow rates;
- Power inputs.

3.1.4.3 Data Requirements

All process data shall be captured as per agreement between the operator entity and the vendor requiring the tests. The latest technologically advanced and accepted data capturing equipment shall be considered during the HTSST loop design.

3.1.4.4 Test Evaluation Criteria

The HTSST loop shall allow tests to be repeated so that results may be compared with existing data. This criterion will be used to prove test repeatability.

Drift analyses shall be performed on the captured data to determine the effects of instrumentation drift.

3.1.4.5 Test Deliverables

All of the tests identified within both the 950°C [1] and the 750°C – 800°C [2] NGNP Technology Development Roadmapping Reports were screened during the initial phase of the requirements elicitation process. This screening process simply identified each test, including both flowing and static tests, as being relevant for testing within the HTSST loop or not. These relevant tests are summarized in Table 2 to Table 11.

A review of all test specifications from both the 750°C – 800°C and 950°C TRL advancement evaluations has been conducted in [6]. The results are given in Table 2 to Table 11which is organized by SSC. For each test, the tables provide an indication of whether it is appropriate to include the test as part of the scope of the proposed HTSST. The columns' headings of these tables are extracted from the statement of work (SOW) [3], which are defined in Table 1.

Table 1: Description of Headings of Table 2 to Table 11

Table column heading	Description
Component	Critical System, Structure or Component (SSC).
Test Description	Description of the test as identified during the Technology Development Roadmapping (TDRM) exercise.
Test Specification or DDN Number	The specific test number that was assigned to the tests during the TDRM exercise.
TRL Goal	The technology readiness level (TRL) at which the SSC will be after the tests (in the previous column) have been completed.
750ºC / 950ºC	Applicability of the test specifications to the different reactor outlet temperature configurations.
Environment	Indicates whether the test must be performed in a helium, air or other environment.
Static / Flowing	Indicates whether the tests must be performed in a static environment where no flow of process gas is required or otherwise.
Approx. Physical size	Indicates the approximate physical size of the test setup where possible and applicable.
Approx. Thermal size	Indicates the approximate thermal size of the test setup where possible and applicable. The thermal heat duty of a HTSST loop is required to be less than 2 MW.
Process conditions	Indicates what typical temperatures, pressures and flow rates should be for performing the test where applicable and possible.
HTSST	Indicates whether the test is suitable to be performed in the HTSST or not.
LAB	Indicates whether the test is suitable to be performed in a laboratory-type setup within the HTSST or in dedicated laboratories (i.e. metallurgical laboratories) outside of the HTSST environment. These would be typically static type tests.
Comments / Limitations	Comments on the decisions that were taken in determining the contents of the previous table columns.

Table 2: HTSST and Laboratory Scale Testing Applicability of Circulator Test Specifications

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
Circulator	EMBs, Catcher Bearings Tests	WEC-TS-CIRC-001	7	950°C 750°C	Helium, TBD	Static	TBD	< 2 MW	TBD	N	Y	HTSST considered too small for environmental testing of submerged EMB components. Would also not be applicable to rotating tests.
Circulator	Helium Rotating Seals Tests	WEC-TS-CIRC-002	7	950°C 750°C	Helium	Flowing	TBD	< 2 MW	TBD	N	N	Rotating seals (presumably dry gas seals would be considered as an alternate to submerged motors with EMBs. Does not require a loop. Not anticipated for the HTSST.
Circulator	Partial or Full-Scale Circulator Model Tests	WEC-TS-CIRC-003	7	950°C 750°C	Air/Nitrogen and other	Flowing	TBD	> 2 MW	TBD	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC.
Circulator	Prototype Circulator Tests	WEC-TS-CIRC-004	8	950°C 750°C	Helium	Flowing	TBD	> 2 MW	TBD	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC.

None of the circulator test specifications form part of the testing scope for HTSST.

Table 3: HTSST and Laboratory Scale Testing Applicability of IHXA Metallic Test Specifications

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
IHXA Metallic	Alloy 617 Material Specification and Procurement	WEC-TS-IHXA-001	3	950°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHXA Metallic	Alloy 617 Joining Technology and Resultant Properties	WEC-TS-IHXA-002	3	950°C	TBD	Static	TBD	TBD	Temperatures up to 1000°C.	N	Y	This specification relates to development of processes for welding, brazing and/or diffusion bonding. Testing can be done at the supplier or in a metallurgical laboratory.
IHXA Metallic	Thermal / Physical and Mechanical Properties of Alloy 617	WEC-TS-IHXA-003	3	950°C	TBD	Static	TBD	TBD	Temperatures up to 1000°C.	N	Y	This specification relates to characterization of material properties. Testing can be done in a metallurgical laboratory.
IHXA Metallic	Effects of thermal Aging and Environment on Alloy 617	WEC-TS-IHXA-004	3	950°C	Helium	Static	TBD	TBD	Temperatures 700°C to 1000°C.	Y	Y	This specification relates first to aging of materials samples in a controlled chemistry environment and then conducting tests to characterize changes in materials properties. The aging step could be done in the HTSST if an environmental testing capability is included.
IHXA Metallic	Effects of Grain Size and Selection Thickness on Alloy 617 Properties	WEC-TS-IHXA-005	3	950°C	N/A	Static	TBD	TBD	Temperatures up to 1000°C.	N	Y	This specification relates to characterization of properties of materials with different grain sizes. Testing can be done in a metallurgical laboratory.
IHXA Metallic	Corrosion Allowances for Alloy 617	WEC-TS-IHXA-006	3	950°C	Helium	Static*	TBD	TBD	Temperatures 700°C to 1000°C at 9MPa with Controlled Impurities.	Y	Y	This is basically a long-term environmental test with controlled impurities. In it's most basic form, it can just be thin material samples in a lab environment. Exposure of samples to the helium environment could be done in the HTSST if an environmental testing capability is included. In addition to what is implied in the Test Specification, it may be worthwhile to expose basic IHX assemblies (e.g., unit cell for PFHE) to the HTGR environment to see if there are any interactions related to joining transitions. In this latter case, the HTSST may be considered. *Also, a procedure is to be established for preserving ALL components used in the test loops, to be available for analysis. All components to be weighed before and after testing to determine mass loss. Corrosion allowance testing could be done in conjunction with other tests.
IHXA Metallic	ASME Selection III Code Case for Alloy 617	WEC-TS-IHXA-007	4	950°C	N/A	N/A	N/A	N/A	Temperatures up to 950°C.	N	N	No test facility or equipment is needed.
IHXA Metallic	Thermal / Fluid Modeling Methods for Metallic IHX A	WEC-TS-IHXA-008	4	950°C	Helium	TBD	TBD	TBD	TBD	Y	N	Results of HTSST tests as described below for WEC-TS-IHXA-013 could be used to validate resulting models.
IHXA Metallic	Methods for Stress / Strain Modeling of Metallic IHX A	WEC-TS-IHXA-009	4	950°C	N/A	N/A	N/A	N/A	N/A	N	N	No test facility or equipment is needed.
IHXA Metallic	Criteria for Structural Integrity of IHX A	WEC-TS-IHXA-010	4	950°C	N/A	N/A	N/A	N/A	N/A	N	N	No test facility or equipment is needed.
IHXA Metallic	Performance Modeling Methods for IHX A	WEC-TS-IHXA-011	4	950°C	Helium	TBD	TBD	TBD	TBD	Y	N	Results of HTSST tests as described below for WEC-TS-IHXA-013 could be used to validate resulting models.
IHXA Metallic	Testing of Heat Exchanger Element	WEC-TS-IHXA-012	See breakdown below									"Heat Exchanger Element" is the compact HX functional equivalent of a 1-tube shell & tube heat exchanger with manifolds. For the Plate-Fin HX addressed in the IHX report, the "Unit Cell" would be an example.
IHXA Metallic	Joint Integrity (Diffusion Bonding)	WEC-TS-IHXA-012_1	5	950°C	Helium	Static	TBD	< 2 MW	Temperatures up to 950°C; Pressures up to 9MPa.	Y	Y	All components used in test setups to be retained for post-operating analysis.
IHXA Metallic	Joint Integrity (Brazing)	WEC-TS-IHXA-012_1	5	950°C	Helium	Static	TBD	< 2 MW	Temperatures up to 950°C; Pressures up to 9MPa.	Y	Y	All components used in test setups to be retained for post-operating analysis.
IHXA Metallic	Creep Lifetime Tests	WEC-TS-IHXA-012_2	5	950°C	Helium	Static	TBD	< 2 MW	Temperatures up to 950°C; Pressures up to 9MPa	Y	Y	All components to be tested to be analyzed before and after tests to detect creep.
IHXA Metallic	Fatigue Life Test	WEC-TS-IHXA-012_3	5	950°C	Helium	Static	TBD	< 2MW	Temperatures up to 950°C; Pressures up to 9MPa.	Y	Y	All components used in test setups to be retained for post-operating analysis.

Table 3 (Continued)

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
IHXA Metallic	Testing of Integrated Compact Heat Exchanger Module (~1.2MW).	WEC-TS-IHXA-013	See breakdown below									Simulation of transient events limited by characteristics of HTSST, e.g., limited ability to impose high pressure differentials in experiments with helium flow. However, a combination of flowing and static tests can simulate or envelope other events, such as loss of secondary pressure with one side of the IHX test article isolated. Specific tests, other than steady state and corresponding test parameters are TBD.
IHXA Metallic	**1. Steady State Tests** Test compact heat exchanger module operating effectiveness and behavior in typical steady state pressure, temperature and temperature / pressure drop environment (Helium).	WEC-TS-IHXA-014	7	950°C	Helium	Flowing	TBD	< 2MW	Temperatures up to 950°C; Pressures up to 9MPa; Temperature delta of ~ 250°C; Pressure delta of ~ 500 to 600 kPa sustained (Primary to Secondary); Mass flow of 1.2 kg/s (As per CTF PCDR); He environment with varied composition.	Y	N	See above.
IHXA Metallic	**2. Transient Tests (Normal Operation)** Simulate selected normal operation duty cycle events (e.g., startup / shutdown).	WEC-TS-IHXA-015	8	950°C	Helium	Flowing	TBD	< 2MW	i. Pressurizing and de-pressurizing transient (ambient to 9MPa in TBD timeframe). Number of cycles and temperature level TBD. Ii. Temperature transient (ambient to 950 °C and vice versa), number of cycles and pressure TBD.	Y	N	See above.
IHXA Metallic	**3. Transient Tests (Licensing Basis Events)** Simulate selected off-normal events (e.g., loss of secondary pressure).	WEC-TS-IHXA-016	9	950°C	Helium	Flowing	TBD	< 2MW	Temperature: 950°C. Pressure 9MPa, Delta P and massflow TBD.	Y	N	See above.
IHXA Metallic	Establishing ASME III Code Cases for Metallic Compact Heat Exchanger Designs	WEC-TS-IHXA-014	6	950°C	Helium	Flowing	TBD	TBD	Temperatures up to 950°C; Pressures up to 9MPa.	TBD	TBD	Specific requirements for testing in support of code case validation are TBD. Tests may help in establishing code requirements, but details are not presently known.
IHXA Metallic	Shell-Side Flow Distribution and Bypass Leakage Testing	WEC-TS-IHXA-015	7	Ambient to 950°C	Air / Helium	Flowing	TBD	< 2MW	Details TBD. Likely to be ambient temperature, pressure.	Y	Y	Potential to characterize shell-side bypass at the module level in a test setup without heating. Should be compared with other ambient temperature and pressure testing options (e.g., plexiglas enclosures for improved visualization).
IHXA Metallic	Multi-Module (3 x 1.2 MW) Heat Transfer Testing	WEC-TS-IHXA-016	7	950°C	Helium	Flowing	TBD	> 2MW	Details TBD.	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC. Investigate module-to-module interactions on both the tube- and shell-sides of the heat exchanger. Confirm bypass leakage and effects.
IHXA Metallic	Testing of Full Size Compact Heat Exchanger (Full-Scale NGNP IHX A)	WEC-TS-IHXA-017	8	950°C	Helium	Flowing	TBD	> 2MW	Temperature varying up to 950°C; Pressure varying up to 9MPa.	N	N	Investigate module-to-module interactions on both the tube- and shell-sides of the heat exchanger.

Table 4: HTSST and Laboratory Scale Testing Applicability of IHXA Ceramic Test Specifications

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
IHXA Ceramic	Trade Study on Candidate Ceramic Material for IHX A	WEC-TS-IHXA-018	3	950°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHXA Ceramic	Trade Study on Candidate Ceramic Designs for IHX A	WEC-TS-IHXA-019	3	950°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHXA Ceramic	Ceramic HX Detailed Design Data Needs (DDNs)	WEC-TS-IHXA-020	4	950°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHXA Ceramic	Ceramic Materials Specifications and Procurement	WEC-TS-IHXA-021	4	950°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHXA Ceramic	Thermal Physical Properties of Ceramics	WEC-TS-IHXA-022	4	950°C	TBD	Static	TBD	TBD	Temperatures up to 1000°C.	N	Y	This specification relates to characterization of material properties. Testing can be done in a metallurgical laboratory.
IHXA Ceramic	Mechanical Properties of Ceramics	WEC-TS-IHXA-023	4	950°C	TBD	Static	TBD	TBD	Temperatures up to 1000°C.	N	Y	This specification relates to characterization of material properties. Testing can be done in a metallurgical laboratory.
IHXA Ceramic	Compatibility of Ceramic Materials to NGNP He Environment	WEC-TS-IHXA-024	4	950°C	Helium	Static	TBD	TBD	Temperatures 700°C to 1000°C at 9MPa with Controlled Impurities.	Y	Y	This specification relates first to aging of materials samples in a controlled chemistry environment and then conducting tests to characterize changes in materials properties. The aging step could be done in the HTSST if an environmental testing capability is included.
IHXA Ceramic	Manufacturing Technologies for Ceramic Heat Exchangers	WEC-TS-IHXA-025	4	950°C	N/A	N/A	N/A	N/A	N/A	N	N	Development of manufacturing technologies typically done by the supplier or in a materials testing laboratory.
IHXA Ceramic	Ceramic Materials Codes and Standards	WEC-TS-IHXA-026	5	950°C	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Specific requirements for testing in support of code case validation are TBD. Tests may help in establishing code requirements, but details are not presently known.
IHXA Ceramic	Methods for Thermal / Fluid and Stress / Strain Modeling	WEC-TS-IHXA-027	5	950°C	TBD	TBD	TBD	TBD	TBD	Y	N	Results of HTSST tests as described below for WEC-TS-IHXA-031 could be used to validate resulting models.
IHXA Ceramic	Structural Integrity Criteria for Ceramic Heat Exchangers	WEC-TS-IHXA-028	5	950°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHXA Ceramic	Performance Modeling of Ceramic Heat Exchangers	WEC-TS-IHXA-029	5	950°C	Helium	TBD	TBD	TBD	TBD	Y	N	Results of HTSST tests as described below for WEC-TS-IHXA-031 could be used to validate resulting models.
IHXA Ceramic	Testing of Heat Exchanger Element	WEC-TS-IHXA-030	5	950°C	Helium	Static	TBD	< 2 MW	Temperatures up to 950°C; Pressures up to 9MPa.	Y	Y	
IHXA Ceramic	Testing of Integrated Compact Heat Exchanger Module (~1.2MW).	WEC-TS-IHXA-031	See breakdown below									Simulation of transient events limited by characteristics of HTSST, e.g., limited ability to impose high pressure differentials in experiments with helium flow. However, a combination of flowing and static tests can simulate or envelope other events, such as loss of secondary pressure with one side of the IHX test article isolated. Specific tests, other than steady state and corresponding test parameters are TBD.
IHXA Ceramic	**1. Steady State Tests** Test compact heat exchanger module operating effectiveness and behavior in typical steady state pressure, temperature and temperature / pressure drop environment (Helium).	WEC-TS-IHXA-032	6	950°C	Helium	Flowing	TBD	< 2MW	Temperatures up to 950°C; Pressures up to 9MPa; Temperature delta of ~ 250°C; Pressure delta of ~ 500 to 600 kPa sustained (Primary to Secondary); Mass flow of 1.2 kg/s (As per CTF PCDR); He environment with varied composition.	Y	N	See above.

Table 4 (Continued)

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
IHXA Ceramic	**2. Transient Tests (Normal Operation)** Simulate selected normal operation duty cycle events (e.g., startup / shutdown).	WEC-TS-IHXA-033	6	950°C	Helium	Flowing	TBD	< 2MW	i. Pressurizing and de-pressurizing transient (ambient to 9MPa in TBD timeframe). Number of cycles and temperature level TBD. Ii. Temperature transient (ambient to 950 °C and vice versa), number of cycles and pressure TBD.	Y	N	See above.
IHXA Ceramic	**3. Transient Tests (Licensing Basis Events)** Simulate selected off-normal events (e.g., loss of secondary pressure).	WEC-TS-IHXA-034	6	950°C	Helium	Flowing	TBD	< 2MW	Temperature: 950°C. Pressure 9MPa, Delta P and massflow TBD.	Y	N	See above.
IHXA Ceramic	ASME III Code Cases for Ceramic Compact Heat Exchanger Designs	WEC-TS-IHXA-032	6	950°C	Helium	Flowing	TBD	TBD	Temperatures up to 950°C; Pressures up to 9MPa.	TBD	TBD	Specific requirements for testing in support of code case validation are TBD.
IHXA Ceramic	Shell-Side Flow Distribution and Bypass Leakage Testing	WEC-TS-IHXA-033	7	950°C	Air / Helium	Flowing	TBD	TBD	Details TBD. Likely to be ambient temperature, pressure.	Y	Y	Potential to characterize shell-side bypass at the module level in a test setup without heating. Should be compared with other ambient temperature and pressure testing options (e.g., plexiglas enclosures for improved visualization).
IHXA Ceramic	Multi-Module Heat Transfer Testing	WEC-TS-IHXA-034	7	950°C	Helium	Flowing	TBD	> 2 MW	Details TBD.	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC.
IHXA Ceramic	Testing of Full Size Compact Heat Exchanger (Full-Scale NGNP IHX A)	WEC-TS-IHXA-035	8	950°C	Helium	Flowing	TBD	< 2MW	Temperature varying up to 950°C; Pressure varying up to 9MPa.	N	N	Exceeds anticipated capacity of HTSST. Would be tested in Demo Plant.

Table 5: HTSST and Laboratory Scale Testing Applicability of IHXB (950°C) and IHX (750°C) Metallic Test Specifications

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
IHX B (950°C) IHX (750°C)	Alloy 800H and Hastelloy X Material Specifications and Procurement	WEC-TS-IHXB-001 WEC-TS-IHX-001	4	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHX B (950°C) IHX (750°C)	Database for Brazed and Diffusion Bonded Alloy 800H and Hastelloy X	WEC-TS-IHXB-002 WEC-TS-IHX-002	4	950°C 750°C	N/A	Static	TBD	TBD	Temperatures up to 850°C.	N	Y	Development of joining technology and associated testing can be done by the supplier or in a metallurgical laboratory.
IHX B (950°C) IHX (750°C)	Alloy 800H and Hastelloy X High Temperature Material Properties	WEC-TS-IHXB-003 WEC-TS-IHX-003	4	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHX B (950°C) IHX (750°C)	Effects of Thermal Aging and Environment on Alloy 800H and Hastelloy X Properties	WEC-TS-IHXB-004 WEC-TS-IHX-004	4	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	No testing.
IHX B (950°C) IHX (750°C)	Effects of Environmental Exposure on Alloy 800H and Hastelloy X Braze and Diffusion Bonded Joints	WEC-TS-IHXB-005 WEC-TS-IHX-005	4	950°C 750°C	N/A	Static	TBD	TBD	Temperatures up to 850°C.	Y	Y	Environmental testing capability proposed for HTSST. Testing could also be done in a metallurgical laboratory.
IHX B (950°C) IHX (750°C)	Effects of Grain Size and Section Thickness on Alloy 800H and Hastelloy X Properties	WEC-TS-IHXB-006 WEC-TS-IHX-006	4	950°C 750°C	N/A	Static	TBD	TBD	Temperatures up to 850°C.	N	Y	Testing can be done in a metallurgical laboratory
IHX B (950°C) IHX (750°C)	Corrosion Allowances for Alloy 800H and Hastelloy X	WEC-TS-IHXB-007 WEC-TS-IHX-007	4	950°C 750°C	Helium	TBD	TBD	TBD	Temperatures 650°C to 850°C at 9MPa with Controlled Impurities.	Y	Y	Environmental testing capability proposed for HTSST. Also, a procedure to be established for preserving ALL components used in the test loops, to be available for analysis. All components to be weighed before and after testing to determine mass loss. Corrosion allowance testing could be done in conjunction with other tests.
IHX B (950°C) IHX (750°C)	Thermal / Fluid Modeling Methods for the IHXB / IHX	WEC-TS-IHXB-008 WEC-TS-IHX-008	4	950°C 750°C	Helium	TBD	TBD	TBD	TBD	Y	N	Results of HTSST tests could be used to validate resulting models.
IHX B (950°C) IHX (750°C)	Methods for Stress / Strain Modeling of the IHXB / IHX	WEC-TS-IHXB-009 WEC-TS-IHX-009	4	950°C 750°C		N/A	N/A	N/A	N/A	N	N	No test facility or equipment is needed.
IHX B (950°C) IHX (750°C)	Criteria for Structural Integrity of the IHXB / IHX	WEC-TS-IHXB-010 WEC-TS-IHX-010	4	950°C 750°C		N/A	N/A	N/A	N/A	N	N	No test facility or equipment is needed.
IHX B (950°C) IHX (750°C)	Performance Modeling Methods for the IHXB / IHX	WEC-TS-IHXB-011 WEC-TS-IHX-011	4	950°C 750°C	Helium	TBD	TBD	TBD	TBD	Y	N	Results of HTSST tests could be used to validate resulting models.
IHX B (950°C) IHX (750°C)	Testing of Heat Exchanger Element	WEC-TS-IHXB-012 WEC-TS-IHX-012	See breakdown below									
IHX B (950°C) IHX (750°C)	Joint Integrity (Diffusion Bonding)	WEC-TS-IHXB-012_1 WEC-TS-IHX-012_1	5	950°C 750°C	Helium	Static	TBD	< 2 MW	Temperatures up to 800°C; Pressures up to 9MPa.	Y	Y	All components used in test loops to be retained for post-operating analysis.
IHX B (950°C) IHX (750°C)	Joint Integrity (Brazing)	WEC-TS-IHXB-012_1 WEC-TS-IHX-012_1	5	950°C 750°C	Helium	Static	TBD	< 2 MW	Temperatures up to 800°C; Pressures up to 9MPa.	Y	Y	All components used in test loops to be retained for post-operating analysis.
IHX B (950°C) IHX (750°C)	Creep Lifetime Tests	WEC-TS-IHXB-012_2 WEC-TS-IHX-012_2	5	950°C 750°C	Helium	Static	TBD	< 2 MW	Temperatures up to 800°C; Pressures up to 9MPa.	Y	Y	All components to be tested to be analyzed before and after tests to detect creep.
IHX B (950°C) IHX (750°C)	Fatigue Life Test	WEC-TS-IHXB-012_3 WEC-TS-IHX-012_3	5	950°C 750°C	Helium	Static	TBD	< 2 MW	Temperatures up to 800°C; Pressures up to 9MPa.	Y	Y	All components used in test loops to be retained for post-operating analysis.
IHX B (950°C) IHX (750°C)	Testing of Integrated Compact Heat Exchanger Module ([TBD] MW Corresponds to 1.2MW IHX A to get Correct Temperatures)	WEC-TS-IHXB-013 WEC-TS-IHX-013	See breakdown below									Simulation of transient events limited by characteristics of HTSST, e.g., limited ability to impose high pressure differentials in experiments with helium flow. However, a combination of flowing and static tests can simulate or envelope other events, such as loss of secondary pressure with one side of the IHX test article isolated. Specific tests, other than steady state and corresponding test parameters are TBD.

Table 5 (Continued)

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
IHX B (950°C) IHX (750°C)	**1. Steady State Tests** Test compact heat exchanger module operating effectiveness and behavior in typical steady state pressure, temperature and temperature / pressure drop environment (Helium).	WEC-TS-IHXB-013 WEC-TS-IHX-013	6	950°C 750°C	Helium	Flowing	TBD	< 2MW	Temperatures up to 750°C to 800°C; Pressures up to 9MPa; Temperature delta of ~ 473°C; Pressure delta of ~ 500 to 600 kPa sustained (Primary to Secondary); Mass flow of 1.2 kg/s (As per CTF PCDR); He environment with varied composition.	Y	N	See above.
IHX B (950°C) IHX (750°C)	**2. Transient Tests (Normal Operation)** Simulate selected normal operation duty cycle events (e.g., startup / shutdown).	WEC-TS-IHXB-013 WEC-TS-IHX-013	6	950°C 750°C	Helium	Flowing	TBD	< 2MW	i. Pressurizing and de-pressurizing transient (ambient to 9MPa in TBD timeframe). Number of cycles and temperature level TBD. Ii. Temperature transient (ambient to 800 °C and vice versa), number of cycles and pressure TBD.	Y	N	See above.
IHX B (950°C) IHX (750°C)	**3. Transient Tests (Licensing Basis Events)** Simulate selected off-normal events (e.g., loss of secondary pressure).	WEC-TS-IHXB-013 WEC-TS-IHX-013	6	950°C 750°C	Helium	Flowing	TBD	< 2MW	Temperature: 750 °C to 800°C Pressure 9MPa, Delta P and massflow TBD.	Y	N	See above.
IHX B (950°C) IHX (750°C)	Establishing ASME III Code Cases for Metallic Compact Heat Exchanger Designs	WEC-TS-IHXB-014 WEC-TS-IHX-014	6	950°C 750°C	Helium	Flowing	TBD	TBD	Temperatures up to 800°C; Pressures up to 9MPa.	TBD	TBD	Specific requirements for testing in support of code case validation are TBD.
IHX B (950°C) IHX (750°C)	Shell-Side Flow Distribution and Bypass Leakage Testing	WEC-TS-IHXB-015 WEC-TS-IHX-015	7	950°C 750°C	Air / Helium	Flowing	TBD	< 2MW	Details TBD. Likely to be ambient temperature, pressure	Y	Y	Potential to characterize shell-side bypass at the module level in a test setup without heating. Should be compared with other ambient temperature and pressure testing options (e.g., plexiglas enclosures for improved visualization).
IHX B (950°C) IHX (750°C)	Multi-Module (3 x 1.2 MW) Heat Transfer Testing	WEC-TS-IHXB-016 WEC-TS-IHX-016	7	950°C 750°C	Helium	Flowing	TBD	> 2MW	Details TBD.	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC. Investigate module-to-module interactions on both the tube- and shell-sides of the heat exchanger. Confirm bypass leakage and effects.
IHX B (950°C) IHX (750°C)	Testing of a Full-Scale Compact Heat Exchanger	WEC-TS-IHXB-017 WEC-TS-IHX-017	8	950°C 750°C	Helium	Flowing	TBD	> 2MW	Temperature varying up to 800°C; Pressure varying up to 9MPa.	N	N	Exceeds anticipated capacity of HTSST. Would be tested in Demo Plant.

Table 6: HTSST and Laboratory Scale Testing Applicability of HTS Piping Test Specifications

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
Piping	PHTS High-Temperature [760°C and 950°C] Piping Cooling, Liner and Insulation Options Trade Study	WEC-TS-PIP-001 WEC-TS-PIP$_{750}$-001	5	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	Trade study.
Piping	PHTS Low-Temperature [350°C] Piping Liner and Insulation Options Trade Study	WEC-TS-PIP-002 WEC-TS-PIP$_{750}$-002	5	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	Trade study.
Piping	SHTS High-Temperature[840°C and 900°C] Piping Liner and Insulation Study	WEC-TS-PIP-003	5	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	Trade study.
Piping	SHTS Medium-Temperature [659°C and 700°C] Piping Liner and Insulation Trade Study	WEC-TS-PIP-004 WEC-TS-PIP$_{750}$-003	5	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	Trade study.
Piping	SHTS Low-Temperature [<300°C] Piping Liner and Insulation Trade Study	WEC-TS-PIP-005 WEC-TS-PIP$_{750}$-004	5	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	Trade study.
Piping	Effects of Helium Infiltration on Thermal Conductivity of Insulation Material	WEC-TS-PIP-006 WEC-TS-PIP$_{750}$-005	6	950°C 750°C	See breakdown below							
Piping	Effects of He Infiltration on Thermal Conductivity of Insulation Material	WEC-TS-PIP-006_1 WEC-TS-PIP$_{750}$-005_1	6	950°C 750°C	Helium	Static	TBD	< 2MW	Temperature to 950°C/9MPa; Temperature to 800°C/9MPa.	Y	Y	Insulation-only test anticipated to be required. Could be done at lab-scale or as environmental test in HTSST.
Piping	Effect of Sudden Depressurization on Insulation at 9Mpa, 950°C	WEC-TS-PIP-006_2 WEC-TS-PIP$_{750}$-005_2	6	950°C 750°C	Helium	Static	TBD	< 2MW	Temperature: 950°C/Ambient; Pressure → 9MPa; Temperature: 800°C/Ambient; Pressure → 9MPa.	Y	Y	Insulation-only test anticipated to be required. Could be done at lab-scale or as environmental test in HTSST. Post-test examination of insulation required.
Piping	Effects of He Impurities on Thermal Conductivity of Insulation Material	WEC-TS-PIP-006_3 WEC-TS-PIP$_{750}$-005_3	6	950°C 750°C	Helium w/ Controlled Impurities	Static	TBD	< 2MW	Temperature to 950°C/9MPa; Temperature to 800°C/9MPa.	Y	Y	Insulation-only test anticipated to be required. Could be done at lab-scale or as environmental test in HTSST.
Piping	Effect of Fluid Impurities (C) on Insulation Properties	WEC-TS-PIP-007 WEC-TS-PIP$_{750}$-006	6	950°C 750°C	Helium	Static	TBD	< 2MW	Temperature to 950°C/9MPa; Temperature to 800°C/9MPa.	Y	Y	Insulation-only test anticipated to be required. Could be done at lab-scale or as environmental test in HTSST. Post-test analysis in a lab is necessary, may be conducted as a result of other testing.
Piping	Re-Evaluation of Needed Maturation Tasks Based on Trade Studies	WEC-TS-PIP-008 WEC-TS-PIP$_{750}$-007	6	950°C 750°C	N/A	N/A	N/A	N/A	N/A	N	N	Trade study.
Piping	Performance and Environmental Testing of Prototypical High-Temperature and Low-Temperature Piping / Insulation System	WEC-TS-PIP-009 WEC-TS-PIP$_{750}$-008	7	950°C 750°C	Helium	Flowing	TBD	TBD	TBD	N	N	Exceeds anticipated capacity of HTSST. Would be tested in CTC. Specific test size (mass flow, geometry, . . .) and characteristics to be verified to be further evaluated in conjunction with trade studies.
Piping	Testing of Full Size PHTS Piping in NGNP	WEC-TS-PIP-010 WEC-TS-PIP$_{750}$-009	8	950°C 750°C	Helium	Flowing	TBD	>2MW	TBD	N	N	Testing in NGNP

Table 7: HTSST and Laboratory Scale Testing Applicability of Mixing Chamber Test Specifications

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
Mixing Chamber	Specification 1: Enhanced Mixing Devices Test Specification	WEC-TS-MC-001	7	950°C	N/A	N/A	N/A	N/A	N/A	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC.
Mixing Chamber	Specification 2: Vibration Damping Devices Test Specification	WEC-TS-MC-002	7	950°C	N/A	N/A	N/A	N/A	N/A	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC.
Mixing Chamber	Partial or Full Scale Flow Mixing Chamber Model Test Specification	WEC-TS-MC-003	7	950°C	N/A	N/A	N/A	N/A	N/A	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC.
Mixing Chamber	Prototype Flow Mixing Chamber Test Specification	WEC-TS-MC-004	8	950°C	N/A	N/A	N/A	N/A	N/A	N	N	Exceeds anticipated capacity of HTSST. Would be tested in upgraded HTSST or CTC.

Table 8: HTSST and Laboratory Scale Testing Applicability of Hydrogen Production Plant Alternative Study

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
Hydrogen Production	Hydrogen Plant Alternative Study (HPAS)	HPAS	TBD	950°C	TBD	TBD	TBD	TBD	None defined at this stage. Experts to indicate whether suitable scope exists for testing within HTSST boundaries.	TBD	N	

Table 9: HTSST and Laboratory Scale Testing Applicability of Steam Generator DDNs

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
Steam Generator	Acoustic Response of Helical Bundle	DDN:PCS-01-03	7	950°C 750°C	Helium / Steam	Flowing	TBD	TBD	Process conditions TBD.	N	N	Size of HTSST to determine the testing capability and applicability. Likely to be an ambient temperature test in a full cross-section, but axially shortened test article. Note that acoustic response of flow baffles may be an equal or greater issue.
Steam Generator	Inlet Flow Distribution	DDN:PCS-01-06	7	950°C 750°C	Helium / Steam	Flowing	TBD	TBD	Process conditions TBD.	N	N	Size of HTSST to determine the testing capability and applicability. Likely to be an ambient temperature test. Can use plexiglas models here.
Steam Generator	Flow Induced Vibration Testing of Helical Bundle	DDN:PCS-01-12	7	950°C 750°C	Helium / Steam	Flowing	TBD	TBD	Process conditions TBD.	N	N	Size of HTSST to determine the testing capability and applicability. Likely to be an ambient temperature test in a full cross-section, but axially shortened test article.
Steam Generator	Orifice Qualification Test	DDN:PCS-01-13	7	950°C 750°C	Helium / Steam	Flowing	TBD	TBD	Process conditions TBD.	N	N	Size of HTSST to determine the testing capability and applicability. As stated in the DDN, the objectives are to measure dP vs. flow and to indicate erosion/corrosion resistance. This would be typically done in a laboratory.
Steam Generator	Helical Bundle and Transition Region Heat Transfer Test	DDN:PCS-01-16	7	950°C 750°C	Helium / Steam	Flowing	TBD	TBD	Process conditions TBD.	Y	N	The infrastructure provided with the HTSST could possibly be used to characterize the water-side heat transfer coefficient (only) in a 1- or 2-tube test, using electrical heating on the shell side. The size and configuration of the tubes would preclude any realistic characterization of the helium-side. This would be a physically large test. Note that, in the 350 MWt MHTGR-SC, the characteristics of the SG tubes and the overall tube bundle were: Tube bundle OD/Height: 3.8m/8.4m; Number of tubes: 439; Thermal power/tube: 0.8MW; Number of coil layers: 28; Tube OD/Length: 22.2mm/131m
Steam Generator	Bimetallic Welding (800H or other High Temperature Alloys)	Not yet identified	7	950°C 750°C	Helium / Steam	Flowing	TBD	TBD	Process conditions TBD.	N	N	More experience with 800H or other high temperature alloys is necessary for technology development.

Table 10: HTSST and Laboratory Scale Testing Applicability of PHTS Backflow Prevention Valve Test Specifications (Not Identified Yet)

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
PHTS Backflow Prevention Valve	Trade Study to Select Type, Location	Not yet Identified	6	950°C	N/A	N/A	N/A	N/A	N/A	N	N	Trade Study
PHTS Backflow Prevention Valve	Confirmatory Testing	Not yet Identified	8	950°C	Helium	Static (Envir) and/or Flowing	TBD	TBD	TBD	Y	N	HTSST could potentially do environmental tests, but may not be optimum

Table 11: HTSST and Laboratory Scale Testing Applicability of "Other" Test Specifications

Component	Test Description	Test Specification or DDN Number	TRL Goal	750°C/ 950°C	Environment	Static / Flowing	Approx. Physical Size	Approx. Thermal Size	Process Conditions	HTSST	LAB	Comments / Limitations
Other	TDL Blower Development Tests	(Ref. CTF PCDR)		950°C 750°C	Helium	TBD	TBD	TBD	TBD	Y	N	HTSST is suggested as the main platform to develop and mitigate circulator related design risks. This aspect should be considered as one of the main drivers behind the HTSST designs
Other	Addition of Chemistry Control of CO, CO_2, CH_4, H_2 and Moisture in the ppm Range	(Ref. SOW: 7342)		950°C 750°C	Helium	TBD	TBD	TBD	TBD	Y	N/A	Can be developed and incorporated in conjunction with other HTSST tests
Other	Loop shall be Used for Long Term Testing (up to 5,000 hours)	(Ref. SOW: 7342)		950°C 750°C						Y	N/A	
Other	Test Loop Design shall Incorporate a Philosophy of Skid-Mounted (Modular & Reconfigurable) Units to Simplify Portability Thereof	(Ref. SOW: 7342)		950°C 750°C						Y	N/A	
Other	Possible Evaluation of Components for Large Scale Testing. E.g.: TDL Hot Gas Duct Development	(Ref. CTF PCDR)		950°C 750°C	TBD	TBD	TBD	TBD	See TDL report for input to test definition.	Y	N	To be developed in conjunction with other test facilities' designs

3.1.4.6 IHX A Metallic and Ceramic Requirements

IHX A Metallic requirements listed in this paragraph are subject to the high-level requirements listed in Paragraph 3.1.4.1.

The following specified service conditions shall be necessary to drive the HTSST requirements for IHXA Metallic- and Ceramic-specific tests.

- The nominal helium temperature at the primary side entrance to IHX A shall be 950 °C, plus or minus 5 °C.
- The nominal helium temperature at the secondary side entrance to IHX A shall be 710 °C, plus or minus 10 °C.
- The nominal helium temperature at the secondary side exit from IHX A should be 900 °C, plus or minus 10 °C.
- The nominal helium temperature at the primary side exit from IHX A should be 760 °C, plus or minus 10 °C.
- The primary IHX to secondary IHX pressure differential shall vary between 500 to 600 kPa (sustained).
- The pressure loss across the entire IHX (IHX A + IHX B) primary side and also across the secondary side of the IHX shall be smaller than 1.23 % of its respective inlet pressures.
- Nominal flow rates shall be [TBD] and power shall be [TBD].
- The IHX module shall be exposed to a high frequency, normal operating temperature and pressure transient [temperature and pressure transient envelopes - TBD], representative of the NGNP startup and shutdown sequence.
    - Pressurizing transient [TBD] (ambient to 9MPa in certain time frame).
    - Depressurizing transient [TBD] (9MPa to ambient in certain time frame).
    - Number of cycles and temperature level [TBD].
    - Heat up transition [TBD].
    - Cool down transition [TBD].
    - Number of cycles and pressure level [TBD].

3.1.4.7 IHX B Requirements

All IHX B (associated with 950°C ROT NGNP) requirements listed in this paragraph are subject to the high-level requirements listed in Paragraph 3.1.4.1.

The following specified service conditions shall be necessary to drive the HTSST requirements for IHX B-specific tests.

- The nominal helium temperature at the primary side entrance to IHX B shall be 760 °C, plus or minus 5 °C.
- The nominal helium temperature at the secondary side entrance to IHX B shall be 287 °C, plus or minus 10 °C.
- The nominal helium temperature at the secondary side exit from IHX B should be 720 °C, plus or minus 10 °C.

- The nominal helium temperature at the primary side exit from IHX B should be 337 °C, plus or minus 10 °C.
- Primary IHX to secondary IHX pressure differential shall vary between 500 to 600 kPa (sustained).
- The pressure loss across the entire IHX (IHX A + IHX B) primary side and also across the secondary side of the IHX shall be smaller than 1.23 % of its respective inlet pressures.

The following requirements are necessary to test compact heat exchanger module behavior in a typical pressure transient environment:

- The IHX module shall be exposed to a high frequency, normal operating temperature and pressure transient [temperature and pressure transient envelopes - TBD], representative of the NGNP startup and shutdown sequence.
    - Pressurizing transient [TBD] (ambient to 9MPa in certain time frame).
    - Depressurizing transient [TBD] (9MPa to ambient in certain time frame).
    - Number of cycles and temperature level [TBD].
    - Heat up transition [TBD].
    - Cool down transition [TBD].
    - Number of cycles and pressure level [TBD].

3.1.4.8 IHX Requirements

All IHX (associated with 750°C – 800°C ROT NGNP) requirements listed in this paragraph are subject to the high-level requirements listed in Paragraph 3.1.4.1.

The following specified service conditions shall be necessary to drive the HTSST requirements for IHX-specific tests.

- The nominal helium temperature at the primary side entrance to IHX shall be 800 °C, plus or minus 5 °C.
- The nominal helium temperature at the secondary side entrance to IHX shall be 217 °C, plus or minus 10 °C.
- The nominal helium temperature at the secondary side exit from IHX should be 750 °C, plus or minus 10 °C.
- The nominal helium temperature at the primary side exit from IHX should be 267 °C, plus or minus 10 °C.
- Primary IHX to secondary IHX pressure differential shall vary between 500 to 600 kPa (sustained).
- The pressure loss across the entire IHX primary side and also across the secondary side of the IHX shall be smaller than 1.23 % of its respective inlet pressures.

The following requirements are necessary to test compact heat exchanger module behavior in a typical pressure transient environment:

- The IHX module shall be exposed to a high frequency, normal operating temperature and pressure transient [temperature and pressure transient envelopes - TBD], representative of the NGNP startup and shutdown sequence.

- Pressurizing transient [TBD] (ambient to 9MPa in certain time frame).
- Depressurizing transient [TBD] (9MPa to ambient in certain time frame).
- Number of cycles and temperature level [TBD].
- Heat up transition [TBD].
- Cool down transition [TBD].
- Number of cycles and pressure level [TBD].

3.1.4.9 Heat Transport System Piping Requirements

All Heat Transport System (HTS) piping requirements listed in this paragraph are subject to the high-level requirements listed in Paragraph 3.1.4.1.

Considering HTS piping tests, the HTSST loop testing space shall provide for the following:

- Provision shall be made to allow for insulation test articles (fibrous and micro-porous) to be exposed to an environment similar to that of the NGNP within the testing space.
- Provision shall be made to allow for measurement of thermal conductivity of insulation materials within the testing space at pressures up to 9 MPa and temperatures up to 950°C.
- Pressure cycling of micro-porous material will be required to see if deterioration results.

3.1.4.10 Circulator Requirements

All circulator requirements listed in this paragraph are subject to the high-level requirements listed in Paragraph 3.1.4.1.

- Prototypical models or parts of the radial and axial Electromagnetic Bearings (EMBs) with their Catcher Bearings (CBs) will be used to support circulator development tests. The shaft will be rotated by an electric motor.
- The supplier is to determine the measured parameters, which may include the following:
  - Rotor-dynamic stability as a function of bearing stiffness and location during simulated start-ups and shutdowns.
  - Loads and rotor-dynamic stability during rundown on CBs.
  - Electric currents, temperatures, loads, shaft displacements, rotor mode shapes and amplitudes, vibration frequencies, and unbalances.
- The supplier is to determine the measured parameters, which may include the following:
  - In the case of usage of rotating seals: Leakages across the rotating seal shall be determined as a function of pressure differential, shaft rotating speed, buffer gas flow rates, and gas pressures and temperatures.

3.1.5 LIFE CYCLE FUNCTIONS

The requirements baselined in this document shall be validated at each of the following acquisition stages.

3.1.5.1 Development

Results of the requirements elicitation phase are to be baselined prior to design, which will be on tender starting FY 2010. However, all requirements shall be managed (i.e. checked for necessity, attainability and verifiability) throughout the HTSST project lifecycle.

3.1.5.2 Testing

The requirements listed in this paragraph will evolve during the conceptual design phase.

3.1.5.2.1 Cold Commissioning

Cold commissioning shall be done on sections of the plant rather than on individual pieces of plant as per a commissioning plan. The objective shall be to verify system functionality, while safely controlling operational and process loads.

The cold commissioning plan shall include the following tests, calibrations or both as well as the following acceptance criteria:

- The HTSST loop shall be fully installed in a designated building at the INL site.
- All instruments purchased without calibration certificates shall be sent to an accredited laboratory (such as the National Institute of Standards and Technology (NIST)) for calibration at the contractor's cost. Calibration shall be performed by taking HTSST site conditions (temperature and air pressure) into consideration.
- Mass flow controllers, shall be physically calibrated at the HTSST site and witnessed and signed off by the Employer.
- Pressure testing of equipment (requirements to be specified) shall be witnessed by representatives of the Employer.
- Appropriate specialists as per Employer request shall be invited to attend and observe these tests.

The Project Team, under jurisdiction of the Employer, shall re-perform any defective service, falling within its own scope that may be identified during cold commissioning.

Construction and commissioning of the HTSST loop may take place outside of INL. After commissioning, the location of the HTSST loop shall be the INL site.

3.1.5.3 Delivery

All delivered items and services shall be subject to INL's Supply Chain Management system.

3.1.5.4 Support

The HTSST's support systems have been identified in Paragraph 3.1.1.

3.1.6 PROGRAM UTILITIES

The following program utilities shall be required:

- Electricity.
- Required waters which may include potable, demineralized and cooling water.
- Instrument air. Instrument air quality shall comply with the requirements of ANSI/ISA S7.0.01 - Quality Air Standard for Instrument Air.
- Storage of coolant fluids.
- Telecommunications and network connectivity.
- Waste collection and waste treatment facilities.
- HVAC for HTSST surrounding space as per INL requirements.

The current state on sewer treatment is to be validated. Necessary expansion to sewer treatment plant shall be supplied or not as per validation.

3.2 Performance Characteristics

Further detail of the performance characteristics shall be defined during initial conceptual design.

3.3 Interface Requirements

Further detail on the interface requirements shall be defined during initial conceptual design.

3.3.1 INTERFACE WITH AUXILLIARY EQUIPMENT OR ACCESSORIES

Inspection walkways and maintenance platforms shall be designed to coincide, where applicable. All instrumented equipment and components due for routine inspection shall be made accessible and unobstructed by designing platforms and walkways in accordance with international Human Factors Engineering (HFE) standards – refer to [7].

No ladders or safety harnesses shall be required to obtain accessibility for inspection or maintenance purposes of instrumented equipment or other components unless overruled by HTSST management or by the INL site Regulator.

Removal paths for all major equipment shall be defined and documented. These paths include aisles, hatches, doors, knockout walls, removable components, ramps, as well as handling devices such as cranes, chain falls, skids and vehicles.

3.3.2 COMPATIBILITY WITH ENVIRONMENT

The HTSST shall be subject to the environmental regulations as stipulated by INL.

3.3.3 EXTERNAL OPERATING ENVIRONMENT

Further detail to be compiled with inception of the conceptual design.

3.3.4 LABELLING AND PACKAGING

Labeling and packaging procedures are subject to INL's Configuration Management System.

The HTSST design shall allow access for dismantlement, cut-up (segmentation), removal, and packaging of equipment from the facility if required.

3.3.5 TOXICITY AND BIOCOMPATIBILITY

Any concerns considering toxicity and biocompatibility shall be addressed during the initial conceptual design.

3.3.6 ELECTROMAGNETIC COMPATIBILITY

Equipment emitting any Electromagnetic Interference (EMI) shall be electromagnetically screened in order to eliminate any interference with sensitive equipment in the vicinity.

The power supply shall be electromagnetically shielded.

3.3.7 PHYSICAL AND CHEMICAL CHARACTERISTICS

Physical and chemical characteristics shall be addressed during the initial conceptual design.

3.3.8 LABORATORIES' STERILITY

Laboratories shall be managed, operated and maintained according to INL's standards.

3.3.9 SECURITY

As far as security is concerned, the HTSST shall reside within the jurisdiction of the INL site.

Operator schedules shall be accessible to all operators and production managers, indicating all operator information and allocated shifts.

3.3.10 SAFETY

Informative safety instruction signs shall be included as per INL regulations.

Explosion and fire hazards shall be assessed, and the necessary detection and protection systems shall be included in the design.

The need for explosion-proof or sealed electrical equipment shall be assessed and shall be included in the design.

The colors used for the plant shall conform to DOE industrial standards.

All outside surfaces exceeding 60°C shall be safeguarded.

3.4 Operational Requirements

Operational requirements will be determined during the conceptual design phase.

3.5 Resource Requirements

The resource requirements will be determined during the conceptual design phase.

3.6 Verification Requirements

The verification requirements will be determined during the conceptual design phase.

3.7 Documentation Requirements

The documentation requirements will be determined during the conceptual design phase.

3.8 Systems Requirements

3.8.1 IN-SERVICE RELIABILITY

The HTSST, excluding articles under test, will have an in-service reliability of greater than 90%.

3.8.2 MAINTAINABILITY

Maintenance includes inspecting, checking, troubleshooting, adjusting, replacing, repairing and servicing activities.

The realization of the overall goal of maintainability requires that associated human factors contributions shall be considered as part of the total design process, thereby promoting maintainability, which considering the HTSST is inseparable from planned human interference. Refer to Paragraph 3.3.1.

3.8.3 DESIGN LIFE

The HTSST shall have an operational lifetime of at least 20 years.

3.8.4 AVAILABILITY OF MATERIALS

Materials shall be identified during the conceptual and basic design phase and verified during the detail design phase.

3.8.5 TRANSPORTABILITY

The HTSST shall be designed so that the system, disassembled into its individual components (and packaged where necessary) into suitable crates, shall be transportable by sea, road or rail from the manufacturer to the final plant destination.

Measures shall be taken to protect the equipment from environmental conditions during transport.

Packages and crates shall be designed for either forklift or overhead crane manipulation, or both.

3.8.6 INTERCHANGEABILITY

Components between duplicate loops installed within the HTSST shall be interchangeable.

Maintenance track records of components shall be kept to verify and manage storage and usage thereof.

3.8.7 MODULARIZATION

The HTSST shall be based upon the principles of modularity in design, where manufacturing and construction are based on standardized units or dimensions to allow for flexibility.

Well-defined modular interfaces shall be used in the HTSST design by making use of industry standards.

Modularity in design shall not be followed where performance could be jeopardized.

Modularization entails that the whole HTSST be divided into subsystems. These individual subsystems shall be able to be designed built and commissioned offsite in any remote location.

In order to implement this modular design concept, control software shall be developed in accordance to predefined guidelines, which shall enable commissioning of modular subsystems off-site as well as integration of these subsystems on-site.

3.8.8 CODIFICATION

The codification of HTSST SSCs will be determined during the conceptual design phase.

3.8.9 COST

The total HTSST cost shall be determined during each acquisition phase.
The cost of the HTSST shall not exceed $ [TBD]

3.8.10 SCHEDULE

The HTSST schedule shall be linked to the cost during each acquisition phase.

3.8.11 LICENSING

No licensing requirements have yet been identified.

3.9 Engineering Design Requirements

Engineering and design requirements will develop during initial conceptual design. Some requirement guidelines are given below.

3.9.1 CIVIL AND STRUCTURAL

No building has yet been identified for the installation of HTSST.

Servitudes for HVAC ducting, cable and pipe routing in all areas as well as the drainage layout, both inside and outside of the anticipated building shall be led by the Utilities Contractor who shall also be responsible for overall plant layout and plant integration. In this regard, the Employer shall cooperate in undertaking design studies, or providing design information as requested, to the Utilities Contractor.

The HTSST layout design shall be such that the implementation thereof will result in the minimum disruption to existing processes.

The facility layout shall be such as to allow adequate room for maintenance of equipment.

The HTSST layout shall allow for emergency escape routes.

The HTSST layout shall allow for future expansion.

The HTSST layout shall provide for a visitors' walkway as well as an observation facility. The visitors' walkway may coincide with the walkway that shall be provided for routine maintenance and inspections – refer to Paragraph 3.3.1.

The facility layout shall make provision for addition of more and larger equipment in order to extend it for larger scale heat transfer component testing.

The following security requirements shall be allowed for in the plant layout:

- Personnel entry to the buildings shall be via access control.
- Access control shall be by means of authorized personal swipe cards or biometric type access systems.
- Other building external doors (e.g. emergency exits) shall be secured in such a way as to eliminate the possibility of unauthorized entry.
- Vehicle movement through the building gates shall be in accordance with the Employer's requirements.

3.9.2 MECHANICAL AND MATERIALS

To be determined during conceptual design.

3.9.3 CHEMICAL AND PROCESS

To be determined during conceptual design.

3.9.4 ELECTRICAL POWER

To be determined during conceptual design.

3.9.5 INSTRUMENTATION AND CONTROL

3.9.5.1 Automation Requirements

3.9.5.1.1 Level of automation

The plant shall be automated to facilitate start-up, shut down and normal operating scenarios.

The level of automation shall be determined by the funding constraints.

Plant automation shall be used to maintain system mass balance and energy balance for all operating conditions.

Process interlocks shall be included to ensure that plant equipment is operated within normal defined operating limits [TBD].

A Safety Instrumented System (SIS) shall ensure that the plant is shutdown to a safe state if a Safety Instrumented Function is activated.

The facility to override individual process interlocks shall be available under management control and all alarms and trip conditions shall still apply. A safe shut-down shall be initiated if the Safety Instrumented Function is required to activate.

3.9.5.1.2 Emergency Stop

A safe shutdown mode of the plant shall be triggered when:

- The manual activation of the emergency stop is initiated.
- Any of the installed field emergency stops are initiated, which then shall initiate the safe shutdown mode.
- A Safety Instrumented Function demands a shut down.

3.9.5.2 Engineering requirements

The following I&C deliverables shall be produced during concept engineering:

- Basic process control philosophy.
- Basic Automation System requirements specification.
-
- The following I&C deliverables shall be produced during basic engineering:
- Plant functional control requirement specification.
- Process and Instrumentation Diagrams.
- Plant layer of protection analysis (Safety Instrumented Functions).
- Plant Automation System hardware requirement specification.
- Plant automation System wiring philosophy diagram.

- Plant Safety Instrumented System hardware specification.
- Preliminary I&C power requirements.
- Preliminary Instrument air consumption requirements.
- Preliminary instrument hook-up specification.

I&C deliverables for detail engineering shall be specified during the basic engineering phase of the project.

3.9.5.2.1 Automation System

A safe shutdown shall be initiated through the Safety Instrumented System (SIS)

The Safety Instrumented System shall be a certified system complying with the Safety Integrity Level of the Safety Instrumented Functions.

Normal regulatory control and process interlocking shall be implemented on the plant PLC or DCS.

3.9.5.2.2 Human Machine Interface (Control Room)

A SCADA system shall be provided to allow the plant to be controlled from a remote control room.

The SCADA shall allow the operators to monitor and control the plant.

SCADA graphics shall be displayed indicating the following:

- Process conditions, i.e. temperature, pressure (gauge and delta P) and mass flow to allow the operator to monitor and control the plant remotely.
- All equipment conditioning indicators to indicate a healthy state or not i.e. bearing temperatures, oil levels, flow switches, electric motor winding temperatures, instrument air pressure, and all utilities' supply status.

Each operator shall log onto the SCADA at the beginning of his or her shift.

Each operator shall log off from the SCADA at the end of his or her shift.

Operators logging onto and off from the SCADA shall do so *via* a unique username and password.

All SCADA activities shall be recorded as plant history data and managed by the Employer.

3.9.5.2.3 Human Machine Interface (Field)

The use of local Human-Machine Interface (HMI) panels shall be investigated and justified if appropriate use thereof could be merited.

Should HMI panels be used the following shall be applicable:

- An operator shall be requested to log onto the HMI panel before access to control the specific component shall be granted. Once the operator's mission has been

completed, he or she shall be requested to log off before operations can commence.

- The control interfacing from HMI panels shall be interlocked by the SCADA which shall ensure that the specific unit or function cannot be controlled from both the SCADA and the panels at the same time.

3.9.5.2.4 Power Failure and Recovery

On power failure, the system shall fail into a "safe state".

On power restoration, the system shall not restart without operator input.

The automation system and the Safety Instrumented System shall be designed to be fail-safe.

In the event of a power restoration, manual re-start shall be based on operator intervention leading to initiation of the power recovery sequence.

3.9.5.3 Measurement Requirements

The accuracy of all measurements required for regulatory control, process interlocking and Safety instrumented functions shall be 2% or better.

Testing requirements for instrumentation and control valves shall be specified during the concept and basic engineering phases of the project.

3.9.5.4 I&C testing

- All software associated with Items Relied on for Safety (IROFS) shall be demonstrated to have been developed against a proper verifiable QA program before cold commissioning shall be regarded as finalized. The Project Team shall ensure that the final version of all control and other software has been installed. A copy of the current installed code shall be made available to the Client.
- All interlocks and alarms shall be demonstrated to be functional.

SCADA programs shall be demonstrated by taking the equipment through its processing cycle.

3.9.6 COMPUTER HARDWARE AND SOFTWARE

Latest tested and proven hardware and software shall be used during installation.

3.9.7 FIRE PROTECTION

To be assessed and confirmed during conceptual design.

3.9.8 TESTING AND MAINTENANCE REQUIREMENTS

To be assessed and confirmed during conceptual design.

3.9.9 OTHER REQUIREMENTS

3.9.9.1 Environment

The HTSST shall be installed into a building at the INL site that has the following nominal environmental conditions:

- Height above sea level: 1524 m.
- Temperature: [TBD]
- Relative humidity: 20% to 100%
- Atmospheric pressure: ~ 89 kPa.
- Seismicity: [TBD]

When the HTSST is operated, the interior environment in this building shall be regulated as follows:

- Temperature: 18 °C to 25 °C (dry bulb temperatures).
- Relative humidity: 40% to 70%.
- Air pressure: 20 Pa below atmospheric pressure.

4. REFERENCES

[1] "NGNP and Hydrogen Conceptual Design Study; NGNP Technology Development Road Mapping Report", NGNP-CTF MTECH-TDRM, Revision 0, December 2008.

[2] "NGNP Technology Development Roadmapping Report - Steam Production at 750°C-800°C," NGNP-TDI-TDR-RPT-G-00008 … 00018, August 2009.

[3] "Statement of Work, Project No. 23843 Heat Transport Small Scale Testing", Document ID: SOW-7432, Revision 1; June 2009.

[4] "NGNP CTF Test Loop Preconceptual Design Report", NGNP-CTF MTECH-TLDR.

[5] "NGNP Hydrogen Plant Alternatives Study", NGNP-HPS SHAW-HPA, Rev. 1, Westinghouse Electric Company LLC, March 2009.

[6] "TRL Advancement through the use of Heat Transport Small Scale Testing (HTSST)", NGNP-TDI-GEN-FRD-G-00020, August 2009, Revision C.

[7] Human Factors. Ergonomics Handbook for the Design for Ease of Maintenance, DOE-HDBK-1140-2001.

[8] Sink, Carl J, Amy C. Taylor and Paul S. Pickard, "An Overview of the Nuclear Hydrogen Initiative", AIChE 2006 Spring National Meeting, Orlando.

5. APPENDIX A: HYDROGEN PRODUCTION SYSTEM

5.1.1 HYDROGEN PRODUCTION TESTING POSSIBILITIES

5.1.1.1 Nuclear Hydrogen Initiative Candidate HPS Technologies

There are three leading hydrogen production technologies in the Nuclear Hydrogen Initiative (NHI) [8]. These are the Sulfur-Iodine cycle, the Hybrid Sulfur cycle and High-Temperature Steam Electrolysis. Each in concept has one or more Process Coupling Heat Exchangers (PCHXs) interfacing with the NGNP secondary helium heat transport circuit. The Hydrogen Production System (HPS) conceptual designs are based on the NGNP with reactor outlet temperature of 950 °C.

Table 12 summarizes the full-scale PCHXs for the three HPS technologies. Clearly none is of the scale that could be directly tested in the HTSST.

5.1.1.2 High-Temperature Small-Scale Heat Transfer Tests

Development testing of each HPS's PCHX will require a high-temperature small-scale heat transfer test capability. The NGNP Hydrogen Plant Alternatives Study report [5] includes Technology Development Road Maps (TDRMs) and Technology Maturation Plans which identified specific Pilot tests that could be considered for the HTSST. These are discussed in the following.

Sulfur-Iodine and Hybrid Sulfur H_2SO_4 Decomposer

The Sulfuric Acid Decomposition Reactor is common to both the Sulfur-Iodine cycle and the Hybrid Sulfur cycle. The Pilot test in the TDRM for the decomposer is based on testing of a full-length bayonet tube with helium heating on the exterior that is representative of the flow field in the full-scale component with the process ongoing inside the tube.

The heat requirement for this Pilot test would be 450 kWt at 910°C, if development were to proceed according to the Technology Maturation Plan in [5][1]. This would be in the range of the HTSST capability. However, feasibility of this test in the HTSST would depend on the accommodation of the added complexity of acid feed and oxygen and sulfur dioxide product handling.

Table 12: PCHXs in Hydrogen Production Systems

Component	Units per Ref. Plant	Thermal Duty per Unit, MWt	Helium Mass Flow per Unit, kg/s	Helium Flow		Process Side Flow *				
				T_{IN}, °C	T_{OUT}, °C	T_{IN}, °C	$T_{REACTION}$, °C	T_{OUT}, °C	Fluid In	Fluid Out
Sulfur-Iodine Cycle										
Sulfuric Acid Decomposition Reactor	6	123	88	910	640	127	870	256	75w/o H_2SO_4	7% O_2 14% SO_2 79% 55w/o H_2SO_4
HI Distillation Column	18	45	29	640	344	272	275	vapor: 288 liquid: 261	10% HI 40% I_2 50% H_2O	vapor: 3% HI 87% H_2O 10% H_2 liquid: 5% HI 62% I_2 33% H_2O
Hybrid Sulfur Cycle										
Sulfuric Acid Decomposition Reactor	4	178	88	910	522	127	870	256	75w/o H_2SO_4	7% O_2 14% SO_2 79% 55w/o H_2SO_4
High-Temperature Steam Electrolysis										
Cathode Feed Heater	2	24	58	910	829	396	NA	870	10% H_2 90% H_2O	10% H_2 90% H_2O
Anode Feed Heater	2	20	46	910	829	177	NA	870	air	air

* % = molar percentage, w/o = percent by mass

In the TDRM for the HPS this test would follow intermediate thermodynamic and materials test, which would advance the technology from its present TRL-4 to TRL-5. Upon successful duration, this HTSST test would advance the sulfuric acid decomposition part of both the Sulfur-Iodine and Hybrid Sulfur cycles from TRL-5 to TRL-6.

This test is shown, along with other HPS tests which might use the HTSST, in Table 13.

Sulfur-Iodine Hydrogen Iodide Distillation Column

The Sulfur-Iodine HPS includes a lower-temperature PCHX in addition to the Sulfuric Acid Decomposition Reactor. These are the reboilers in Hydrogen Iodide (HI) distillation columns.

In the Reference design [1], these PCHXs are large, but if Pilot testing at 1/10 scale were acceptable, then the tests might be small enough for the HTSST. That would be a heat duty of 1.5 MWt.

The TDRM proposes that the HI distillation column be tested together with a Bunsen Section (making H_2SO_4), and this would appear to be a more complicated test than is envisioned for the HTSST. In addition, it is also likely that requirements for handling H_2SO_4, HI and I_2 would warrant a dedicated testing facility for HI Distillation Column testing.

In the TDRM for HPS these tests would follow further design definition, thermodynamic data confirmation and materials tests, which would advance the technology from its present TRL-2 to TRL-4. Upon successful duration, this HTSST test would then advance the HI section from TRL-4 to TRL-8.

High-Temperature Steam Electrolysis Feed Heaters

Heat is input to the High-Temperature Steam Electrolysis HPS through two PCHXs. In a Cathode Feed Heater, the steam feed and a recycled stream of hydrogen (10% mole fraction) are heated further from 800°C to 870°C with 910°C helium. The steam and hydrogen feed are already superheated with recuperated electrolyzer module effluent. In parallel on the helium side, an Anode Feed Heater air is heated from 800°C to 870°C. These two streams are then supplied to the electrolyzer modules.

These heat exchangers have large duties in the HPS design [5], and even at 1/10 scale it appears that they would be at or beyond the 2 MWt limit of the HTSST.

Table 13: Pilot Tests Relative to HTSST Capability

Component	Feasible	Pilot Test No.*	Scale	Thermal Duty, kWt
Sulfur-Iodine Cycle				
Sulfuric Acid Decomposition Reactor	Yes	#8	one tube, full-scale	450
HI Distillation Column	Maybe	#4 & 5	~ 1:10	~ 1,500
Hybrid Sulfur Cycle				
Sulfuric Acid Decomposition Reactor	Yes	#8	one tube, full-scale	450
High-Temperature Steam Electrolysis				
Feed Heaters	No	- -	- -	≥ 2,000
Electrolyzer (SOEC module)	Yes	#5	one stack, full-scale	320

* The test numbers refer to the TDRMs and the Technology Maturation Plans in the NGNP Hydrogen Plant Alternatives Study report [5].

5.1.1.3 High-Temperature Solid Oxide Electrolyzers

The electrolyzers for High-Temperature Steam Electrolysis are made up of Solid Oxide Electrolysis Cells (SOEC). The pre-conceptual design calls for modules of 2,500 cells (square active area, 500 mm on a side) in four stacks of cells per module. Whereas the feed heaters for the High-Temperature Steam Electrolysis HPS are too large to be tested at reasonable sub-scale in the HTSST, one stack of the SOEC module from the NGNP Hydrogen Plant Alternatives Study report [5] could be tested in the HTSST at full scale. The electrolyzer module would be in a secondary loop with small Feed Heaters receiving heat from a primary helium loop. The Cathode Feed Heater and Anode Feed Heater would require only 180 and 140 kW each, respectively, not accounting for losses in the secondary heat transport circuit. The single cell stack would be tested in a full-scale electrolyzer vessel.

In the TDRM for HPS, this test would follow a laboratory test of the full cell stack with reference design interconnections and cell sealing, which would advance the technology from its present TRL-4 to TRL-5. Upon successful test duration, this HTSST test would advance the High-Temperature Steam Electrolysis module from TRL-5 to TRL-8 if done at design pressure and otherwise in the operational environment.

The SOEC module test is included in Table 13.

5.1.2 HIGH-TEMPERATURE HELIUM VALVES

In each of the NHI candidate HPS designs, there are multiple parallel process trains and, in some, two PCHXs in series in each train. In applications applying these designs, the secondary helium circuit will likely require valves in the loop that can either isolate the respective PCHX or modulate the flow of the secondary loop between PCHXs. For these

functions, a High-Temperature Helium Valve will be needed. The technology for such valves requires development and verification testing. The HTSST would be a place where developmental valves could be tested, although probably in reduced scale. Such tests are included in all of the HPS TDRMs and Technology Maturation Plans in the NGNP Hydrogen Plant Alternatives Study [5]. The objectives of the tests are to assure functionality while verifying material compatibility in the operating environment.

5.1.3 HIGH-TEMPERATURE SMALL-SCALE TEST CAPABILITY AND OTHER NGNP PROCESS HEAT APPLICATIONS

There are other direct process heat applications for the NGNP design in addition to hydrogen production, and so a variety of PCHXs could be candidates for eventual testing in the HTSST. Examples of these applications are steam methane reforming and ethylene cracking. Generally these process applications would require hot helium to their PCHX at various temperatures, and the process fluids on the tertiary side would differ. Different concepts apply to NGNP designs with reactor outlet temperatures of 950°C or 750 - 800°C. Applications can also be considered also where the secondary heat transport medium is other than helium, such as steam, air or liquid salt.

The plant designs for other directly heated processes are not further conceptualized at this stage, and so without details of the designs, as is the case with the hydrogen alternatives, functions and requirements for component testing cannot presently be determined.