INL/EXT-12-26219

Technology Development Roadmap for the Advanced High Temperature Reactor Secondary Heat Exchanger

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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EXECUTIVE SUMMARY

This Technology Development Roadmap (TDRM) study presents the path forward for deploying large-scale molten salt secondary heat exchangers and presents the benefits of using molten salt as the heat transport medium for advanced high temperature reactors. The roadmap will aid in the development and selection of the required heat exchanger for power production (the first anticipated process heat application), and other process heat applications, such as, hydrogen, methanol to gasoline, and ammonia production. It also (a) establishes the current state of readiness for molten salt secondary heat exchanger technology, (b) defines a path forward that systematically and effectively tests this technology to overcome areas of uncertainty, (c) demonstrates the achievement of an appropriate level of maturity prior to construction and plant operation, and (d) identifies issues and prioritizes future work for maturing the state of secondary heat exchangers technology.

The TDRM was developed to identify the research and development activities, modeling, design, fabrication, and scaled testing that must occur to satisfy the requirements of advancing technological readiness. TDRMs provide the framework and structure required to systematically perform decision analysis, reduce risk, and mature technologies in a cost effective and timely manner. The roadmap uses the Technology Readiness Level (TRL) as a measure of the level of technical maturity of a technology, that is, the ability to design, fabricate, and deploy a component or system. The Secondary Heat Exchanger (SHX) is currently at a TRL-3 and the challenges addressed in this study must be overcome to mature this technology into a viable and reliable heat transfer system. Also addressed in this study is the potential future work, which will help in further enhancing the SHX TRL.

This study discusses the results of a preliminary design analysis of the SHX. The efficient transfer of energy for industrial applications depends on the ability to incorporate cost-effective heat exchangers between the nuclear heat transport system and industrial process heat transport system.

The heat exchanger required for AHTR is subjected to a unique set of conditions that bring with them several design challenges not encountered in standard heat exchangers. The somewhat corrosive molten salts, especially at higher temperatures, require materials throughout the system to avoid corrosion, and adverse high-temperature effects such as creep.

Fuels salts received considerable testing and development in the Molten Salt Reactor Experiment (MSRE) program at Oak Ridge National Laboratory during the 1950s through 1970s, but relatively little research has been conducted on coolant salts. The corrosion data for various alloys in coolant salts (i.e., FLiBe, FLiNaK, KCl-$MgCl_2$, $NaNO_2$-$NaNO_3$-KNO_3 and KF-ZrF_4) are too limited for reliable comparisons of corrosion resistance of the various alloys, or the relative aggressiveness of these molten salts.

Tritium produced in the Advanced High Temperature Reactor could permeate salt mixture, pipe walls, and heat exchanger walls into the steam generator and possibly escape from the system with steam or in the industrial process side application. As a radioactive isotope of hydrogen, tritium should be avoided because it forms a hazardous gas or liquid if released into the atmosphere. It is regulated by the Nuclear Regulatory Commission and the U.S. Environmental Protection Agency.

For materials of construction, nickel and alloys with dense nickel coatings are effectively inert to corrosion in fluorides, but not so in chlorides. Hence, additional testing of selected alloys for resistance to intergranular corrosion is needed, as is a determination of corrosion rate as a function of contaminant type and alloy composition with respect to chromium and carbon to better define the optimal chromium and carbon composition, independent of galvanic or differential solubility effects.

The efficient transfer of energy for industrial applications depends on the ability to incorporate cost-effective heat exchangers between the nuclear heat transport system and industrial process heat transport system. The heat from the reactor is anticipated to be used for power generation and process heat applications. Given the very high steam generator pressure of the supercritical steam cycle, it is anticipated that water tube and salt shell steam generators will be used in the near term rather than compact heat exchangers.

The coupling to a supercritical steam cycle can likely be simplified by applying lessons from decades of successful operation of fossil supercritical plants. These include the materials of the piping, turbine, and other components, and the components such as condensate demineralizers and deaerators to protect them. Though, potential for solidifying salt is greater in steam cycles (because of lower reactor temperature) supercritical CO_2 cycle should be studied further.

While a wide variety of instrumentation is commercially available for high temperature test components and loops, instrumentation should be developed for testing and to support potential application in the heat transfer system test chambers and loops, and perhaps the power plant. Additional research is needed on high-temperature, low-drift thermocouples and resistive temperature devices; optical measurements of temperature, pressure, and strain; acoustic sensors and algorithms to locate and identify cracking in the test coupons, pressure boundary, and other components; multidimensional displays and associated human factors studies; and online condition of materials in the heat transport systems.

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FIGURES

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ACRONYMS

AHTR	advanced high temperature reactor
ARE	Aircraft Reactor Experiment
ASME	American Society of Mechanical Engineers
AWS	American Welding Society
BPV	Boiler and Pressure Vessel
DOD	Department of Defense
DOE	U.S. Department of Energy
DRACS	direct reactor auxiliary cooling system
FHR	fluoride-salt-cooled high temperature reactor
HCHE	helical coil heat exchanger
HTGR	high temperature gas-cooled reactor
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
LOCA	loss of cooling accident
LWR	light water reactor
MSR	molten salt reactor
MSRE	molten-salt reactor experiment
NASA	National Aeronautics and Space Administration
PCHE	printed circuit heat exchanger
SHX	molten salt secondary heat exchanger
NDE	nondestructive examination
NGNP	Next Generation Nuclear Plant
NGNR	Next Generation Nuclear Reactor
NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
R&D	research and development
RTD	resistance temperature device
SHX	secondary heat exchanger
SSCs	systems, structures, and components
TDRM	Technology Development Roadmap
TEV	Technical Evaluation
TRL	Technology Readiness Level
V&V	verification and validation

NOMENCLATURE

Basis of Rating	Justification for calculated readiness, including what test(s) and actions were completed
Bench-Scale	Integrated components that provide a representation of systems, structures, and components (SSCs) and that can be used to determine concept feasibility and develop technical data. Typically configured for laboratory use to demonstrate the technical principles of immediate interest. May resemble final SSC in function only. (~1:3600 scale)
Engineering-Scale	A model or facsimile of the system used as a basis or standard for proof of principle testing and/or operation. The model or facsimile may progress through several evolutions, but is not necessarily in form or fit a final version. (~1:20 scale)
Experimental-Scale	A component to be tested that will provide the data or prove the intended function, but is not necessarily like the design of the final SSC. (~1:1000 scale)
Pilot-Scale	A model or facsimile of the subsystem used as a basis or standard for functional testing and/or operation. The model or facsimile may progress through several evolutions, but is not necessarily in form or fit a final version. (~1:100 scale)
Prototype-Scale	Subsequent to pilot/engineering-scale model or facsimile of the SSC, a version that is intended to be the final version or is an evolutionary step toward the final version. (~1:4 scale)
Laboratory Environment	Refers to a controlled environment in which effects can be quantified with appropriate accuracy.
Operational Environment	For SSCs normally operating when the plant is running, the operational environment consists of the normal operating fluids and anticipated temperatures (static and transient) and pressures (static and transient). For SSCs not normally operating, the operational environments are the design basis operating fluids, temperatures, and pressures.
Relevant Environment	Environment that simulates the key aspects of the operational environment. This environment can be (1) a real-world environment that simulates key operational requirements and specifications required of the final SSC, or (2) a simulated environment that allows for testing of a model or facsimile of the SSC. The environment may not necessarily have the same temperatures, pressures, and fluids as the operational environment, but is similar insofar as simulating the thermo-hydraulic pressure drops and corrosion/reaction rates.

Technology Development Roadmap for the Advanced High Temperature Reactor Secondary Heat Exchanger

1. INTRODUCTION

This Technology Development Roadmap (TDRM) presents the path forward for deploying large-scale molten salt secondary heat exchangers (SHX) and evaluating the benefits of using molten salt as the heat transport medium for advanced high temperature reactors (AHTRs). This TDRM will aid in the development and selection of the required heat exchanger for power production (the first anticipated process heat application), and other industrial process heat applications, such as, hydrogen, methanol to gasoline, and ammonia production. This TDRM:

- Establishes the current state of SHX technology readiness
- Defines a path forward that systematically and effectively tests this technology to overcome areas of uncertainty
- Defines a methodology for the achievement of an appropriate level of maturity prior to construction and plant operation
- Identifies issues and prioritizes future work for maturing the state of SHX technology.

This study discusses the results of a preliminary design analysis of the SHX and explains the evaluation and selection methodology. An important engineering challenge will be to prevent the molten salt from freezing during normal and off-normal operations because its high melting temperature (390°C for $KF\text{-}ZrF_4$) is well above ambient temperatures. The efficient transfer of energy for industrial applications depends on the ability to incorporate cost-effective heat exchangers between the nuclear heat transport system and industrial process heat-transport system.

The need for efficiency, compactness, and safety challenges the capabilities of existing heat exchanger technology. The description of potential heat exchanger configurations or designs (such as printed circuit, spiral or helical coiled, ceramic, plate and fin, and plate type) is covered in an earlier report (Sabharwall et al. 2012). Significant future work, much of which is suggested in this report, is needed before the benefits and full potential of the AHTR can be realized. The execution of this TDRM will focus research efforts on the near-term qualification, selection, or maturation strategy as detailed in this report. Development of the integration methodology, along with research and development (R&D) needs, are ongoing tasks that will be covered in the future reports as work progresses. Section 2 briefly presents the integration of AHTR technology with conventional chemical industrial processes. See Idaho National Laboratory (INL) Technical Evaluation (TEV) TEV-1160 (2011) for further details.

2. OVERVIEW OF AHTR TECHNOLOGY

The AHTR is part of the fluoride-salt-cooled high temperature reactor (FHR) class of nuclear reactors that has recently been included in the advanced reactor concept program. The primary mission for the AHTR is the generation of low-cost electricity while maintaining full passive safety (Holcomb et al. 2011). Necessary knowledge for the operation of AHTRs has been gained by the following research and operational (Flanagan et al. 2012) experience:

- Molten salt reactors (MSR) have provided data about appropriate materials, procedures, and components necessary to use high-heat capacity liquid fluoride salts as primary or secondary coolants
- Liquid metal reactors have provided design experience on using low-pressure liquid coolants, passive decay heat removal, and hot refueling
- High temperature gas-cooled reactors (HTGRs) have provided experience with coated particle fuel and graphite components
- Light water reactors have shown the potential of transparent, high-heat capacity coolants with low chemical reactivity
- Modern coal-fired power plants have provided design experience with advanced supercritical-water power cycles.

AHTRs will produce high outlet temperatures (704°C) using coated particle fuel and can potentially improve upon the attributes of other reactors. The AHTR reactor core consists of coated particle fuel embedded within graphite fuel elements. Graphite reflectors provide additional moderation and core structure. Heat removed from the reactor is transferred to an intermediate salt that is then transferred to a tertiary side for power production and/or process heat applications. The first FHR is still in the early development stage, but may, of necessity, require a test-scale reactor sized demonstration approximately the same scale as the molten salt reactor experiment (MSRE) in order to validate the system attributes before proceeding to larger-scale systems (Holcomb et al. 2009). So far, FHR analyses have focused mainly on power production, but new concepts are under investigation for process heat applications, making them more attractive to industry.

AHTR, which provides high-temperature heat to increase thermal efficiency for power production and process heat applications, could be scaled to higher thermal power for better economics and still meet or exceed the safety performance of other advanced reactor concepts (Ingersoll et al. 2004). AHTR design attributes that promote favorable economics are also listed in Table 2-1.

Table 2-1. AHTR design attributes (Ingersoll et al. 2004).

AHTR Attribute	Phenomenological Impact(s)	Cost Implications
High primary coolant volumetric heat capacity	Low fluid pumping requirements Near constant temperature energy transport	Compact coolant and heat transport loops (small pipes, pumps, heat exchangers)
Low primary system pressure	Low pipe break/loss of cooling accident (LOCA) energetic Low source term driving pressure	Thin-walled reactor vessel and piping Smaller, less complex containments
Transparent coolant with low chemical activity	Visible refueling operations Low pipe break/LOCA efficiencies	Efficient refueling Smaller containments
High primary system temperatures	High power conversion efficiencies	Lower fuel costs and hot refueling
Tristructural isotropic fuels	Large fuel temperature margins Good fission product containment	Robust operating margins and safety case

Pebble bed, prismatic, and plate fuel type reactor designs are being considered for an AHTR. Plate fuel requires additional research because of the minimal pressure drop advantage of pebble bed cores. A conceptual drawing of a pebble bed AHTR proposed by the University of California at Berkeley is shown in Figure 2-1.

The minimal pressure drop characteristic of liquid salt coolants increases natural circulation flow through the core during a loss-of-forced flow accidents, thereby lowering peak accident fuel temperatures and enhancing passive safety (Holcomb et al. 2012). These advanced reactor concepts will also have higher fuel burnup (Sabharwall et al. 2012). AHTR fuel assemblies are slightly buoyant in liquid salt, which limits damage in the event of a fuel drop (Flanagan et al. 2012).

Heat in an AHTR is transferred from the reactor core by the primary liquid-salt coolant to an intermediate heat-transfer loop through intermediate heat exchangers (IHX). The intermediate heat-transfer loop also uses a liquid-salt coolant to move the heat through an SHX to a power conversion system and/or a process heat industrial application. The reactor outlet temperature for a first-of-a-kind demonstration will be 704°C; thus the heat exchangers in the AHTR concept operate in a severe environment and their performance is directly related to the overall system efficiency and safety. They are considered key components that need to be extensively investigated.

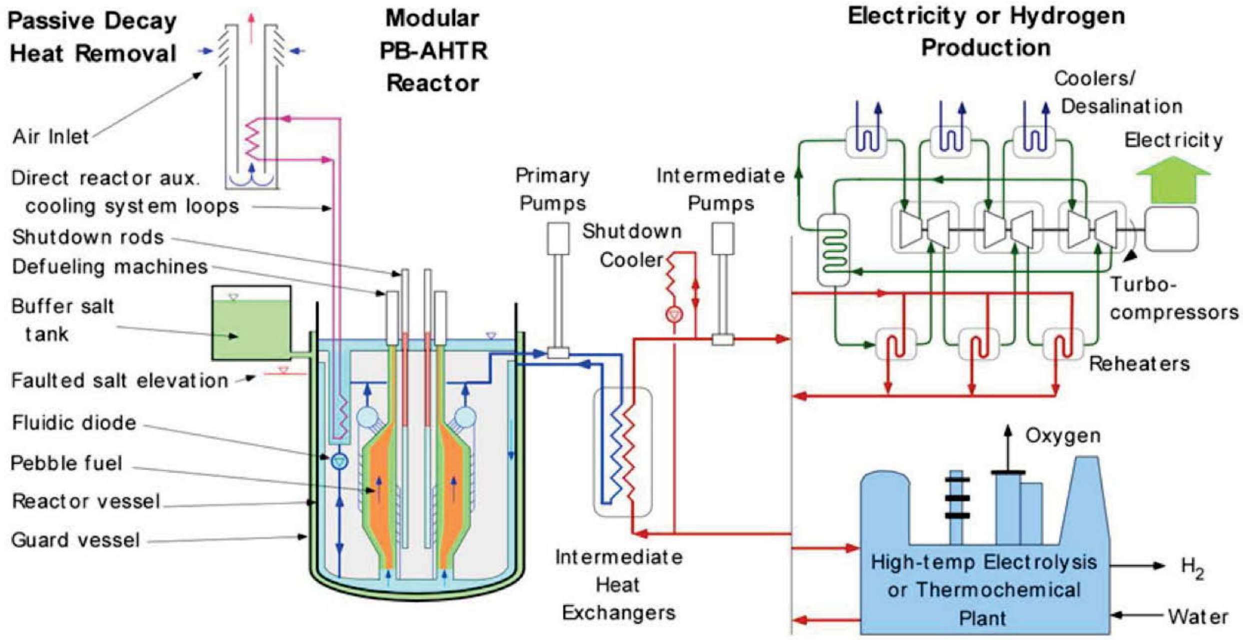


Figure 2-1. Conceptual design of a pebble bed AHTR with power generation cycle (Holcomb et al. 2009).

An AHTR may use several heat exchangers and/or configurations to transfer heat from the reactor primary loop to the power-conversion system or industrial plants. Three SHXs are currently planned and will transfer heat from the reactor primary to the intermediate heat transfer loop(s). One, two, or three intermediate loops will be used and the final configuration will depend largely on the power conversion requirements. Employing three SHXs and power-conversion systems decreases the probability of a “loss of ultimate heat sink accident”—losing 100% of the system primary heat sink at once (Holcomb et al. 2012).

2.1 AHTR Programs and Current Status

AHTRs are intended to increase energy efficiency in the production of electricity and/or provide high temperature heat for industrial processes. This source of heat for these industrial processes is the intermediate loop. The intermediate loop reduces the required volume of expensive primary coolant salt and provides physical separation between the energetic power cycle processes and the reactor systems (Holcomb et al. 2012). Current design efforts focus on maximizing the system's economic performance by employing modular, open-top construction to minimize cost, and on maintaining full passive safety during severe environmental challenges (Holcomb et al. 2012). The primary loop reference salt for AHTR is currently Li_2BeF_4, referred to as Flibe. Heat in an AHTR is transferred from the reactor core by the primary liquid-salt coolant to an intermediate heat-transfer loop through IHXs. The intermediate heat-transfer loop uses an intermediate liquid-salt coolant through an SHX to move the heat to a power conversion system (Rankine cycle) as shown in Figure 2-2. Previous analysis (Sabharwall et al. 2011a) of the power conversion system to produce electricity showed that the Rankine subcritical and supercritical cycle with a turbine inlet temperature of 679°C (based on a reactor outlet temperature of 704°C) can yield a conversion efficiency of 42 and 44%, respectively, with $KF\text{-}ZrF_4$ as the secondary salt coolant. The heat exchangers are considered key components that need to be extensively investigated because they are operated in a severe environment and their performance is directly related to the overall system efficiency and safety.

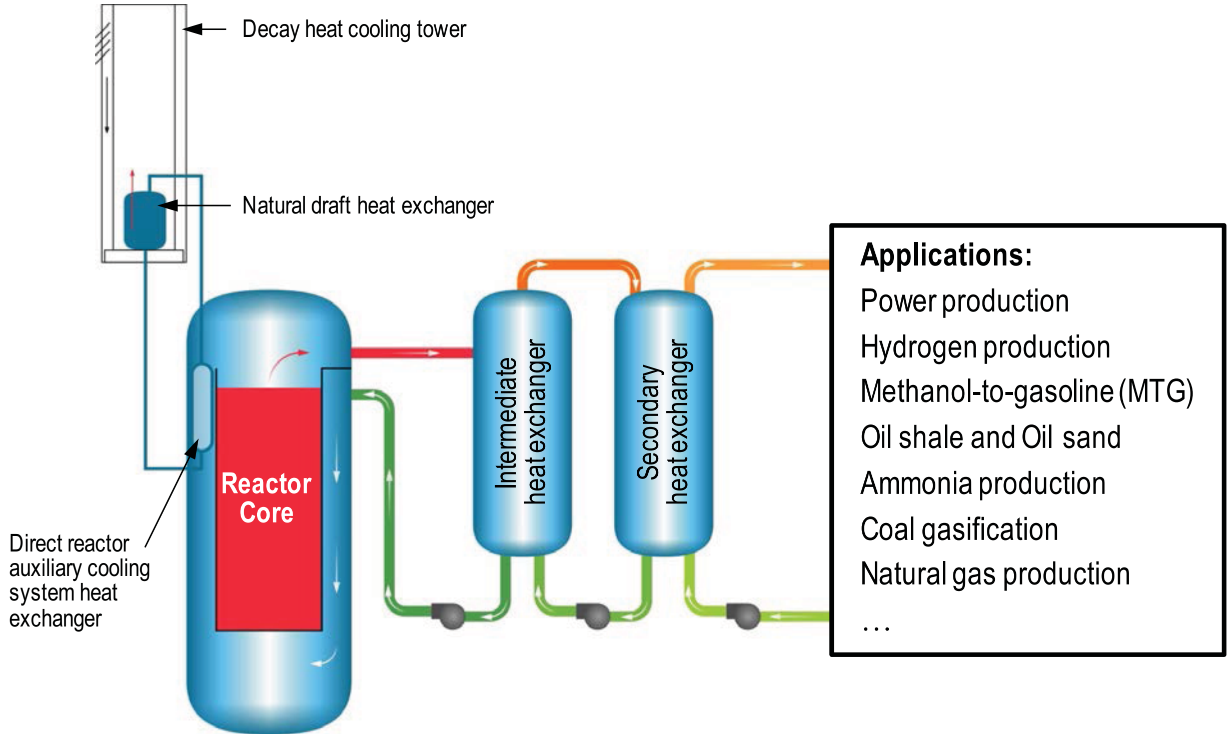


Figure 2-2. Thermal energy transfer in AHTR for power production.

2.2 SHX Benefits

The efficient transfer of energy for power production depends on the ability to incorporate effective heat exchangers between the nuclear heat transport system and the power production process. However, the need for efficiency, compactness, and safety challenges the boundaries of existing heat exchanger technology. Heat exchanger selection is most strongly influenced by the process application and operational conditions that determine or influence requirements for cost, size, reliability, robustness, maintenance, expected life, etc.

The intent of this work is to identify issues and prioritize future work for advancing SHX technology. The SHX technology, coupled with an AHTR, provides a high safety margin with passive decay heat removal systems that passively cool themselves in the event of severe accident scenarios. For AHTR, the SHX will transfer heat to the process side as shown in Figure 2-2 above. Two main aspects in determining the effectiveness of a coolant are heat transfer and transport capabilities. Heat transfer capability can be defined by the heat transfer coefficient, while heat transport capability is defined by the ratio of thermal power removed to the pumping power required (Latzko 1970). A coolant could provide good heat transfer capability but have poor heat transport capability. For example, sodium and lithium offer superior heat transfer capability because of larger thermal conductivity, but liquid salts have a much higher value for density compared to both lithium and sodium and so are better coolants in heat transport (Latzko 1970; Sabharwall et al. 2010).

Molten salts are excellent candidates because they can be heated up to 1000°C and still maintain thermal stability. This allows high energy steam generation at utility-standard temperatures of 11.4 MPa and 550°C, thus achieving high thermodynamic cycle efficiencies of approximately 40% in modern steam turbine systems. However, no single-component salt meets the requirement of low melting temperature. Hence, multicomponent eutectic mixtures characterized by a single melting point are needed to reduce the melting temperature to less than 500°C. Combining multiple salts to form a eutectic composition provides compositional and phase stability, and therefore, uniform thermophysical properties in the operating temperature range (Grimes et al. 1972; Ingersoll et al. 2007).

The IHX and SHX reside between the nuclear reactor and the balance of plant—the non-nuclear power production and industrial applications that use the reactor's heat. The low pressure liquid-salt intermediate loop of an FHR enables separating, by several tens of meters, the reactor building from the energy use processes with their potential for adverse mechanical or chemical impacts on the nuclear island. The reactor is thus also separated from the pressure waves propagating down the intermediate loop piping by rupture disks or other pressure relief mechanisms so that a disturbance within the energy use portion of the plant should not propagate to the nuclear island.

2.3 Industrial Process Heat Applications

Some of the industrial process heat applications being considered for integration with AHTR are: hydrogen production via steam methane reforming of natural gas and high temperature steam electrolysis, substitute natural gas production, oil sands recovery via steam assisted gravity drainage, coal-to-liquid production, natural gas-to-liquids production, methanol-to-gasoline production, ammonia production, and ex situ and in situ oil shale extraction. The temperature ranges of applications that could be coupled to the AHTR with the current reactor outlet temperature (green band) and others that could potentially be coupled if the reactor outlet temperature was raised (red band) are shown in Figure 2-3. For more information on industrial process applications refer TEV-1160.

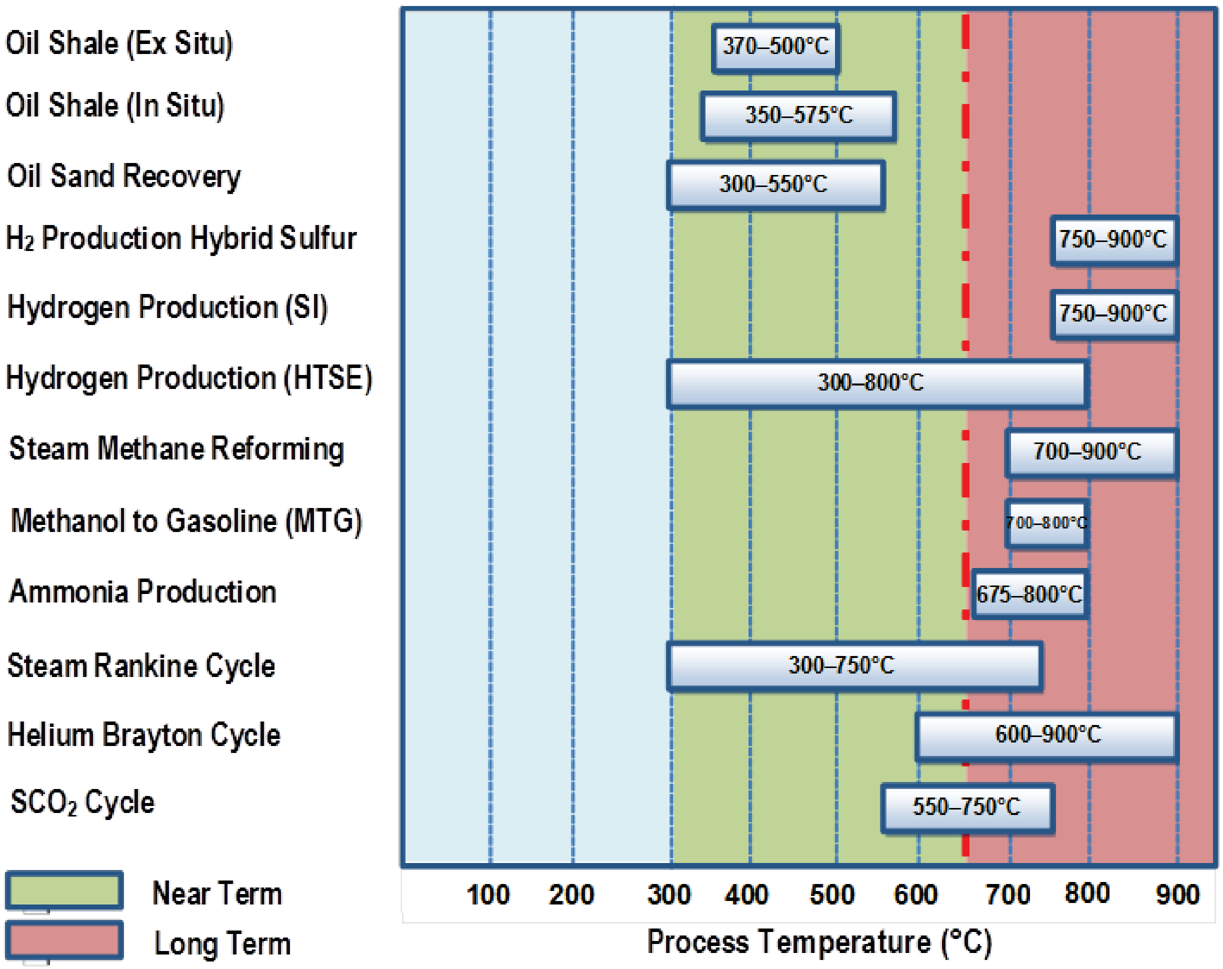


Figure 2-3. Potential process applications for AHTR (TEV-1160).

3. MOLTEN SALT-SECONDARY HEAT EXCHANGER TECHNOLOGY MATURATION APPROACH AND PHILOSOPHY

The tools used to analyze the existing reactors for safety and to develop the bases for the licensing of future reactor designs must be validated so that there is an assurance that the analytical results reflect the response of the heat exchanger in final plant configurations. This verification and validation (V&V) effort will require data from representative tests demonstrated in relevant environments of physical systems.

The iterative process for modeling and analysis of reactors with process heat transfer involves developing the analytical tools, identifying the testing needs, and developing data to support the V&V in representative tests, as shown in Figure 3-1.

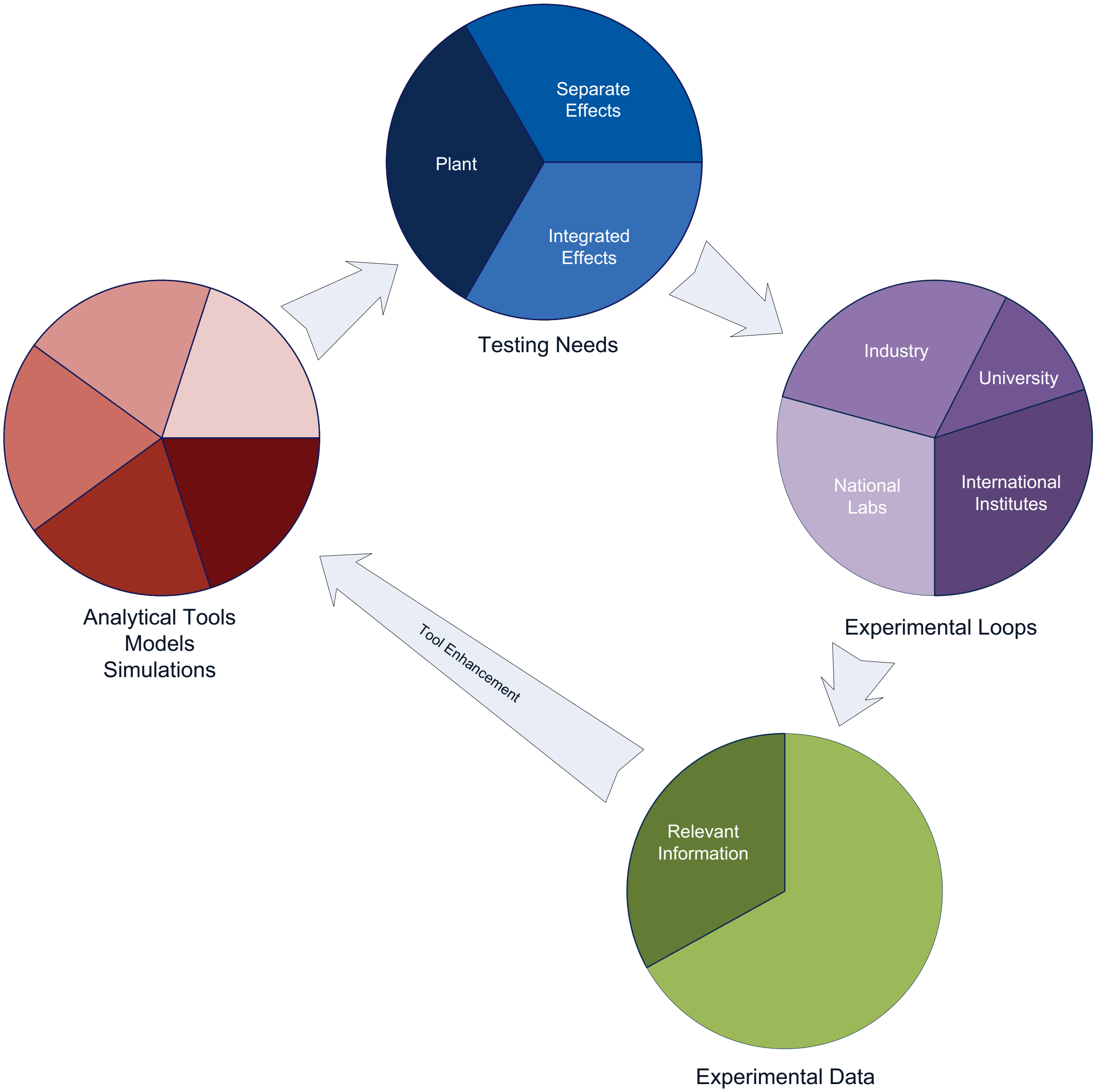


Figure 3-1. Interconnection between tools, testing needs, and testing capabilities.

The V&V tests will include:

- Separate effects tests—tests intended to isolate a particular phenomenon of interest from other associated phenomena that may complicate the interpretation of the results
- Integrated effects tests—tests that combine particular phenomena of interest to determine their cumulative or synergistic effects on the specimen
- Plant tests—tests conducted in a relevant environment such as the actual plant or a plant prototype.

These empirical test data and the derived relevant information will advance understanding of the physical systems in relevant environments, inform the licensing efforts, and help identify needed enhancements to the analytical tools.

3.1 Technology Readiness Assessment Methodology

The Molten Salt Project is adopting a Technology Readiness Level (TRL) system to guide the technology development of SHXs. TRLs are scales representing the state of technological maturity of the SSCs that comprise the heat exchanger in a final integrated plant configuration. TRL scales are used within project management to inform programmatic decisions concerning technology advancement, technology down-selects, task planning, risk analyses, task prioritization, and allocation of resources.

The TRL process originates with National Aeronautics and Space Administration (NASA) and the U.S. Department of Defense (DOD) and evaluates the readiness of new technological systems to perform their function integrated with all other plant systems. This project follows Department of Energy (DOE) Guide 413.3-4A, “Technology Readiness Assessment Guide,” (DOE 2011) and uses TRLs with a tailored scale of 1–9, comparable to the Standard 1–9 scale used by NASA and DOD. TRLs are an input to inform project management of the readiness of a particular technology, component, or system. An assessment for TRLs 1–5 typically occurs on an individual technology or component with a calculated roll up TRL for the associated system made up of individual components. Small-scale and relatively inexpensive testing, at TRLs 1–5, facilitates the discovery of technology enhancements that can be incorporated into the final design with high confidence of success, because they have been demonstrated prior to full-scale deployment.

As a technology or component progresses to higher levels of maturity, integrated testing occurs, allowing TRL assessments directly against subsystems and full systems. TRL is not an indication of the quality of technology implementation in the design. The integrated testing or modeling occurs at increasingly larger scales and in increasingly relevant environments, thus achieving higher TRL ratings (TRLs 6–9). Abbreviated TRL definitions and their corresponding physical systems are shown in Figure 3-2.

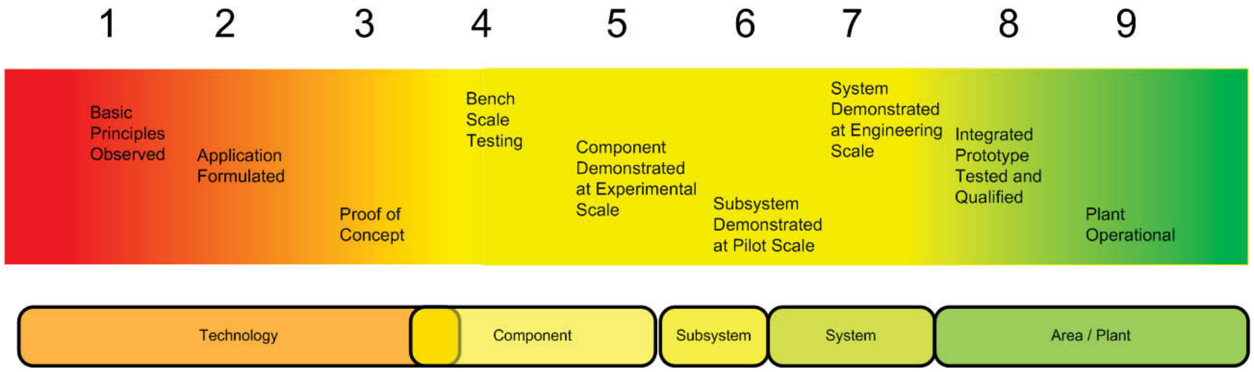


Figure 3-2. Technology readiness levels.

3.2 TRL Definitions

TRL indicates the maturity level of a given technology. The TRL scale ranges from 1 (basic principle observed) through 9 (total system used successfully in project operations). Testing should be done in the proper environment and the technology tested should be of an appropriate scale and fidelity.

Detailed and abbreviated definitions for each TRL have been adapted specifically for the AHTR program. These adapted definitions are contained in Table 3-1.

Table 3-1. TRL definitions and abbreviations.

Rating	TRL Definition	Abbreviated Definition
1	Basic principles observed and reported in white papers, industry literature, lab reports, peer-reviewed literature, etc. Scientific research without well-defined application.	Basic principles observed
2	Technology concept and application formulated. Issues related to performance and technology concept have been identified. Paper studies indicate potentially viable system operation.	Application formulated
3	Analytical and experimental critical function and/or characteristic proven in laboratory. Technology or component tested at laboratory scale to identify/screen potential viability in anticipated service.	Proof of Concept
4	Technology or Component is tested at bench scale to demonstrate technical feasibility and functionality. For analytical modeling, use generally recognized benchmarked computational methods and traceable material properties.	Bench-scale testing
5	Component demonstrated at experimental scale in relevant environment. Components have been defined, acceptable technologies identified, and technology issues quantified for the relevant environment. Demonstration methods include analyses, verification, tests, and inspection.	Component verified at experimental scale
6	Components have been integrated into a subsystem and demonstrated at a pilot scale in a relevant environment.	Subsystem verified at pilot scale in a relevant environment
7	Subsystem integrated into a system for integrated engineering scale demonstration in a relevant environment.	System demonstration at engineering scale
8	Integrated prototype of the system is demonstrated in its operational environment	Integrated prototype tested and qualified in a nonradiological operating environment
9	Commercial scale in final configuration operated in facility at design temperature, pressure, and flow rate	Plant Operational

The characteristics of a maturing technology are:

- *Relevant Environment*. The environment (temperature, pressure, fluid, flow rate) in which testing occurs becomes increasingly identical to the AHTR environment.
- *Scale*. The size of the test increases from lab scale to full scale.

- *Systems Integration*. The technologies tested are increasingly and progressively integrated with the testing of multiple components, subsystems, and systems and with final plant (AHTR) testing, which includes multiple areas.

The technology readiness assessment assesses how far technology development has proceeded based on documented evidence. It is not a pass/fail exercise, nor is it intended to provide a value judgment of the technology developers or the technology development program. Rather, it is a review process to ensure that critical technologies reflected in a project design have been demonstrated to work as intended (technology readiness) before committing to construction expenses (DOE G 413.3-4A).

4. SHX TECHNOLOGY READINESS ASSESSMENT

The current state of SHX readiness is based on the preliminary selection of materials of construction, design, fabrication processes, and the molten salt coolant. These selections are preliminary and will be revisited as additional R&D data warrants. These preliminary selections comprise the reference configuration detailed below.

4.1 SHX Design Description and Assumptions

4.1.1 SHX Functions and Components

The SHX accepts heat from the secondary loop and transfers it to the process heat applications via the tertiary loop. The SHX interfaces with the IHX on the upstream side and with industrial processes on the downstream side. The IHX transfers heat between the reactor and the SHX. The SHX transfers heat to the downstream applications, including hydrogen production, power production (steam generation), and process heat.

The primary function of the SHX is to transport thermal energy, in the form of heat, from the reactor to the downstream applications while isolating the upstream and downstream coolants from each other. Secondary functions include providing a pressure boundary and insulating the vessel.

4.1.2 Reference Configuration

There are multiple options for the SHX vessel design and internals, including materials, fluids, structure types, and number of heat exchangers.

Seven candidate materials are being considered for the pressure vessel: Haynes 242, Alloy 800H, Inconel 617, Hastelloy N, 316 SS, silicon carbide (future), and ceramic metal composites (future).

The key decision discriminators for the materials of vessel construction include: material properties (creep fatigue, embrittlement, thermal expansion, thermal fatigue, crack resistance, oxidation resistance, carburization resistance, thermal conductivity); availability of adequate evaluation data; and performance in various modes (steady-state, depressurized, conduction, and cool down). Additional discriminators may include: maturity of material data, R&D status, service experience, American Society of Mechanical Engineers (ASME) code qualification, fabricability, licensing, availability, and cost.

The candidate configurations for the heat exchanger are:

- Conventional shell and tube
- Shell and tube helical coil
- Printed circuit heat exchanger (PCHE).

The key structural design decision discriminators for the type of heat exchanger includes: localized stress/strain, erosion, and corrosion; dust susceptibility; material thickness; qualification/codification; process heat application; and capital and operating costs. Additional discriminators may include: transient condition acceptability, in-service inspectability, tritium migration allowance, compactness, performance (heat transfer rate), fabricability, repairability, and availability.

The five candidates being considered for the secondary molten salt fluid are KF-ZrF_4, FLiBe, FLiNaK, KCl-$MgCl_2$, and $NaNO_3$-$NaNo_2$ KNO_3 (HiTec Nitrate—nitrite salt).

The key fluid decision discriminators include: heat transfer capacity, melting point, infiltration to the primary loop in an accident scenario and ease of recovery; availability of the fluid; purification capability (removal of tritium); interaction with IHX material (i.e., corrosion) and cost.

The multiple options result in many different configurations. For the purposes of this discussion, the reference configuration consists of:

- Hastelloy N as the material of construction
- Helical coil shell and tube heat exchanger
- KF-ZrF_4 as the secondary coolant
- Coupling with the supercritical Rankine cycle to Oak Ridge National Laboratory's (ORNL) 3400 MW AHTR design
- Three heat exchangers (for redundancy)
- Reheat from steam (downstream of high pressure turbine), not within the heat exchanger (too close to KF-ZrF_4 freezing temperature)
- Molten salt (KF-ZrF_4) is on shell side and steam on tube side.

While the PCHE has significant heat transfer efficiency and a cost advantage over the competitors, it has numerous technical issues yet to be overcome. As such, it is recommended that both the helical coil heat exchanger (HCHE) and PCHE be developed in parallel with the HCHE being used in the first of a kind SHX. The PCHE should be employed after technical issues are resolved.

The explanation of each of the options and the reasons for preliminary selection of the reference configuration is further explained in Section 5 of this report.

4.2 SHX Current Technology Readiness

The authors of this report believe the SHX is currently at a TRL-3. The SHX has surpassed a TRL-1 and 2 because basic principles have been observed and the SHX technology concept and application is well formulated. Issues related to performance and technology concept have been identified. Paper studies indicate potentially viable system operation. Furthermore, proof of concept has been established. The SHX (in both HCHE and PCHE forms) has been tested and proven in a helium environment at bench scale, and shows potential viability in anticipated service.

A TRL rating of 3 is based on the need to enhance understanding of material properties and complete material qualification, develop simulation models for the SHX and develop the methods for performance modeling of both HCHE and PCHE, respectively.

4.3 SHX Analysis and Selection

The SHX provides the interface between the intermediate coolant and the power conversion system or process application. The identification of a viable SHX concept is based on the options for the power conversion scheme or the process heat application design needs.

While the IHX serves as the primary coolant boundary, the SHX also serves as the coolant boundary and must be constructed to maintain system integrity under normal, off-normal, and accident conditions. To maintain high cycle efficiencies, it must also minimize temperature differences between the intermediate molten salt and the process working fluid while minimizing the pressure drop. The difference in pressure required in the power-conversion system and process heat applications imposes stringent requirements on the heat exchanger design, which is explained in detail in Sabharwall et al. 2011a.

The AHTR SHX design framework is shown in Figure 4-1. Heat exchangers for an AHTR is subjected to a unique set of conditions that impose several design challenges not encountered in standard heat exchangers. Corrosive molten salts, especially at higher temperatures, require specialized materials (alloys) throughout the system to mitigate corrosion.

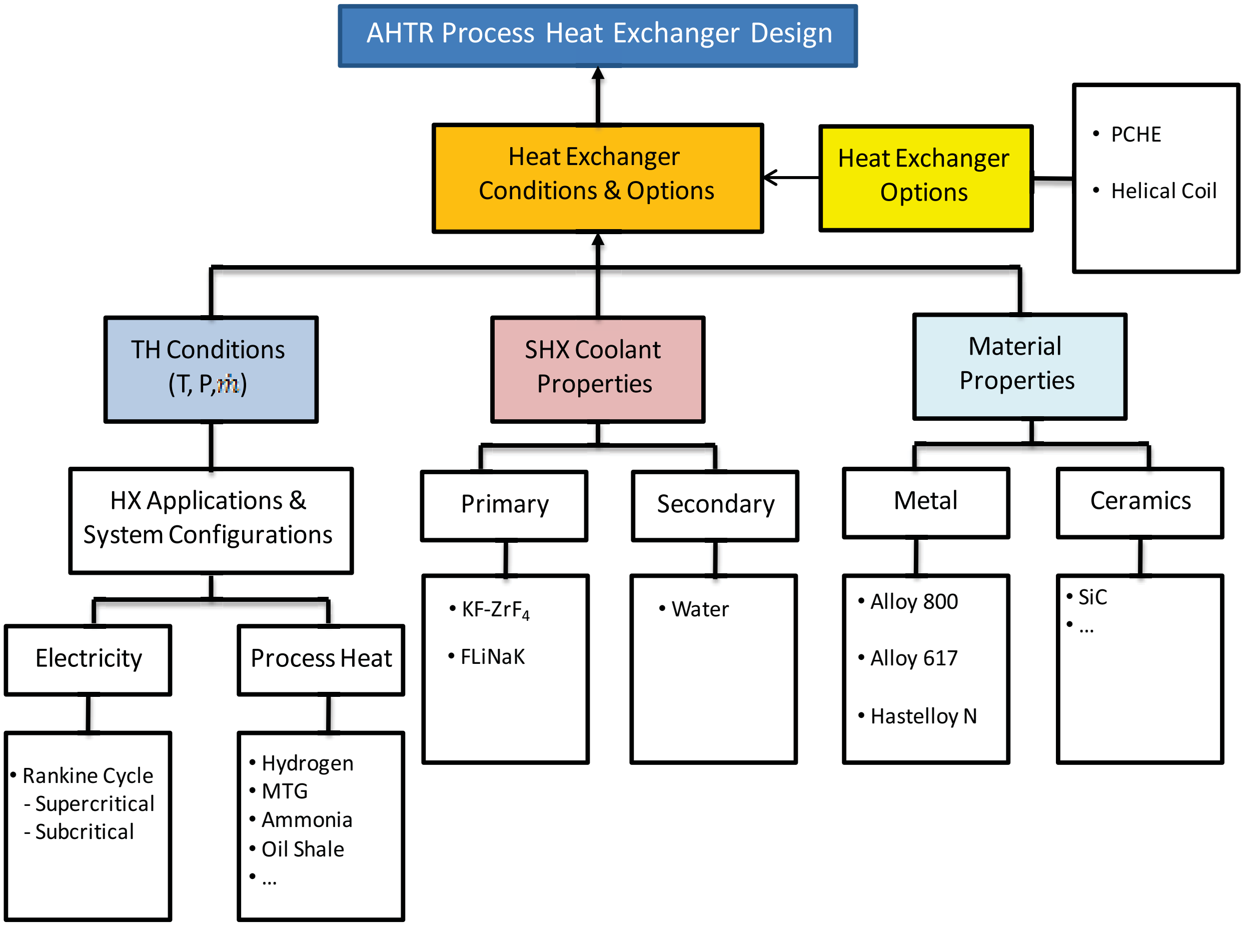


Figure 4-1. AHTR SHX heat exchanger design framework.

A variety of heat exchangers are available in industry, including shell-and-tube, plate-and-frame, brazed-plate, plate-and-fin, PCHE, bayonet, etc. Heat exchanger design and selection involves many trade-offs associated with geometrical and operational variables. Candidate heat exchangers were selected based on operating parameters, mainly temperature and pressure (Sabharwall et al. 2011a and 2011b). More detailed comparisons were then carried out among the candidate designs using an evaluation matrix. Further multicriteria decision analysis was used based on the criteria shown in Table 4-1, to select the optimum heat exchanger for a given application (Sabharwall et al. 2011 and 2011b).

Table 4-1. Criteria for AHTR SHX selection.

Criteria	Subcriteria
Thermal Performance	Heat Transfer Performance (heat transfer/pumping power) Effectiveness Fouling
Structural Performance (Evaluated by ASME B&PV Design rules)	Mechanical Stress Thermal Stress Vibration
Material Performance	Geometry (heat exchanger wall thickness) Corrosion Allowance in Design (uniform corrosion) Localized Corrosion/Environmental Cracking Fluid Compatibility
Technology Readiness	Material Fabrication Method ASME B&PV Code Status Industrial Experience
System Integration	Size Adaptability Scalability
Tritium Permeation	Material Geometry (total heat transfer area + wall thickness)
Inspection	Ease of Inspection (geometry) and field access
Maintenance	Cleaning Waste Repairing
Initial Cost [a]	Material Fabrication Installation
Operability	Reliability Operating & Maintenance

The shell and tube configuration is the most common configurations used in industry. It consists of a number of tubes that pass through and are sealed to thick metal plates (tubesheets) on both ends. This tube bundle is installed in a cylindrical vessel, the shell. One fluid flows through the tubes and the other, contained by the shell, flows over the exterior of the tubes. A variation on the shell and tube heat exchanger is the helical tube and the shell design. In this design the tubes are wound in a helical fashion, providing some flexibility to accommodate thermal expansion of the tubes. A helically wound tube and shell design is currently being used in Japan Atomic Energy Agency High Temperature Engineering Test Reactor as shown in Figure 4-2. For AHTR-SHX HCHE is also being considered, for detailed preliminary design and analysis information refer Sabharwall et al. 2011b.

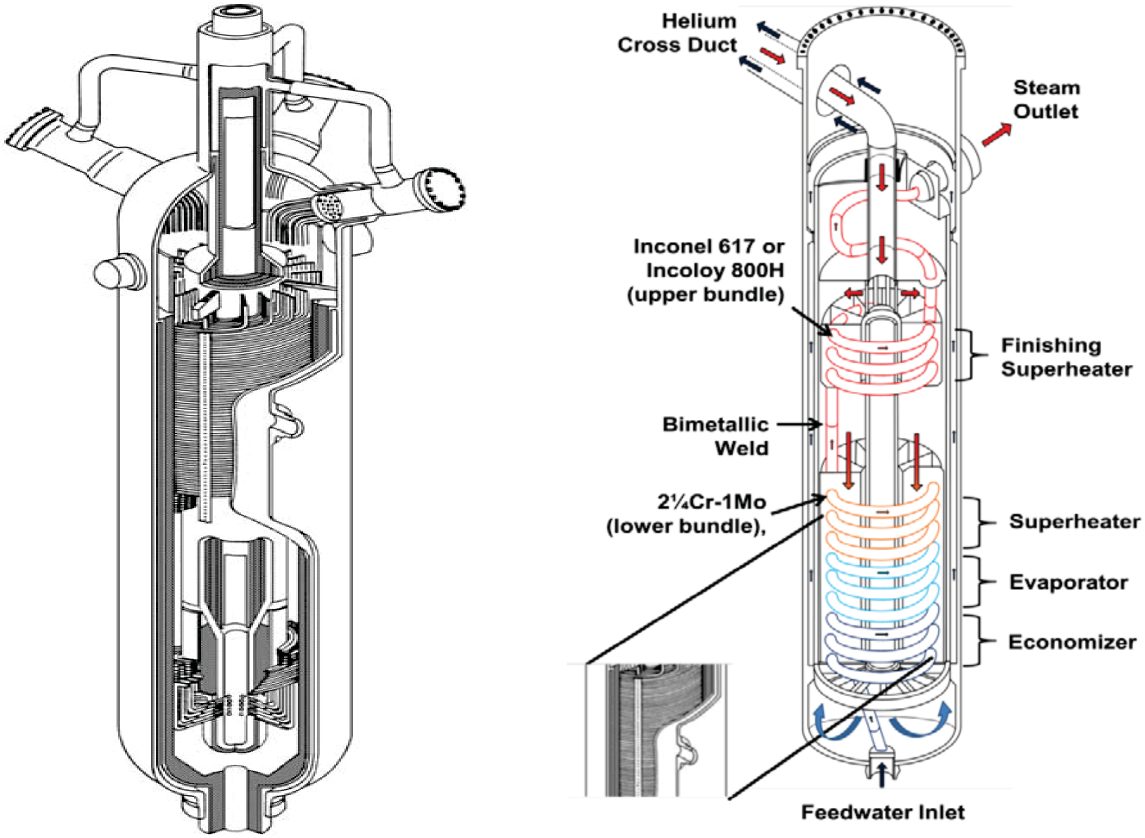


Figure 4-2. Helical coil heat exchanger (Hoffer et al. 2011).

The other type of the heat exchanger being considered is the compact heat exchanger. Compact heat exchangers provide much more heat transfer area per unit volume than the shell and tube designs and thus take up less room in the reactor building, and could be made in a large number of configurations. Compact configurations include plate-fin, printed circuit, capillary tube, and plate stamped. The plate-fin design typically uses corrugated metal structures sandwiched between flat plates to form the primary and secondary fluid flow paths. The printed circuit design uses stack of plates into which flow channels have been etched or machined as shown in Figure 4-3. For detailed preliminary design and analysis information refer to Sabharwall 2011b.

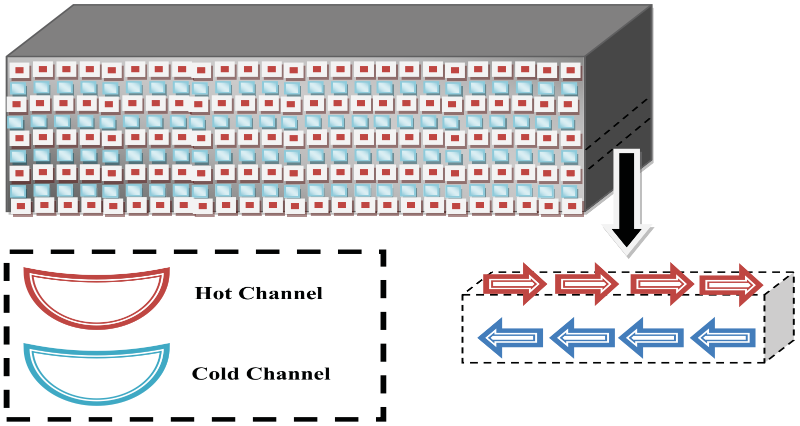


Figure 4-3. Printed circuit heat exchanger.

4.3.1 SHX Requirements

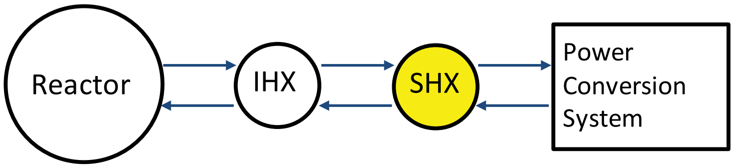
The heat exchanger required for AHTR is subjected to a unique set of conditions that bring with them several design challenges not encountered in standard heat exchangers. The somewhat corrosive molten salts, especially at higher temperatures, require specialized materials throughout the system to avoid corrosion, and adverse high-temperature effects such as creep. Table 4-2 summarizes the basic design conditions and requirements for the AHTR SHX with a coupled Rankine power cycle.

Table 4-2. SHX design requirements and basic conditions for the AHTR (Sabharwall et al. 2011b).

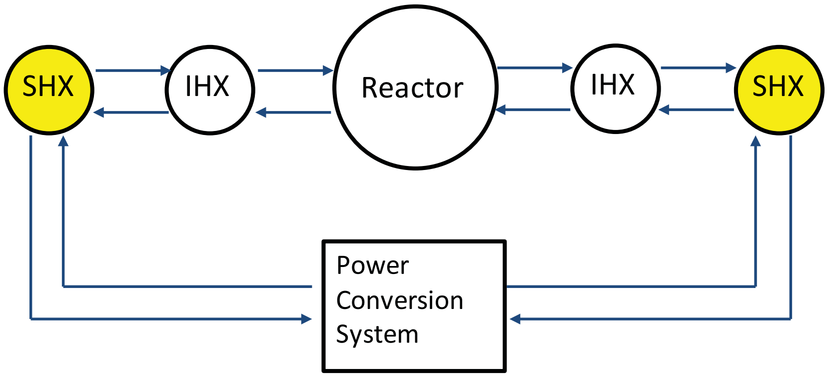
Parameter	Requirements
Reference System Configuration	AHTR + Supercritical Steam Rankine Power Conversion System
Heat Exchanger Type s	Helical coil & Printed circuit
Heat Exchanger Duty (MW)	3400/1700/1130
Primary Coolant	KF-ZrF$_4$
Secondary Coolant	Water/Steam
Primary Temperature (Tin/Tout)	679/587°C (supercritical Rankine cycle) 679/586.1°C (subcritical Rankine cycle)
Secondary Temperature (Tin/Tout)	251/593°C (supercritical Rankine cycle) 241.7/550°C (supercritical Rankine cycle)
Primary Pressure (MPa)	0.103
Secondary Pressure (MPa)	25 (supercritical Rankine cycle) 17.3 (subcritical Rankine cycle)
Tube Material	Alloy N
Shell Material	Alloy N

- As shown in Table 4-3, the total thermal duty of the AHTR heat exchangers is 3400 MW(t). In this design, three different options were considered based on the number of heat exchangers and arrangement as shown in Figure 4-4: (1) 1 SHX, (2) 2 SHXs, and (3) 3 SHXs (Sabharwall et al. 2011b). The Rankine Cycle was chosen as the coupled power cycle for the following reasons (for detail analysis on power conversion study and comparison refer Sabharwall et al. 2011a):
- The supercritical Rankine steam cycle has the highest power cycle efficiency and the advantage of being a current commercial technology, but the disadvantage of the highest turbine inlet pressure
- The supercritical power cycle has the highest efficiency but the highest pressure difference (23.9 MPa); supercritical cycles heated by coal and natural gas have the same problem.
- The subcritical Rankine cycle has a pressure difference of 16.9 MPa, which would reduce the stress on the heat exchanger with only a shift from 44 to 42% efficiency.

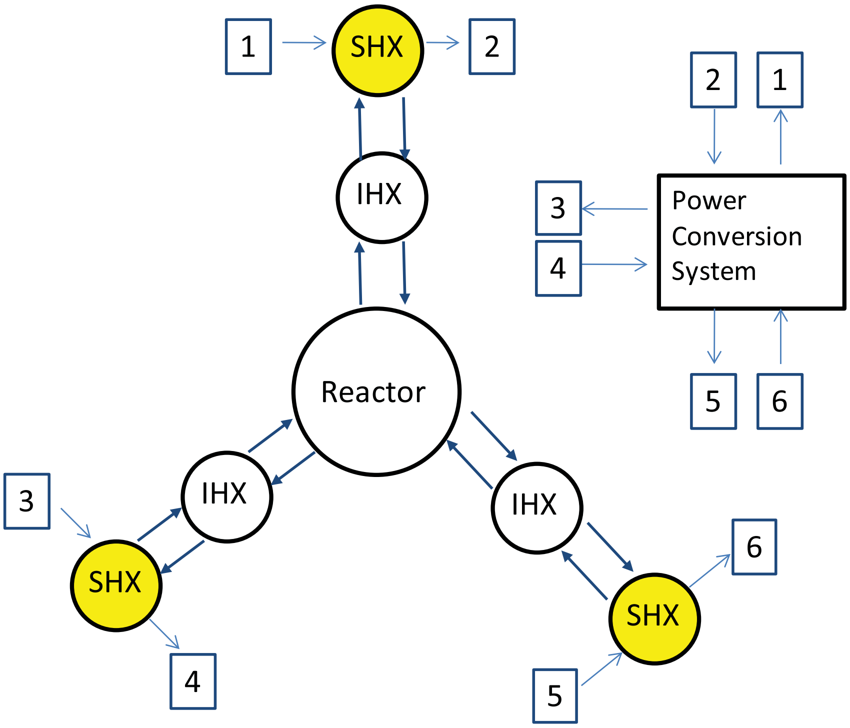
A simple thermal design method was used for determining overall design specifications including geometry, sizing, and configurations (Sabharwall et al. 2011b). Tables 4-3 and 4-4 summarize the key thermal performance parameters for HCHEs and PCHEs respectively. For the same heat duty, the HCHE showed a five times greater overall heat transfer coefficient, along with a much higher secondary pressure drop. Flow regime in the PCHE is usually in the laminar regime or low Re turbulent flow regime because of its small channel diameter. If the Reynolds number is large for the PCHE, it requires too high frictional loss. Therefore, the flow channel length should be very short, which is not preferred in the HX design. However, flow regime in the helical coil is generally in the high Re turbulent flow regime. Therefore, the Nusselt number can be large even though the surface area density is much smaller than the PCHE. Further experiments should be carried out for validation and for overall uncertainty quantification.



(a) Option 1 – 1 SHX



(b) Option 2 – 2 SHXs



(c) Option 3 – 3 SHXs

Figure 4-4. Schematics of SHX arrangements.

Table 4-3. SHX analysis for HCHE.

Heat Duty	MW(t)	3400	1700	1130
Number of Units		1	2	3
Primary Coolant		KF-ZrF$_4$	KF-ZrF$_4$	KF-ZrF$_4$
Secondary Coolant		Water/Steam	Water/Steam	Water/Steam
Supercritical Rankine Cycle				
Overall Heat T/F Coefficient	W/m^{2}K	3804.16	3422.89	3366.13
Heat T/F Surface Area	m^2	4871.92	2707.29	1829.9
Primary Pressure Drop	KPa	15.1	13.1	14.87
Secondary Pressure Drop	KPa	36.3	10.83	6.7
Subcritical Rankine Cycle				
Overall Heat T/F Coefficient	W/m^{2}K	3959.51	3571.62	3522.38
Heat T/F Surface Area	m^2	3914.71	2169.92	1462.52
Primary Pressure Drop	kPa	11.66	9.76	11.05
Secondary Pressure Drop	kPa	52.57	15.64	9.66

Table 4-4. SHX analysis for PCHE.

Heat Duty	MW(t)	3400	1700	1130
Number of Units		1	2	3
Primary Coolant		KF-ZrF$_4$	KF-ZrF$_4$	KF-ZrF$_4$
Secondary Coolant		Water/Steam	Water/Steam	Water/Steam
Supercritical Rankine Cycle				
Overall Heat T/F Coefficient	W/m^{2}K	759	686	631
Primary Pressure Drop	kPa	38	10.5	5
Secondary Pressure Drop	kPa	1.6	0.3	0.1
Subcritical Rankine Cycle				
Overall Heat T/F Coefficient	W/m^{2}K	764	692	638
Primary Pressure Drop	kPa	37.8	10.4	5
Secondary Pressure Drop	kPa	3.2	0.5	0.2

4.3.2 Cost Analysis

The costs of the shell and tube and printed circuit heat exchangers were developed using the cost for a boiler of a supercritical Rankine power conversion unit and the material cost of both types of heat exchangers, for further details refer to Sabharwall et al. 2011b. Based on the analysis, a potential of over 50% reduction of cost may be achieved, if the PCHE can be developed for heat exchange with molten salts, as is shown in Table 4-5.

Table 4-5. Cost comparison of molten salt heated shell and tube heat and PCHE heat exchangers.

	Number of units	Duty (MWt)	Cost per unit (2010 $)	Total cost to exchange 3400 MWt of heat (2010 $)
Shell and Tube Heat Exchanger	1	3400	$301,693,000	$301,693,000
	2	1700	$ 199,043,000	$398,086,000
	3	1133	$ 155,785,000	$ 467,354,000
Printed Circuit Heat Exchanger	1	3400	$116,000,000	$116,000,000
	2	1700	$86,000,000	$172,000,000
	3	1133	$73,800,000	$221,000,000

4.4 Interface with Power Cycles for Power Production

This section explores the challenges associated with adapting power cycles to an AHTR. The cycles currently under consideration are the supercritical and subcritical steam Rankine cycles, the closed Brayton gas cycle with helium, and the supercritical carbon dioxide modified Brayton gas cycle. For detail information on these cycles refer Sabharwall et al. 2011a. A comparison of the thermal efficiencies heat exchanger return temperatures and maximum cycle pressures are given in Table 4-6.

Table 4-6. Thermal efficiencies and maximum pressures of power cycles assuming an AHTR reactor outlet temperature of 700°C

Power Cycle	Thermal efficiency	IHX Inlet Temperature (°C)	Maximum Pressure (MPa)
Subcritical Rankine	42.0%	242	17.7
Supercritical Rankine	44.0%	251	25.0
Supercritical CO_2 Brayton	43.9%	500	21.7
Helium Brayton	40.4%	500	7.5

The Rankine steam cycles are currently used in commercial nuclear reactors and have decades of experience with respect to construction, maintenance and operation. The gas cycles are under development with the supercritical CO_2 Brayton cycle at a lab scale, (Moore & Conboy, 2012). The high efficiency cycles have high pressures which would require materials that would need to withstand the large pressure differences across the IHX.

The type of power cycle may determine the type of IHX needed for power production. Using the shell and tube heat exchanger for the Rankine steam cycles has a legacy of experience. Currently, PCHE heat exchangers are used in the lab scale demonstration of the supercritical CO_2 Brayton cycle due to compactness, (Moore & Conboy, 2012).

Rankine cycles have low return temperatures into the steam generator that could freeze the molten salt. As shown in Table 4-6, typical steam generator return temperatures are 240 to 250°C and freezing temperatures of salts can range from 390 to 450°C (Sohal, et.al. 2010). Freezing salt on the feedwater header, where feedwater enters the steam generator and where steam generator tubes are attached, will significantly reduce heat transfer to the water inside the header and tubes, because the solid salt adds another layer of thermal resistance. This leads to colder water further downstream in the tubes, possibly accompanied by salt freezing on additional tubing. The propagation of cold water inside the tubes and subsequent freezing of salt outside might cool the steam header and steam piping and lead to other problems such as excessive fatigue usage. Significant thermal cycles may occur if the salt cracks or breaks off, thereby allowing hot molten salt to contact the cold metal. The molten salt could freeze, thaw, and break off, and the cycle could repeat, perhaps quickly. Each repeated cycle might consume a small amount of fatigue usage and in time result in cracking. Normal operation of the plant will require supplemental heating of the feedwater. There is precedence for supplemental heating; it was used at Experimental Breeder Reactor II (EBR-2), a liquid metal fast breeder with steam generators (Koch 2008). If this issue can not be resolved, gas power cycles will need to be considered for power production. For further information refer to Sabharwall et al. 2011b.

Gas cycles have return temperatures that are above the freezing point of the molten salt and do not have the same issues.

4.5 Interface with Balance of Plant

4.5.1 Control System Challenges

4.5.1.1 Control Systems for the MSR SHX (Salt/Water or Salt/Steam Generator)

The heat exchanger will operate with very high differential pressures and might require instrumentation to detect cracking before the cracking propagates through the wall. The pressure of the salt side will be slightly above atmospheric, whereas the water and steam side is anticipated to be very high pressure supercritical or high pressure superheated steam. Because of the high freezing point of the salt, water entering the heat exchanger is anticipated to be heated to near the freezing point of salt so thermal stresses on the compact heat exchanger will probably be less than if a primary coolant other than salt was used. The compact heat exchanger is anticipated to have many small restricted passages and it might be difficult to develop the instrumentation and associated algorithms to detect, quantify, and locate cracking which requires further R&D.

4.5.1.2 Control Systems Baseline Configuration

Control systems consist of sensors and other instruments, computers, algorithms, human-machine interfaces, data storage and sharing, and devices that vary parameters such as valves and other control devices and functions. They control parameters within specified limits and ensure operation within predefined envelopes; trend, display, and store data; present information to human operators; and enable human operators to interface with the computers and control facilities.

4.5.2 Molten Salt Challenges and the Role of Control Systems in Addressing Chemistry Control and Measurements

Sensing and control instrumentation is essential to good chemistry control. The salt and water sides of the heat exchanger will require systems that are capable of accurately controlling very low amounts of impurities in the circulating fluids. The direct measurement of contaminants in the flowing fluids might be impossible because of high temperatures and pressures in the piping and heat exchanger. Separate automated sampling systems that remove a portion of the fluids, called slipstream sampling, might be required. It is anticipated that contaminants might be volatile at low quantities that require use of a gas chromatograph.

Moisture-measuring instruments will be an integral part of test chambers, loop, and power plants. The common sources of moisture in test chambers, loops, and power plants include air, carefully controlled small amounts of water, and leakage from water-cooled heat exchangers and steam generators.

Changes in the conductivity of water and perhaps salt can be used to measure a variety of parameters, including amount of contaminants. The flow rate of water can be measured by magnetic and/or coriolis flow meters.

Commercially available pressure transmitters should be adequate for measuring pressures in large components such as cover gas pressure in a tank and water and steam pressures. However, local pressure measurements at the discharge of passages and at the pressure boundaries may require high temperature pressure rakes or local pressure measurements along optical fibers for measuring pressure in opaque and transparent fluids, or optical techniques relying on distortion in transparent fluids.

While the density of single-phase steam and subcooled water can be inferred from their temperature and pressure, there may be a need to measure the density of water as it boils and eventually forms superheated steam inside simulated steam generator tubes. The gamma ray densitometer does not need to physically touch the tube so it will not disturb or distort heat transfer. The gamma ray densitometer has been used to measure density under steady-state and transient conditions.

Temperatures in high temperature test chambers, test loops, and molten salt cooled reactors (such as AHTRs) can be measured by several devices. Thermocouples are the most common temperature sensors for process and test applications. High-temperature thermocouples and other potential temperature detectors, including infrared, optical, and ultrasonic, warrant further development. Thermistors are a type of resistor whose resistance varies with temperature. They can be used as small fast-responding temperature sensors. Their small size and fast response make them potentially attractive for temperature rakes for low temperature applications (<300°C). Temperatures below approximately 650°C can be accurately measured by resistance temperature devices (RTDs). The high accuracy of RTDs requires high-purity platinum. Fiber optic temperature measurements are being developed to map temperature and neutron fluence in reactor cores, and might be useful in assessing the temperature, pressure, and flow rate distributions in molten heat exchangers and steam generators, ,. Commercially available infrared temperature measurement systems might be useful in measuring temperatures up to 1000°C (Omega.Com 2010). Temperature measurement based on the time-of-flight through a medium between two sensors is commonly used to measure the temperature of feed water in LWRs and could be used for the MSR's feedwater system.

Acoustic detection involves detecting energy resulting from the impact of loose parts, cracking, and corrosion. A passive system detects the acoustic energy. Commercial acoustic systems are available to detect and analyze loose parts, cracking, and corrosion. Leakage of fluid through small orifices is the transition of fluid from high pressure inside a pipe or vessel to a lower external pressure. The turbulent flow produces an acoustic signal. Leak detectors have been used for steam at boilers, natural gas, water, and other pipelines and gases such as natural gas. Acoustic sensors, typically piezoelectric accelerometers, are typically attached to LWRs to sense loose parts that could damage components in the reactor coolant system, including fuel. Acoustic emission detection is the only online method to sense the cracking of materials in real time. Acoustic emission crack detection should be incorporated in test chambers and loops to help determine when cracking occurred and, if possible, the location of the cracking. It is also possible to detect corrosion, although the amplitudes of the resulting mechanical waves are much smaller than those produced by cracks.

Stress in a test piece that is closed in a pressurized heated test volume might be inferred and/or measured by surface mounting of one or more high-temperature, fiber-optic fibers. Strain is an important material property that can be measured by a laser speckle extensometer (DOLI MGMBH Industrie Elekotonik 2010). The laser speckle extensometer is noncontacting and measures strain in two dimensions.

Thermography measures the temperature of surfaces and fluids from a distance. Thermography is expected to find many applications, including measuring the temperatures of supports to ensure that the concrete and other attachments are at a tolerable temperature, evaluating the effectiveness of insulation on hot vessels and piping, assessing the temperature of electrical connections, insulation, and motor windings, and finding leakage.

4.5.3 Operational Issues

From the standpoint of applying experience in test chambers and loops to the power plant, test chambers and loops likely will provide opportunities to (1) evaluate long-term performance of sensors to high-temperature, high-pressure environment (2) develop, demonstrate, and evaluate algorithms and displays that involve multiple sensors and instruments for a variety of uses; and (3) develop and demonstrate online monitoring and analysis techniques to infer the external and internal material condition of components and materials based on readings from sensors located outside the components, chambers, or loops.

5. MATURING THE SHX TECHNOLOGY

The higher temperature TDRM for the SHX addresses four general areas for maturation of the technology:

- SHX materials of construction
- Fabrication processes
- Tritium permeation
- Regulatory issues.

This section discusses each of these areas and the challenges involved in maturing them.

5.1 SHX Construction Materials

Candidate materials of construction include materials that exhibit (in varying degrees) high temperature tensile and creep strength and resistance to environmental degradation in molten salts. Longer-term R&D programs will evaluate ceramic and composite designs. Issues that must be addressed during the design process include materials compatibility with both the intermediate salt and the working fluid used in the power conversion system, high temperature strength, creep and creep-fatigue resistance, and the fabrication processes needed to manufacture an acceptable design (Holcomb et al. 2009).

Some of the material options that could potentially be used in the SHX are discussed here. The SHX could have a molten salt on one side of the heat transfer barrier and an oxidizing environment such as supercritical steam on the other side. Haynes Alloy N is the baseline material chosen for the SHX, but other material options being considered include: Alloy 242, Alloy 800H, Alloy 617, and Type 316 stainless steel. The major alloying elements for these metals are shown in Table 5-1 (for reference only, not complete specifications). SiC (ceramic) is also being considered, but is at a lower level of maturity.

The alloys that exhibit the greatest corrosion resistance to molten salts are not codified for use in nuclear applications. Those that are currently codified are inferior, and their use will result in shorter heat exchanger life.

Table 5-1. Major alloying elements in materials being considered for SHX use

	Ni	Cr	Fe	Mo	Co
Alloy N	bal	6-8	5*	15-18	0.2*
Alloy 242	bal	7-9	2*	26-28	2.5*
Alloy 617	bal	20-24	3*	8-10	10-15
316L	10-14	16-18	bal	2-3	--
Wt%, * = max; for reference only, not complete specifications					

5.1.1 Materials Selection History

These materials must demonstrate adequate strength (long term and short term), good thermal-aging properties, resistance to irradiation degradation, fabricability, and good corrosion resistance (Ingersoll et al. 2004). Ingersoll et al. (2004) also reported on some of the alloys that are considered for use in the SHX, and their suitability. Their results are summarized in Tables 5-2 and 5-3 for long-term strength at 500 and 1000ºC respectively.

Table 5-2. Alloys potentially suited for the SHX (Ingersoll et al. 2004).

Coated Monolithic Candidate Materials	Salt Corrosion Resistance	Air Corrosion Resistance	Long-Term Strength at 500ºC	Highest Usage Temperature (ºC)	Metallurgical Stability	Irradiation Resistance	Fabric-ability	Maturity	Codified
Alloy 800H or HT	Poor-Fair	Good	Very good	980	Good	Good	Good	High	Sect. I, III, VIII
Alloy N	Excellent	Good	Very good	730	Good	Good	Good	High	Sect. III, VIII
Alloy 242	Very good	Good	Very good	540	Good	Adequate	Good	Low	Sect. VIII
Alloy 800H or HT	Poor-Fair	Good	Very good	980	Good	Good	Good	High	Sect. III, VIII

Table 5-3. Alloys potentially suited for the SHX (Ingersoll et al. 2004).

Coated Candidate Materials	Salt Corrosion Resistance	Air Corrosion Resistance	Long-Term Strength at 1000ºC	Highest Usage Temperature (ºC)	Metallurgical Stability	Irradiation Resistance	Fabric-ability	Maturity	Codified
Inconel 617	Needs Evaluation	Good	Very good	1000	Good	Good	Good	High	Sect. VIII
Alloy 800H	Needs Evaluation	Poor	Good	1000	Good	NA	Good	High	Sect. I, III, VIII

5.1.2 Material Selection Planning

The following plan is suggested to determine the best metallic material to use for the SHX:

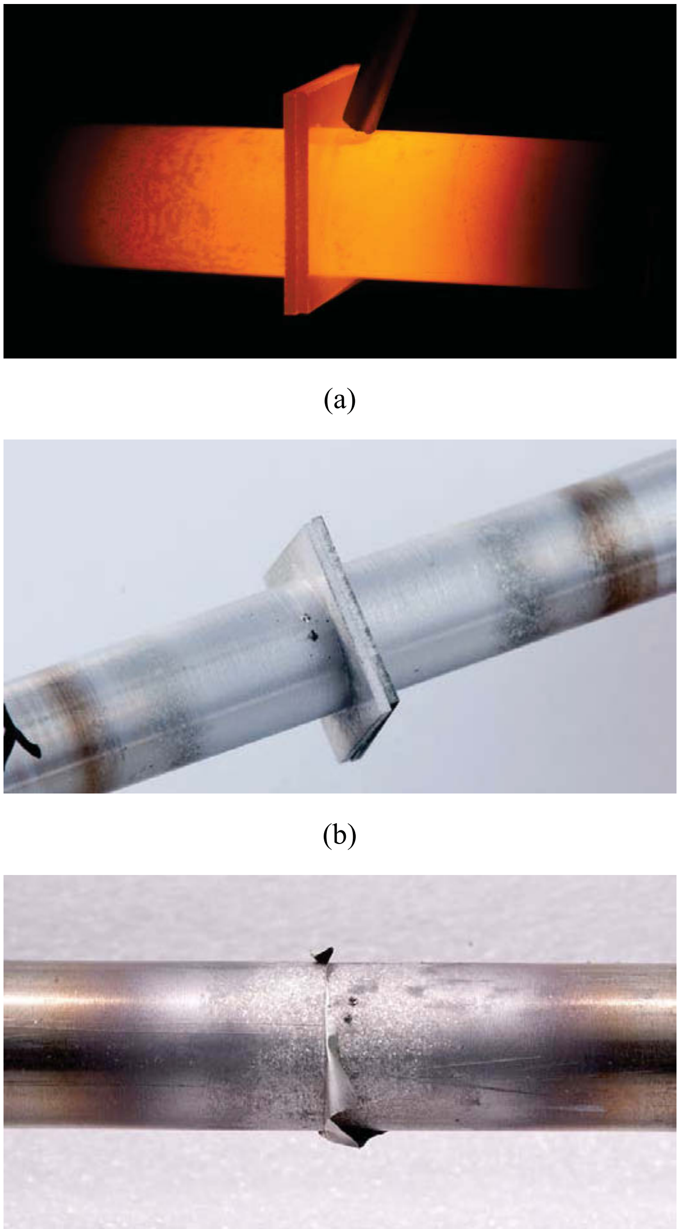
1. Perform the tests and demonstrations per Section III Division 5, Class B, necessary to codify Hasetelloy N, which exhibits the best properties relative to corrosion resistance in molten salt.
2. Perform plasticity evaluations at the indicated scales as described below:
   a. Microstructural, via computational thermodynamics/experimental microstructure, and using orientation imaging microscopy and electron back-scattering diffraction to obtain grain orientation distributions.
   b. At the meso scale, apply plasticity theory with internal variables characterizing microstructure, including anisotropy of plastic response to different loading modes, supporting TRL-3 evaluations for the moltent salt reactor (MSR) heat exchanger.
   c. On the macroscopic scale, transition from TRL-3 to TRL-4 without losing the information from the microstructural scale modeling via the construction of yield surfaces and modern plasticity models.
3. Perform corrosion testing of alloys, including testing of the diffusion welded joint and also address the effect of varying the nickel foil thickness. Apply hot corrosion models with ideal salt properties at TRL-3, including additional phases for subsequent modeling during TRL-4.
4. Perform post-corrosion testing to compare ultimate tensile strength and creep-fatigue cycles imposed on the welded joint, after it is exposed to a salt environment, as well as to provide data to verify the predictions of the corrosion modeling.

5.2 Fabrication Processes

5.2.1 Welding

Diffusion welding is a mature welding process with wide application in many industries. Its application to SHX material selection and fabrication can be found in EXT-12-24589, “Diffusion

Welding of Alloys for Molten Salt Service – Status Report.” A typical joint is shown in Figure 5-1. Other welding processes, e.g., arc welding, will need to be investigated for other fabrication aspects.



(a)

(b)

(c)

Figure 5-1. Alloy N base metal with Alloy N inserted sheets, diffusion weld in progress in the Gleeble; (b) same weld completed; (c) Alloy 800H weld with nickel foil interlayer.

5.2.2 Dissimilar Metal Joining

Dissimilar metal joining is an important aspect of fabricating systems such as those under consideration for the SHX, where very different and severe environmental conditions may be found in proximity (e.g., molten salt on one side of a heat exchanger and supercritical CO_2 or steam less than 1 mm away). There is little difficulty in setting up and making such welds; one attractive aspect of diffusion welding is that different materials can be diffusion welded together. Long-term compatibility under service conditions must be investigated, however, including, for example, the likelihood of deleterious second phases at interfaces. Thermodynamic modeling can help in such predictions.

5.2.3 Ceramic/Metal Joining

Joining ceramic materials to metals is difficult and a less mature technology than metal/metal joining. The materials are very different in structure (metallic versus covalent bonding), have very different lattice parameters, and typically have very different coefficients of thermal expansion. Yet, ceramics have unique properties of interest in high temperature energy systems—very high strength at high temperatures, resistance to creep, and resistance to oxidation—because they are typically oxides.

5.2.4 Corrosion and Materials Degradation

5.2.4.1 Thermodynamic Assessment of Hot Corrosion Mechanisms of Superalloys

The great variety of salt systems, environmental conditions, and possible materials containing leads to a huge test matrix in designing reactor and heat transfer systems. Experimental corrosion work is necessary as these variables are gradually reduced to final choices for system use. Experimental data are the fundamental basis of construction codes, and it is inconceivable that a reactor system would be built without an extensive database. Such experimental work can be very expensive; however, any technique that can shorten this process and make the experimental choices more efficient is worth investigating. Recently, the development of computer codes based on fundamental thermodynamics and extensive material databases has revolutionized the process. Experimental work is still needed, but these new tools offer a number of advantages.

One such investigation into materials of interest in molten salt systems was conducted at INL (Glazoff 2012). The code used for these models was ThermoCalc and its associated nickel database. The materials compared were Haynes Alloys N and 242 (see compositions in Table 5-4) in KF-ZrF_4 molten salt at 740°C. Although no data existed in the literature for this particular combination of materials, a report by Rothman (Rothman et al. 1991) gives the following data. The model prediction was close to the observed corrosion rates in the chloride/fluoride salt mixture.

Table 5-4. Comparison of corrosion rates for Alloys N and 242.

	Thickness loss, mils (0.001 in.)	
Condition	Alloy N	Alloy 242
70% HF, 1670°F, 136 hr	15.8	12.6
Chloride/fluoride salt mixture 1290 -1650°F, 40 hr	1.4	1.9
5% HF, 175°F	20	14
10% HCl, boiling	204 mils/yr	22 mils/yr

5.2.4.2 Materials Degradation

A large amount of corrosion data have been generated by ORNL and others on molten fuel salt corrosion for application in MSRs such as the Aircraft Reactor Experiment (ARE), MSRE, and the Molten Salt Breeder Reactor (MSBR) with review articles that summarize the results (Grimes et al. 1972; McCoy 1967, 1969, 1970, 1971, and 1978; Williams, Toth, and Clarno 2006).

Corrosion Mechanisms

The molten salt literature has identified several corrosion mechanisms, including:

- Intrinsic corrosion, with molten salt as the reactant. The mechanism is driven by the difference in free energy of formation between the salt constituents and the most susceptible transition metal corrosion product (the more negative the free energy of reaction, the more likely is the reaction).
- Corrosion by oxidizing contaminants in the molten salts, such as HF, HCl, H2O, residual oxides of metals, or easily reducible ions, especially some polyvalent metal ions.
- Differential solubility because of thermal gradients in the molten salt system, with formation of a metal ion concentration cell that can drive corrosion.
- Galvanic corrosion, wherein metals or materials with differing electromotive potentials are maintained in electrical contact by the molten salt, driving the oxidation of the anodic material.

MSR Secondary and Tertiary System Materials vs. Fluoride and Chloride Salts

Molten salt technology has been used for many decades in industrial heat transfer, thermal storage, heat treatment, high-temperature electrochemical plating, and other materials processing applications. The potential utility of molten salts as heat transfer agents was also demonstrated for nuclear reactors, as the liquid fuel in the ARE and the MSRE programs.

The issues of radiation embrittlement and intergranular cracking will not be a major concern for the secondary loop, except where the primary to secondary heat transfer takes place. An issue will be the diffusion of tritium from the primary loop to the secondary loop. A feature of molten fluoride salts is that they can easily dissolve passive oxide layers such as the chromium oxide film (Cr_2O_3), providing corrosion resistance for stainless steels and nickel based alloys in many aqueous and high temperature environments. This, in fact, is the very reason fluorides are used in fluxes for many welding processes. Moisture and oxide impurities in fluorides can cause corrosion (oxidation) of the metal alloy in the molten salt.

Corrosion by the Molten Salt

Some chloride corrosion products have greater solubility in the molten chloride salt, favoring the reaction. The relative stability of fluoride compounds correlates approximately with the free energy of formation per mole fluoride, with thermodynamic stability increasing with decreasing (more negative) free energy.

Corrosion by Contaminants

While alkali and alkaline earth fluorides, and to a lesser degree the corresponding chlorides, are very stable and therefore very weak oxidants of metals, contaminants in these salts often are the cause of structural alloy corrosion (Ozeryanaya 1985, White 1983). Dissolved contaminants in the molten salts generally increase the oxidation potential of the salt, and therefore increase the probability and rate of corrosion. Such contaminants are water, HF or HCl, metal oxides, and dissolved polyvalent foreign cations (metal ions) that can oxidize constituents of the structural alloys.

Differential Solubility

The corrosion of soluble fluorides and chlorides may be limited by the saturation solubility of the transition metal ions in a static, isothermal salt. On the other hand, in a system with significant temperature gradients, differential solubility of corrosion products in the salt can drive persistent long-term corrosion.

Galvanic Corrosion

Molten salts are ionic fluids that can sustain electrical currents and electrochemical processes that depend on electron transfer. Molten salts can sustain the electrochemical corrosion mechanisms usually associated with aqueous systems, including galvanic corrosion. The design considerations for a molten salt coolant system may dictate the use of several different materials, which may have differing electromotive potentials (galvanic potentials) and be susceptible to galvanic corrosion.

5.2.4.3 Salt-specific corrosion issues

Corrosion in FLiNak

Based on thermodynamic principles, neither FLiBe nor FLiNaK can corrode the transition metal components of structural alloys to any significant degree. However, arguments have been made that FLiNaK is inherently more corrosive to structural metals than FLiBe, based on Lewis acid-base arguments (William et al. 2006, Ingersoll et al. 2006). As with FLiBe, the corrosion database for FLiNaK coolant salts is insufficient and needs further development for reliable selection of compatible alloys.

Corrosion in KCl-MgCl$_2$

Molten chloride salts have long been applied by industry for heat transfer, heat treatments, high-temperature electrochemical coatings, and other processes. The corrosion characteristics have been studied for some common structural alloys in a variety of salts.

Corrosion in KF-ZrF$_4$

To understand the interaction of Hastelloy N with KF-ZrF$_4$, specimens prepared at INL were shipped to the University of Wisconsin, for exposure to KF-ZrF$_4$ at high temperatures. Although a circulating loop was available at Wisconsin, these initial tests in molten KZrF salts were performed in still, molten salt. Weld specimens were made with two pieces of 0.041 in. Alloy N sheet material sandwiched between two bars of Alloy N material. For more information refer to INL/EXT-12-24589 (Clark et al. 2012).

5.3 Tritium Permeation

FLiBe has been chosen for the AHTR primary coolant, mainly because of its higher heat-transfer performance and lower neutron absorption cross section. But a particular concern is the production of tritium gas (mainly because of lithium in the salt), which could permeate through the IHX to the process application, as shown in Figure 5-2. Testing of diffusion of tritium surrogates across prototypical subassemblies will provide data for extrapolation to the larger assemblies.

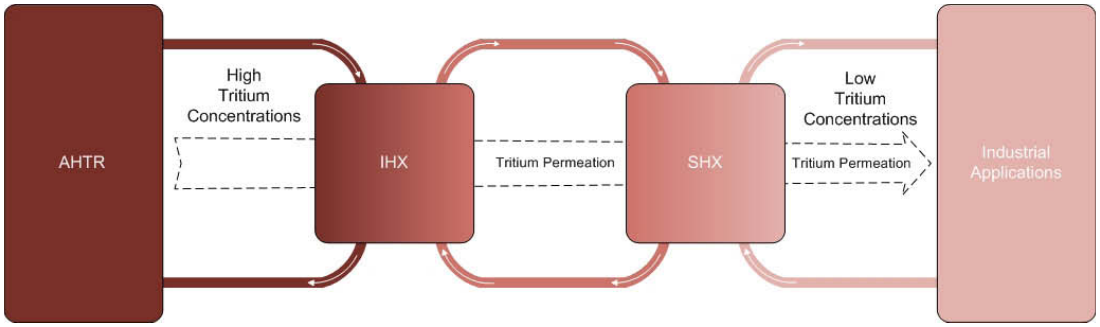


Figure 5-2. Tritium permeation pathway in the heat transport loop.

The anticipated difficulty in containing tritium justifies special care in system design. A sound understanding of tritium's generation rate as well as its properties and possible ways to prevent its escape are an integral part of any plan for proposed AHTRs. Tritium, like hydrogen, is highly mobile and can readily permeate into and through materials, especially metals at higher temperatures, it behaves chemically as hydrogen, it can undergo isotope exchange reactions with hydrogen-containing chemicals (H_2O, H_2, CH_4, etc.) in downstream industrial processes and become incorporated into the plant's process chemicals or products. Tritium emissions to the environment are regulated by the Nuclear Regulatory Commission (NRC) and the U.S. Environmental Protection Agency (EPA). Strategies being discussed for mitigation including advanced materials for the piping and heat exchangers, inert gas sparging, additional coolant lines, and chemical removal.

5.4 Regulatory Acceptance

In order for a material to be used commercially by industry, it has to meet certain standards and requirements put forth by the American Society of Mechanical Engineers (ASME). To take advantage of the heat transfer efficiency obtained through the use of molten salts as a secondary heat transfer fluid, additional development is needed to assure the heat exchanger is robust enough to successfully operate for the 60 year anticipated life. One of the important heat exchanger issues currently hindering longevity of robust operation is the corrosive environment to which materials of construction would be subjected. This report suggests the use of Hastelloy N as a baseline material. Although Hastelloy N exhibits good properties under the corrosive environment of molten salt, it is not codified by the ASME BPV for nuclear application. In the event that Hastelloy N fails codification, 800H (previously codified to 760°C) will serve as a backup to Hastelloy N. Some consideration is also being given to 800H with Hastelloy N as a liner. This section describes the work required to secure codification.

5.4.1 Introduction

ASME has been involved in codes and standards for over 125 years. The most widely recognized ASME code is the Boiler Pressure Vessel (BPV) Code, first originating in 1914. The BPV Code addresses both nuclear and non-nuclear facilities.

In 1999, an international collaborative initiative for the development of advanced (Generation IV) nuclear reactors was started. The idea behind this effort was to advance nuclear energy as a sustainable limited green house gas energy source to increase proliferation resistance and support concepts able to produce energy (both electricity and process heat) at competitive costs. DOE supported this effort by pursuing the development of next generation nuclear reactors (NGNRs) such as the AHTR. This support has been in the form of R&D of pertinent data, initial regulatory discussions, and engineering for developing various codes and standards.

This section of the report provides a current update on those major ASME codes and standards (both nuclear and non-nuclear) that will most likely be used in the construction of an AHTR and associated high temperature critical components such as SHX. This section presents the purpose of ASME codes and standards, additional background information on ASME activities occurring in the last few years (including FY 2010) that have been supporting the development of codes and standards relating to NGNRs, the path forward to codify anticipated materials of construction for SHX; and expectations of what ASME activities might achieve in the near future.

As discussed in this report, Section III of the ASME BPV Code addresses the rules for nuclear facility components. The components and supports covered by Section III are intended to be installed in a nuclear power system that serves the purpose of producing and controlling the output of thermal energy from nuclear fuel and those associated systems essential to the functions and overall safety of the nuclear power system. Section VIII of the BPV Code addresses the rules needed to construct non-nuclear pressure vessels. Pressure vessels not subject to nuclear requirements (e.g., the balance of plant pressure vessels) can use these rules. Section VIII is considered to be non-nuclear, safety with special treatment.

The design, construction, and operation of nuclear and non-nuclear components are based on their categorization (safety related or nonsafety related special treatment). In simplified terms, safety related or nonsafety related special treatment is determined based on the consequence of failure. Obviously, the reactor and its associated primary components are safety related. For instance, if the primary coolant fails, the consequence is severe so the system is safety related. Next, most likely, the primary coolant from the reactor is exchanging heat with an IHX. If the failure in the primary heat transfer loop (main heat sink for the reactor) is caused by failure of the IHX and there is no backup system, the IHX is considered safety related.

Since the AHTR SHX systems are not identified and are still in conceptual design, it is assumed that ASME Section III, Division 5, Class B (High Temperature Reactors) is the most applicable ASME Code. This assumption implies that if the SHX fails, it is safety related. This separation is shown in Figure 5-3, where the AHTR and the heat exchangers are considered to be safety related and the SHX is assumed to follow ASME Section III, Division 5, Class B. It should be noted that if the system is designed as the SHX becoming nonsafety related special treatment, the design based on ASME Section III may easily be converted to meet ASME Section VIII requirements.

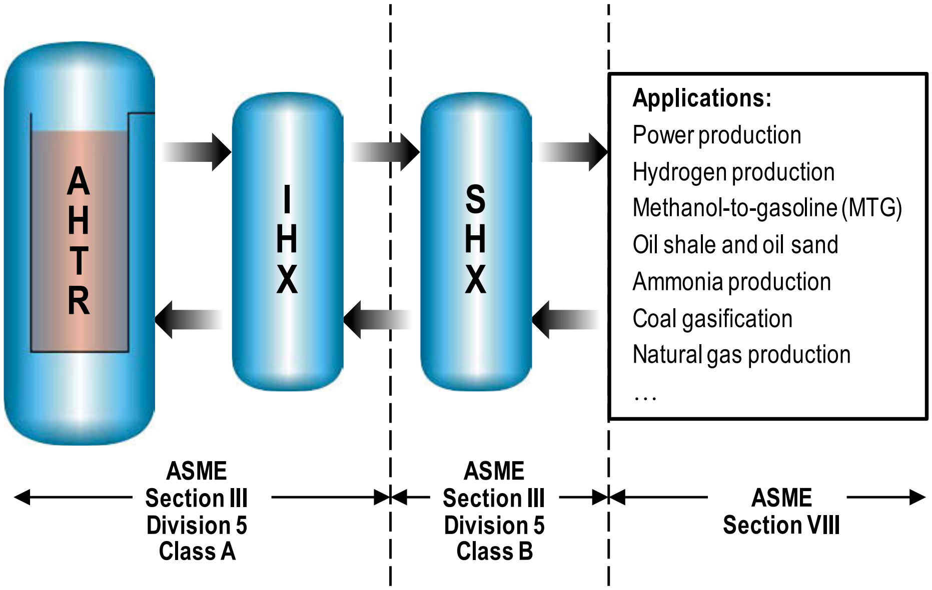


Figure 5-3. Division of the reactor and high temperature components per ASME Standards.

The following sections provide a current update on the major ASME codes and standards (both nuclear and non-nuclear) that will most likely be used to codify SHX materials of construction.

5.4.2 Purpose of ASME Codes and Standards

According to ASME (ASME 2011) a standard and a code are defined as follows:

> *A standard can be defined as a set of technical definitions and guidelines, "how to" instructions for designers, manufacturers and users. Standards promote safety, reliability, productivity and efficiency in almost every industry that relies on engineering components or equipment. Standards can run from a few paragraphs to hundreds of pages, and are written by experts with knowledge and*

> *expertise in a particular field who sit on many committees. Standards are considered voluntary because they serve as guidelines, but do not of themselves have the force of law. ASME cannot force any manufacturer, inspector, or installer to follow ASME standards. Their use is voluntary. Standards become mandatory when they have been incorporated into a business contract or incorporated into regulations. A code is a standard that has been adopted by one or more governmental bodies and has the force of law.*

Codes and standards assure that appropriate margins exist for the safe use of the final product. Codes and standards also define the quality levels needed and promote the standardization of components, parts, and items for ease of interchangeability. It is not uncommon for parts (such as a nut and a bolt or piping and a fitting) to be procured in different locations from different companies with the expectation that they will fit together as needed.

The following subsections identify the specific ASME codes and standards where each subsection will address the purpose of the code or standard.

5.4.3 Boiler and Pressure Vessel Code

As mentioned previously, the ASME BPV Code addresses construction rules for both nuclear and non-nuclear facilities. It contains 12 distinct sections. However, Sections III, and VIII of the BPV Code will be of primary importance for the AHTR, along with critical supporting information found in Section II. The 2010 Edition of the ASME BPV Code with the 2011 Addenda will be used here as the basis for defining BPV Code content and status.

The BPV Code typically addresses components that perform the function of a pressure boundary. This means that the construction rules focus on achieving the pressure integrity of these components for safety purposes.

5.4.3.1 Section III

Section III of the ASME BPV Code addresses the rules for nuclear facility components. Components include metal vessels and systems, pumps, valves, piping, component supports, and core support structures. The components and supports covered by Section III are intended to be installed in a nuclear power system that serves the purpose of producing and controlling the output of thermal energy from nuclear fuel and those associated systems essential to the functions and overall safety of the nuclear power system. Section III provides requirements for new construction and includes consideration of mechanical and thermal stresses because of cyclic operation. Deterioration, which may occur in service as a result of radiation effects, corrosion, erosion, or instability of the material, is typically not addressed.

Section III currently has five divisions:

1. Division 1 provides requirements for the materials, design, fabrication, examination, testing, inspection, installation, certification, stamping, and overpressure protection of nuclear facility components, typically those associated with LWRs.
2. Division 2 provides requirements for concrete reactor vessels and containments
3. Division 3 provides requirements for containment systems for storage and transport packaging for spent nuclear fuel and high-level radioactive waste
4. Division 4 has been assigned for future rules addressing components for fusion reactors
5. Division 5 is a new division recently approved that provides construction rules associated with high temperature reactors, including HTGRs and liquid metal reactors.

Table 5-5 of Section III (see below) lists the divisions and subsections that comprise the current Section III. The BPV Committee on Construction of Nuclear Facility Components (III) is responsible for the contents of Section III. Since Section III, Division 5, Class B is considered for the preliminary/conceptual design of a SHX in the following section, it is briefly described.

Table 5-5. Section III- Rules for Construction of Nuclear Facility Components (Morton, D. K., 2011)

Subsection Identifier	Subsection Title
NCA	General Requirements for Division 1 and 2
Division 1	
NB	Class 1 Components
NC	Class 2 Components
ND	Class 3 Components
NE	Class MC Components
NF	Supports
NG	Core Support Structures
NH	Class 1 Components in Elevated Temperature Service
Appendices	
Division 2 - Code for Concrete Containments	
CC	Concrete Containments (Prestressed or Reinforced)
Division 3 - Containments for Transportation and Storage of Spent Nuclear Fuel and High Level Radioactive Material and Waste	
WA	General Requirements
WB	Class TC Transportation Containments
WC	Class SC Storage Containments
Division 4 - (reserved for fusion reactors)	
Division 5 - High Temperature Reactors	
HA	General Requirements
HB	Class A Metallic Pressure Boundary Components
HC	Class B Metallic Pressure Boundary Components
HF	Class A and B Metallic Supports
HG	Class A Metallic Core Support Structures
HH	Class A Non-Metallic Core Support Structures

5.4.3.2 ASME Section III, Division 5, High Temperature Reactors[a]

Section III of the ASME BPV Code addresses the rules for nuclear facility components. Components include metal vessels and systems, pumps, valves, piping, component supports, and core support structures. The components and supports covered by Section III are intended to be installed in a nuclear power system that serves the purpose of producing and controlling the output of thermal energy from nuclear fuel and those associated systems are essential to the functions and overall safety of the nuclear

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[a] http://files.asme.org/STLLC/23256.pdf, accessed August 24, 2011.

power system. Section III provides requirements for new construction and includes consideration of mechanical and thermal stresses because of cyclic operation. Section III is considered to be safety related.

Section VIII of the BPV Code addresses the rules needed to construct non-nuclear pressure vessels. Pressure vessels not subject to nuclear requirements (e.g., the balance of plant pressure vessels) can utilize these rules. Section VIII is considered to be nonsafety related special treatment.

The design, construction, and operation of nuclear and non-nuclear components are based on their categorization (safety related or non-safety related special treatment). Since the NGNR (such as AHTR) heat exchanger systems are not identified, and still are in the conceptual phase, it is assumed that the ASME Section III, Division 5, Class B is the most applicable ASME Code. If this assumption is changed or modified, the design based on the ASME Section III could be easily converted to meet the ASME Section VIII requirements. Section III, Division 5 is briefly discussed below.

General Discussion

The Divisions within Section III are broken down into Subsections and are designated by capital letters preceded by the letter “N” for Division 1, by the letter “C” for Division 2, by the letter “W” for Division 3, and by the letter “H” for Division 5.

Division 5 — High Temperature Reactors[a,b]
Subsection HA — General Requirements
Subsection HB — Class A Metallic Pressure Boundary Components
Subsection HC — Class B Metallic Pressure Boundary Components
Subsection HF — Class A and B Metallic Supports
Subsection HG — Class A Metallic Core Support Structures
Subsection HH — Class A Nonmetallic Core Support Structures

Scope

The rules of this Subsection HA, Subpart A constitute the general requirements associated with metallic components used in the construction of high temperature gas-cooled reactor and liquid metal reactor systems and their supporting systems. Only those metallic components that are considered to be safety-related or nonsafety related with special treatment are covered by these rules.

1. The rules of Subsection HA, Subpart A are contained in Divisions 1 and 2, Subsection NCA, except for those paragraphs or subparagraphs (with numbered headers) replaced by or responding numbered HAA paragraphs or subparagraphs in this Subpart or new numbered HAA paragraphs or subparagraphs added to this Subpart.
2. Division 1 rules may use different terminology than Division 5 (e.g., Class 1 and Class 2 versus Class A and Class B, etc.), but the application and use of these rules is identical for Division 5 construction.
3. Division 1, Class 1 requirements are applicable to Division 5 construction, but shall be referred to as Division 5, Class A.
4. Division 1, Class CS requirements are applicable to Division 5 construction, but shall be referred to as Division 5, Class A.
5. Division 1, Class 2 requirements are applicable to Division 5 construction, but shall be referred to as Division 5, Class B.

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[b] Elevated temperature service: service where the component(s) or core support structure(s), during normal, upset, emergency, or faulted operating conditions, experience temperatures in excess of those established in Table HAA-1130-1 for the material under consideration.

Limits of These Rules

Excluding Subsections HF and HH and this Subsection HA, the Subsections of Division 5 consist of two subparts: Subpart A addresses the rules for low temperature service and Subpart B addresses the rules for elevated temperature service. Table 5-6 establishes the maximum temperature limits for the material under consideration at which the low temperature service rules shall be used. Elevated temperature service rules shall be used for temperatures above those listed in Table 5-6 (but limited to temperatures established in the applicable rules), for the material under consideration.

Table 5-6. Values of T_{max} for various classes of permitted materials (ASME 2010a).

MATERIALS	T_{max}	
	^oF	(^oC)
Carbon Steel	700	(370)
Low Alloy Steel	700	(370)
Martensitic stainless steel	700	(370)
Austenitic stainless steel	800	(425)
Nickel-chromium-iron	800	(425)
Nickel-copper	800	(425)

Purpose of Classifying Items of a Nuclear Power Plant

Construction rules are specified for items that are designated Code Classes A and B. These Code classes are intended to be applied to the classification of items in high temperature gas-cooled reactor and liquid metal reactor systems and their supporting systems. Reflecting the design approach of high temperature reactors, Class A rules address those items deemed to be safety-related, and the Class B rules address those items deemed to be nonsafety related with special treatment. These safety classifications reflect the risk-based approach derived from safety criteria established for high temperature reactor plants. Remaining items not in the two classifications listed above shall satisfy the requirements of other appropriate non-nuclear codes and standards.

Scope

The rules of this Subsection HC, Subpart B constitute the requirements associated with metallic components used in the construction of high temperature gas-cooled reactor and liquid metal reactor systems and their supporting systems. Only those systems that are considered to be nonsafety related with special treatment are covered by these rules.

1. Subsection HC, Subpart B provides rules for the material, design, fabrication, examination, installation, testing, overpressure relief, marking, stamping, and preparation of reports by the Certificate Holder of metallic pressure boundary components or portions of those components that are intended to conform to the requirements for Class B construction for service when Service Loading temperatures exceed the appropriate temperature limits established in Table 5-6 for the material under consideration.
2. The rules of Subsection HC, Subpart B are contained in Division 1, Subsection NC, except for those paragraphs or subparagraphs (with numbered headers) replaced by corresponding numbered HCB paragraphs or subparagraphs in this Subpart or new numbered HCB paragraphs or subparagraphs added to this Subpart. Class B in Division 5 equates to Class 2 in Division 1.

3. Division 1 rules may use different terminology than Division 5 (e.g., Class 1 and Class 2 versus Class A and Class B, etc.), but the application of these rules is identical for Division 5 use.

General Requirements for Material

All pressure-retaining material and material welded thereto shall meet the requirements of Division 1, Article NC-2000, except as modified herein. In addition, the material shall also conform to the specification, grade, class, and type requirements of the Tables in Mandatory Appendix HCB-II of the ASME Section III Code.

Permitted Material Specifications

Pressure retaining material shall conform to the requirements of one of the specifications for materials given in Tables 1A, 1B, and 3 (ASME Section II, Part D, Subpart 1) including all applicable notes in the tables, and to all of the requirements of this Article that apply to the product form in which the material is used. Attachments that perform a pressure retaining function shall be pressure retaining material. For vessels that are designed in accordance with NC-3200, the materials shall be restricted to those materials listed in Tables 2A, 2B, and 4, Section II, Part D, Subpart 1, including all applicable notes in the tables, and to the following clad product specifications, provided they are composed of materials listed in Tables 2A, 2B, and 4, Section II, Part D, Subpart 1:

1. SA-263, Specification for Corrosion-Resisting Chromium-Steel Clad Plate, Sheet, and Strip
2. SA-264, Specification for Corrosion-Resisting Chromium-Nickel Steel Clad Plate, Sheet, and Strip
3. SA-265, Specification for Nickel and Nickel-Base Alloy Clad Steel Plate.

5.4.3.3 Section VIII

Section VIII of the BPV Code addresses the rules needed to construct non-nuclear pressure vessels. Pressure vessels not subject to nuclear requirements (e.g., the balance of plant pressure vessels) can utilize these rules. Section VIII provides requirements applicable to the design, fabrication, inspection, testing, and certification of pressure vessels operating at either internal or external pressures exceeding 15 psig (100 kPa). This pressure may be obtained from an external source or by the application of heat from a direct or indirect source, or any combination thereof.

Section VIII includes three divisions: Division 1 provides basic coverage, Division 2 discusses alternative rules, and Division 3 presents alternative rules for construction of high pressure vessels.

In comparison to the basic design-by-rule approach of Division 1, the requirements of Division 2 on materials, design, and nondestructive examination (NDE) are more rigorous. However, Division 2 also permits higher allowable design stress intensity limits, resulting in more efficient construction (thinner vessel walls). The rules of Section VIII allow temperatures greater than those allowed in Section III, Division 1 (with the exception of Subsection NH). Division 3 addresses vessels operating at either internal or external pressures generally above 10,000 psi (69 MPa). The BPV Committee on Pressure Vessels (VIII) is responsible for the contents of Section VIII.[c]

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[c] Approval of revisions by the higher ASME Committees does not result in their immediate publication but when the next scheduled publication cycle occurs. Publication (meaning copies available for purchase) occurs near the date of issuance, either before or shortly thereafter. The BPV Code may be used beginning with the date of issuance but compliance is mandatory after the time interval specified in the Foreword of each section. A similar process exists for other ASME codes.

5.4.3.4 Supporting BPV Sections

The major relevant supporting sections of the ASME BPV Code that will most likely support the construction of an NGNR (such as AHTR) include the following three sections:

- Section II – Materials
  - Part A – Ferrous Material Specifications
  - Part B – Nonferrous Material Specifications
  - Part C – Specifications for Welding Rods, Electrodes, and Filler Metals
  - Part D – Properties.
- Section V – Nondestructive Examination
- Section IX – Welding and Brazing Qualifications.

Only section II is discussed here, because the conceptual design of the system is considered and other systems of the reactor concept are not identified and discussed in detail. To codify Hastelloy N, it is first accepted by Section II as a base material.

5.4.3.5 Section II

Part A is a service book to the other BPV Code sections, providing material specifications for ferrous materials adequate for safety in the field of pressure equipment. Table 5.7 provides the permissible base materials for structures other than bolting. These specifications contain requirements for heat treatment, manufacture, chemical composition, heat and product analyses, mechanical test requirements and mechanical properties, test specimens, and methods of testing. They are designated by SA numbers and are derived from ASTM International ‘A’ specifications. Part B is also a service book to the other BPV Code sections providing material specifications for nonferrous materials adequate for safety in the field of pressure equipment. Containing the same type of information as Part A, the Part B specifications are designated by SB[d] numbers and are derived from ASTM International ‘B’ specifications. The Part C service book provides material specifications for the manufacture, acceptability, chemical composition, mechanical usability, surfacing, testing requirements and procedures, operating characteristics, and intended uses for welding rods, electrodes, and filler metals. These specifications are designated by SFA numbers and are derived from American Welding Society specifications.

Finally, Part D is a service book to other BPV Code sections providing tables of design stress values, tensile and yield strength values, and tables and charts of material properties. Part D facilitates ready identification of specific materials to specific sections of the BPV Code. Part D also contains appendices that contain criteria for establishing allowable stress and stress intensity values, the bases for establishing external pressure charts, and information required for the approval of new materials. The BPV Committee on Materials (II) is responsible for the contents of Section II.

Guideline on the Approval of New Materials under the ASME Boiler and Pressure Vessel Code (ASME 2010b)

If ASME Codes are considered to be utilized to design a system, only material specified in the ASME Section II, Part D may be used. If the material is not specified in Section II, it shall be submitted to

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[d] Nominal compositions are defined by various groups within the ASME Code committee structure and there are no published guidelines describing how these designations are developed. These designations have the greatest relevance in the arrangement of ferrous materials and, as indicated previously, the simplest way to obtain these designations is to look in Section IX of the ASME Boiler and Pressure Vessel Code and use Table QW/QB-422, which is arranged by increasing specification number. These start with the “SA” specification numbers, followed by the “SB” numbers.

ASME for approval. This section provides guidelines on the approval of new materials under the ASME boiler and pressure vessel code. Table 5-7 shown below lists ASME permissible base materials.

Table 5-7. Permissible base materials for Structures other than bolting (Morton, D.K. 2011).

Best Material	Spec No.	Product Form	Types, Grades or Classes
Type 304 SS and 316 SS			
	SA-182	Fittings & Forgings	F 304, F 304 H, F 316, F316H
	SA-213	Smls. Tube	TP304, TP304H, TP316, TP 316 H
	SA-240	Plate	304, 316, 304 H, 316 H
	SA-249	Welded Tube	TP304, TP304H, TP316, TP 316 H
	SA-312	Welded & Smls. Pipe	TP304, TP304H, TP316, TP 316 H
	SA-358	Welded Pipe	304, 316, 304 H, 316 H
	SA-376	Smls. Pipe	TP304, TP304H, TP316, TP 316 H
	SA-403	Fittings	WP 304, WP 304H, WP 316, WP 316H
			WP 304W, WP304 HW
			WP 316 W, WP 316 HW
	SA-479	Bar	304, 316, 304 H, 316 H
	SA-965	Forgings	F 304, F 304 H, F 316, F316H
	SA-430	Forged & Bored Pipe	FP 304, FP 304H, FP 316, FP 316H
Ni-Fe-Cr (Alloy 800H)			
	SB-163	Smls.Tubes	UNS N08810
	SB-407	Smls. Pipe & Tube	UNS N08810
	SB-408	Rod & Bar	UNS N08810
	SB-409	Plate, Sheet &Strip	UNS N08810
	SB-564	Forgings	UNS N08810
2 1/4Cr-1Mo			
	SA-182	Forgings	F 22, Class 1
	SA-213	Smls. Tube	T 22
	SA-234	Piping Fittings	WP 22, WP 22W [Note (6)]
	SA-335	Forg. Pipe	P 22
	SA-336	Fittings, Forgings	F 22a
	SA-369	Forg. Pipe	FP 22
	SA-387	Plate	Gr 22, Class 1
	SA-691	Welded Pipe	Pipe 2 1/4 CR (SA-387, Gr 22, Cl 1)
9Cr-1 Mo-V	SA-182	Forgings	F91
	SA-213	Smls. Tube	T91
	SA-335	Smls. Pipe	P91
	SA-387	Plate	91

Code Policy

It is the policy of the ASME BPV Committee to adopt for inclusion in Section II only such specifications as have been adopted by ASTM International, American Welding Society (AWS), and other recognized national or international organizations.

It is expected that requests for Code approval will normally be for materials for which there is a recognized national or international specification. For materials made to a recognized national or international specification other than those of ASTM International or AWS, the inquirer shall give notice to the standards developing organization that a request has been made to ASME for adoption of their specification under the ASME Code, and shall request that the organization grant ASME permission to reprint the specification. For other materials, a request shall be made to ASTM International, AWS, or a recognized national or international organization to develop a specification that can be presented to the Code Committee.

It is the policy of the ASME BPV Committee to consider requests to adopt new materials only from boiler, pressure vessel, or nuclear power plant component manufacturers or users. Further, such requests should be for materials for which there is a reasonable expectation of use in a boiler, pressure vessel, or nuclear power plant component constructed to the rules of one of the Sections of this Code. Requests for new materials shall be accompanied by a communication from an ASME Certificate Holder, an end user, or an organization that specifies materials and contracts with Certificate Holders for the construction of products to the rules of one of the Sections of this Code. The letter shall state the inquirer's name and status as one of these three types of organizations.

Application

The inquirer shall identify to the Committee the Section or Sections and Divisions of the Code in which the new material is to be incorporated, the temperature range of application, whether cyclic service is to be considered, and whether external pressure service is to be considered. The inquirer shall identify all product forms, size ranges, and specifications for which incorporation is desired.

Mechanical Properties

Together with the specification for the material, the inquirer shall furnish the Committee with adequate data on which to base design values for inclusion in the applicable tables. The data shall include values of ultimate tensile strength, yield strength, reduction of area, and elongation, at 100°F intervals, from room temperature to 100°F above the maximum intended use temperature, unless the maximum intended use temperature does not exceed 100°F. Any heat treatment that is required to produce the mechanical properties should be fully described.

If adoption is desired at temperatures at which time-dependent behavior may be expected to control design values, stress-rupture and creep rate data for these time-dependent properties shall be provided, starting at temperatures about 50°F below the temperature where time-dependent properties may govern (see ASME Sction II, Part D, Appendix 1) and extending to about 100°F above the maximum intended use temperature. The longest rupture time at each test temperature must be in excess of 6,000 hr and the shortest about 100 hr, with at least three additional tests at stresses selected to provide rupture times nominally equally spaced in log (time); i.e., times nominally of 100, 300, 800, 2,200, and 6,000 hr at each test temperature. Obviously, longer times and additional tests are beneficial. The interval between successive test temperatures shall be chosen such that rupture lives shall not differ by more than a factor of about 10 at any given stress for two adjacent temperatures. In general, test temperatures should be in about 50°F intervals if maximum test times are no longer than 6,000 hr. The goal of the testing is to facilitate data analysis to estimate the average and minimum stresses for rupture in 100,000 hr and an average creep rate of 10^{-5} % per hour for each temperature where design stresses are established.

Alternative test plans that deviate from the prior description but achieve the overall objective may be considered.

Minimum creep rate data shall be provided over the same range of temperatures as above, with the lowest stress at each temperature selected to achieve a minimum creep rate of 1.0 to 2.0×10^{-4} % per hour or less. Creep rate data may be obtained in the course of stress-rupture testing or may be obtained on additional specimens. If it can be conclusively demonstrated that creep rate does not control the design stresses, the creep rate data may be sparse in relation to the stress-rupture data. Submission of creep curves for evaluation of creep rate behavior is acceptable and encouraged.

If the material is to be used in cyclic service and the Construction Code in which adoption is desired requires explicit consideration of cyclic behavior, fatigue data shall also be furnished over the range of design temperatures desired.

Other Properties

The inquirer shall furnish to the Committee adequate data necessary to establish values for coefficient of thermal expansion, thermal conductivity and diffusivity, Young's modulus, shear modulus, and Poisson's ratio, when the Construction Code in which adoption is desired requires explicit consideration of these properties. Data shall be provided over the range of temperatures for which the material is to be used.

Weldability

The inquirer shall furnish complete data on the weldability of material intended for welding, including data on procedure qualification tests made in accordance with the requirements of Section IX. Welding tests shall be made over the full range of thickness in which the material is to be used. Pertinent information, such as postweld heat treatment required, susceptibility to air hardening, effect of welding procedure and heat-affected zone and weld metal notch toughness, and the amount of experience in welding the material shall be provided.

Physical Changes

For new materials, it is important to know the structural stability characteristics and the degree of retention of properties with exposure at temperature. The influence of fabrication practices, such as forming, welding, and thermal treatment, on the mechanical properties, ductility, and microstructure of the material are important, particularly where degradation in properties may occur. Where particular temperature ranges of exposure or heat treatment, cooling rates, combinations of mechanical working and thermal treatments, fabrication practices, exposure to particular environments, etc., cause significant changes in the mechanical properties, microstructure, resistance to brittle fracture, etc., it is of prime importance to call attention to those conditions that should be avoided in service or in manufacture of parts or vessels from the material.

New Materials Checklist

To assist inquirers desiring Code coverage for new materials, or extending coverage of existing materials, the Committee has developed the following checklist of items that ought to be addressed by each inquiry. The Committee reserves the right to request additional data and application information when considering new materials, such as:

1. Has a qualified inquirer request been provided?
2. Has a request either for revision to existing Code requirements or for a Code Case been defined?

3. Has a letter to ASTM International or AWS been submitted requesting coverage of the new material in a specification, and has a copy been submitted to the Committee? Alternatively, is this material already covered by a specification issued by a recognized national or international organization and has an English language version been provided?
4. Has the Construction Code and Division coverage been identified?
5. Has the material been defined as ferrous or nonferrous and has the application (product forms, size range, and specification) been defined?
6. Has the range (maximum/minimum) of temperature application been defined?
7. Has mechanical property data been submitted (ultimate tensile strength, yield strength, reduction of area, and elongation at 100°F intervals, from room temperature to 100°F above the maximum intended use temperature for three heats of appropriate product forms and sizes)?
8. If requested temperatures of coverage are above those at which time-dependent properties begin to govern design values, has appropriate time-dependent property data for base metal, weld metal, and weldments been submitted?
9. If coverage below room temperature is requested, has appropriate mechanical property data below room temperature been submitted?
10. Have toughness considerations required by the construction Code been defined and has appropriate data been submitted?
11. Have external pressure considerations been defined and have stress–strain curves been submitted for the establishment of external pressure charts?
12. Have cyclic service considerations and service limits been defined and has appropriate fatigue data been submitted?
13. Has physical properties data (coefficient of thermal expansion, thermal conductivity and diffusivity, Young's modulus, shear modulus, Poisson's ratio) been submitted?
14. Have welding requirements been defined and has procedure qualification test data been submitted?
15. Has influence of fabrication practices on material properties been defined?

Hastelloy N Codification Requirements

Some of the mechanical properties produced in the development of the MSRE are summarized in this section.

The historic tensile properties data for Hastelloy N were collected and reanalyzed in accordance with the current procedures for recommending stress allowable values consistent with the criteria for Table 1B (Section I; Section III, Classes 2 And 3; Section VIII, Division 1; and Section XII Maximum Allowable Stress Values S for Nonferrous Materials) that are specified in Section II, Part D, Appendix 1. Calculated values for Y-1 (Yield Strength Values S_y for Ferrous and Nonferrous Materials) and U (Tensile Strength Values S_u for Ferrous and Nonferrous Materials). Tables were produced for comparison with the existing values in Section II, Part D. The recalculated Y-1 values were found to be higher than the existing values for temperatures above 300°F. The values for the U table were the same except at 800°F and above. Based on this reevaluation, it appeared that the current S (yield strength) values in the time-independent range are conservative. It was observed that Hastelloy N (UNS N10003) is the only nickel alloy that does not provide a high-stress line in Table 1B.

Recalculated values for allowable stress in the time-dependent range, *S,* were produced for comparison with the values in Section II, Part D for temperatures to 1300°F. It was observed that the recalculated time-dependent S values for Hastelloy N (UNS N10003) were close to the current values in Table 1B for temperatures above 1150°F.

The historic fatigue and aging effects data for Hastelloy N (UNS N10003) were collected and discussed relative to the data needs to qualify the alloy for incorporation into ASME Section III, Division 5, covering rules for construction of Class B nuclear facility components. The fatigue curve based on stress-controlled testing was observed to be higher than the curve based on strain-controlled test at 1300°F for lives in excess of 10,000 cycles. However, the original strain-controlled fatigue data were not recovered and no data were available to independently evaluate the strain controlled fatigue curves.

Tensile properties of aged material were collected and compared to unexposed material. Additional data of value to the development of construction codes were reviewed. These included relaxation data and weldment tensile and creep-rupture data.

A more detailed study of the references provided in this report would be useful in establishing a Code Case to qualify Hastelloy N for construction of Class B components under the rules of ASME Section III, Division 5. Other aspects of the developmental work could be helpful in developing the data needs for a Code Case to qualify the material under the rules of ASME Section III, Subsection NH.

Recommendations

Two important considerations with respect to the use of Hastelloy N as a structural material for AHTR of course, are the irradiation resistance and the corrosion behavior. These issues have been reviewed by Ren et al. (2011) and are not addressed in this work. Here are some recommendations:

1. The existing tensile data are adequate to establish the time-independent allowable stressesunder the rules of Section VIII, Division 1 which are referenced in Section III, Division 5 for Class B components.
2. Consideration should be given of establishing a high stress line in the ASME Section II, Part D Table 1B.
3. A series of tensile curves to 2% strain are needed to confirm the validity of the buckling charts currently assigned to Hastelloy N in Section II, Part D.
4. The recommended values for *SU* (ultimate strength) and *SY* (yield strength) may be used to include Hastelloy N into Table HGB-II-3000-2.2 and HGB-II-3000-3.2, if needed to extend temperatures to 1300°F.
5. Data pertaining to the upper temperature-time limits for cold worked material (Table HCB-4215-1) are not available and some work could be undertaken if needed.
6. The current time-dependent allowable stresses in Section II, Part D Table 1B are conservative relative to the data produced from commercial plate products and are representative of other sheet and plate products except at 1100°F and below where the Table 1B values appear to be slightly higher. No changes in Section II, Part D, Table 1B are recommended, but new values will be needed in the 1050 to 1150°F range if a high stress line is added to the table.
7. The establishment of Time-Temperature Limits for Creep and Stress-Rupture Effects (HCB-III) was not within the scope of this effort. As part of additional work, and effort could be made to develop a curve for Hastelloy N.
8. The establishment of aging reduction factors [HCB-II-2000-1(e)] was not within the scope of this effort. However, data pertaining to the effect of aging on subsequent creep-rupture was examined by McCoy (1971, 1978) and found to be minimal. As part of additional work, consideration should be given to adding Hastelloy N to Table HCB-II-2000-1(e) along with justification for the values.

9. Hastelloy N should be added to Table HCB-II-3000-1(d).
10. The establishment of allowable stress values for Table HCB-II-2000-1 was not within the scope of this effort. As part of additional work, and effort could be made to develop allowable stresses meeting the criteria for this table for Hastelloy N.
11. The establishment of the maximum number of cycles and the stress range reduction factor for piping (HCB-1) was not within the scope of this work. However, careful consideration of the high-cycle rotating beam data could be of benefit in making some initial estimates for Table HCB-I-2002 and Table HGB-II-3000-9.2 in the 105 to 106 cycle range.
12. Further testing is needed to establish the strain-fatigue behavior of Hastelloy N.
13. A detailed study should be undertaken to identify the data requirements to produce a Code Case for design and construction under the rules of Section III, Subsection NH.

6. METHODS TO ADVANCE SHX READINESS AND OVERCOME CHALLENGES

The SHX is currently at a TRL-3 (as described in Section 4.2) and the challenges note in Section 5 must be overcome to mature this technology into a viable and reliable heat transfer system. This section describes the steps needed to systematically assure technical maturity.

A Technology Development Roadmap (TDRM) was developed to identify the research and development activities, modeling, design, fabrication, and scaled testing that must occur to satisfy the requirements of advancing readiness levels. As shown in Figure 6-1, the research and development testing is closely coordinated with modeling, which serves to better the design and fabrication of scaled demonstrations. (Note: Full T&P refers to Temperature and Pressure consistent with that expected in the heat exchanger.)

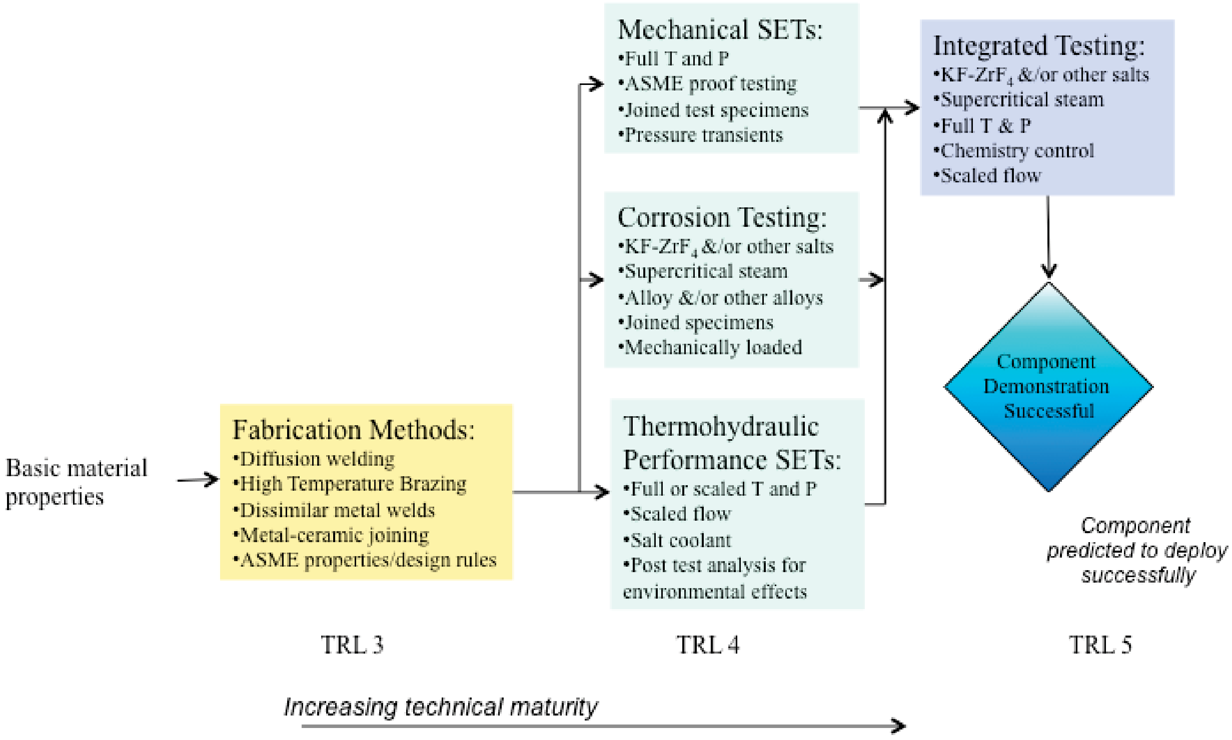


Figure 6-1. TRL Advancement through single effect tests and integrated testing.

The TRL systems assume that greater TRLs correspond to greater reliability, that technologies with higher TRLs function more closely to the desired end-state of the technology, and that the cost of performing a validation test increases at larger-scale demonstrations. Because of the high cost of larger scale demonstrations, the largest risk and uncertainty must be reduced lower TRLs and with small scale demonstrations, testing, and modeling.

TDRMs provide the framework and structure required to systematically perform decision analysis, reduce risk, and mature technologies in a cost effective and timely manner. The roadmap uses the TRL as a measure of the level of technical maturity of a technology, that is, the ability to design, fabricate, and deploy a component or system. The integrated testing or modeling helps to achieve higher TRL ratings at increasingly larger scales and in increasingly relevant environments (Collins 2009). Abbreviated TRL definitions are shown in Figure 6-2.

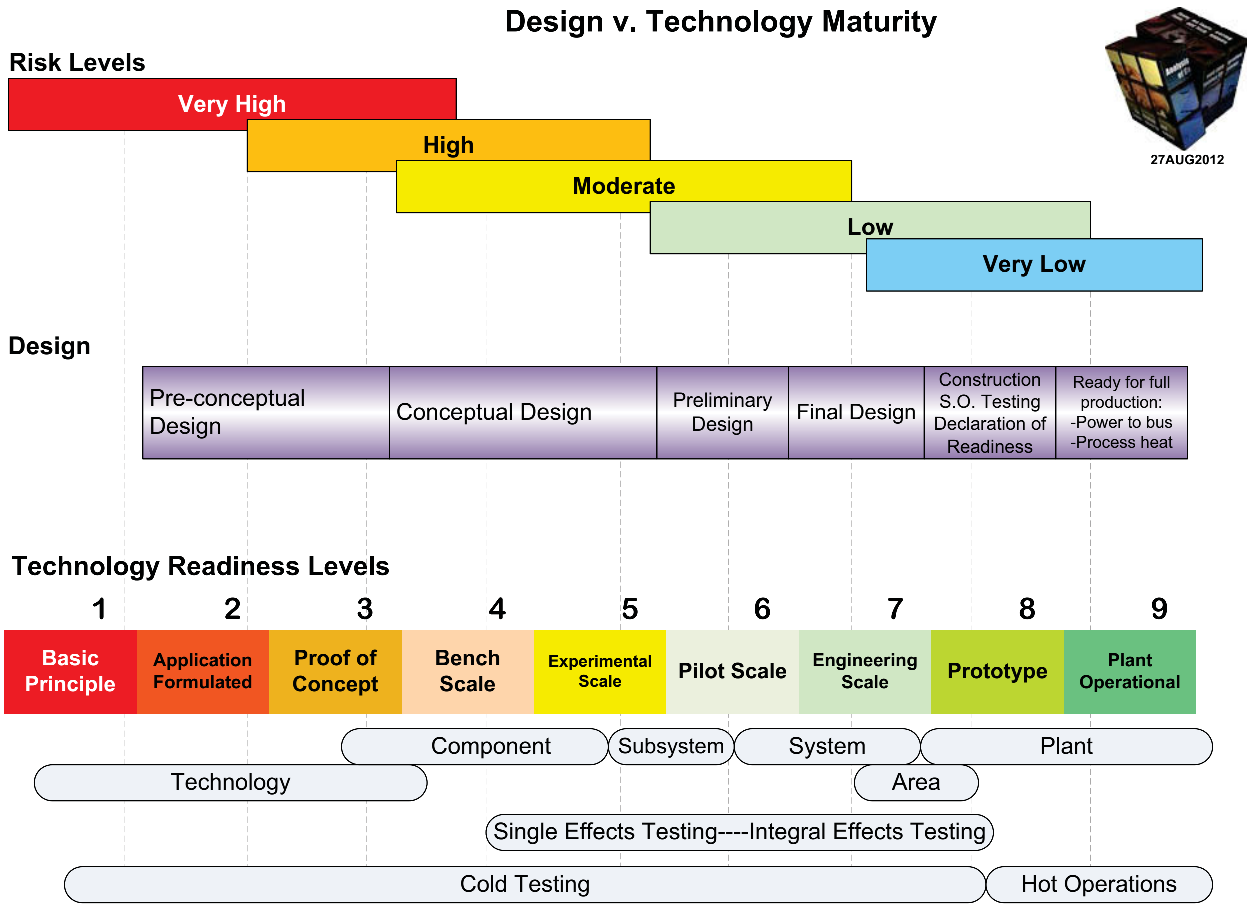


Figure 6-2. Technology readiness levels.

A TDRM documents the tasks needed to obtain information in key discriminating criteria to support technology down selection and the tasks and tests required to sufficiently mature the technology and enhance project performance. The set of TDRMs, along with their associated documentation, will represent the path forward for the Molten Salt project to complete its mission to develop and demonstrate design, performance, operational, licensing, and economic viability of HTGR and leading process heat technologies. Performance criteria are shown on the TDRM as a basis for TRL advancement (where specific values are not known, TBD [to be determined] is used). This document contains the TDRMs necessary to facilitate risk-informed decision making, technology down selection, management of technical uncertainty, and technology qualification and maturation for the SHX, while also serving to coordinate engineering, R&D, and licensing efforts and mitigate risks early in the project.

This process provides the following benefits to the SHX project:

- Identifies precise project objectives and helps focus resources on critical technologies that are needed to meet those objectives
- Creates a consensus vision of SHX project needs based on capabilities needed now and in the future
- Provides early identification of high-risk items and allows early focused attention to enhance project cost and schedule success
- Supports engineering, R&D, and management priorities, which inform schedule development and resource allocation

- Sets the vision for and drives the needed actions to down select technologies and designs
- Ensures technology readiness is demonstrated through testing, modeling, piloting, and prototyping
- Develops the test plans required to provide demonstrable evidence of the technology maturation required for codification and qualification.

The major technical risks identified for each SSC represent the overall uncertainties that must be addressed and reduced to enhance the probability of a successful molten salt system. These risks are generally reduced as technology is developed per the TDRMs. The coupling of components represents a risk that must be reduced through integrated and large-scale systems testing rather than mere component testing or single effects testing. This risk is not reduced entirely until the SHX demonstrates full system operability and successfully receives a TRL-8. Performance criteria have been established for each TRL decision gate. The components must successfully meet these criteria to be granted the next TRL level, which represents significantly increased technical maturity.

The characteristics of a maturing technology are demonstrated in increasingly relevant environments, at more representative scales, and integrated with other components into full systems. These measures of maturity are defined as follows:

- *Relevant Environment*. The environment (temperature, pressure, fluid, flow rate) in which testing occurs becomes increasingly identical to the AHTR environment.
- *Scale*. The size of the test increases from lab-scale to full-scale.
- *Systems Integration*. The technologies tested are increasingly and progressively integrated with the testing of multiple components, subsystems, and systems, and with final plant (AHTR) testing, which includes multiple areas.

6.1 SHXs Maturation Path Forward to TRL-4 and TRL-5

Three SHX technology development areas illustrated in the TDRM (see Figure 6-3) address the major challenges noted in Section 5 of this report. In each case, a preliminary down selection has been made and maturation tasks identified to advance the components to TRL-4 and TRL-5. Next, each component is integrated into a heat exchanger system for demonstration at a pilot scale to achieve a TRL-6.

The TDRM represents an iterative process of learning from each activity and applying that knowledge to successive activities and demonstrations. TRL criteria will be reviewed and updated after achieving each TRL, or when discovery adds a new technical issue.

6.1.1 SHX Materials Testing Needs to Achieve TRL-4 and -5

Advancing from a TRL-3 requires successful completion of bench-scale testing to demonstrate technical feasibility and functionality. A TRL-4 is granted once material qualification/codification and constitutive modeling and analysis tasks begin. To achieve a TRL-5, significant SHX materials properties need to be matured and associated tasks must be completed. Overall, these maturations orient around material qualification/codification and constitutive modeling and analysis. Joining procedures need to be extrapolated to include Hastelloy N creep data for a 60 year life cycle, prior to achieving a TRL-7.

If Hastelloy N maturation tasks fail to fully codify the alloy, 800H (previously codified to 760°C) will serve as a backup to Hastelloy N. However, since its corrosion resistance is inferior to Hastelloy N, some consideration is being given to use of 800H with Alloy N as a liner in coordination with FHR codification efforts.

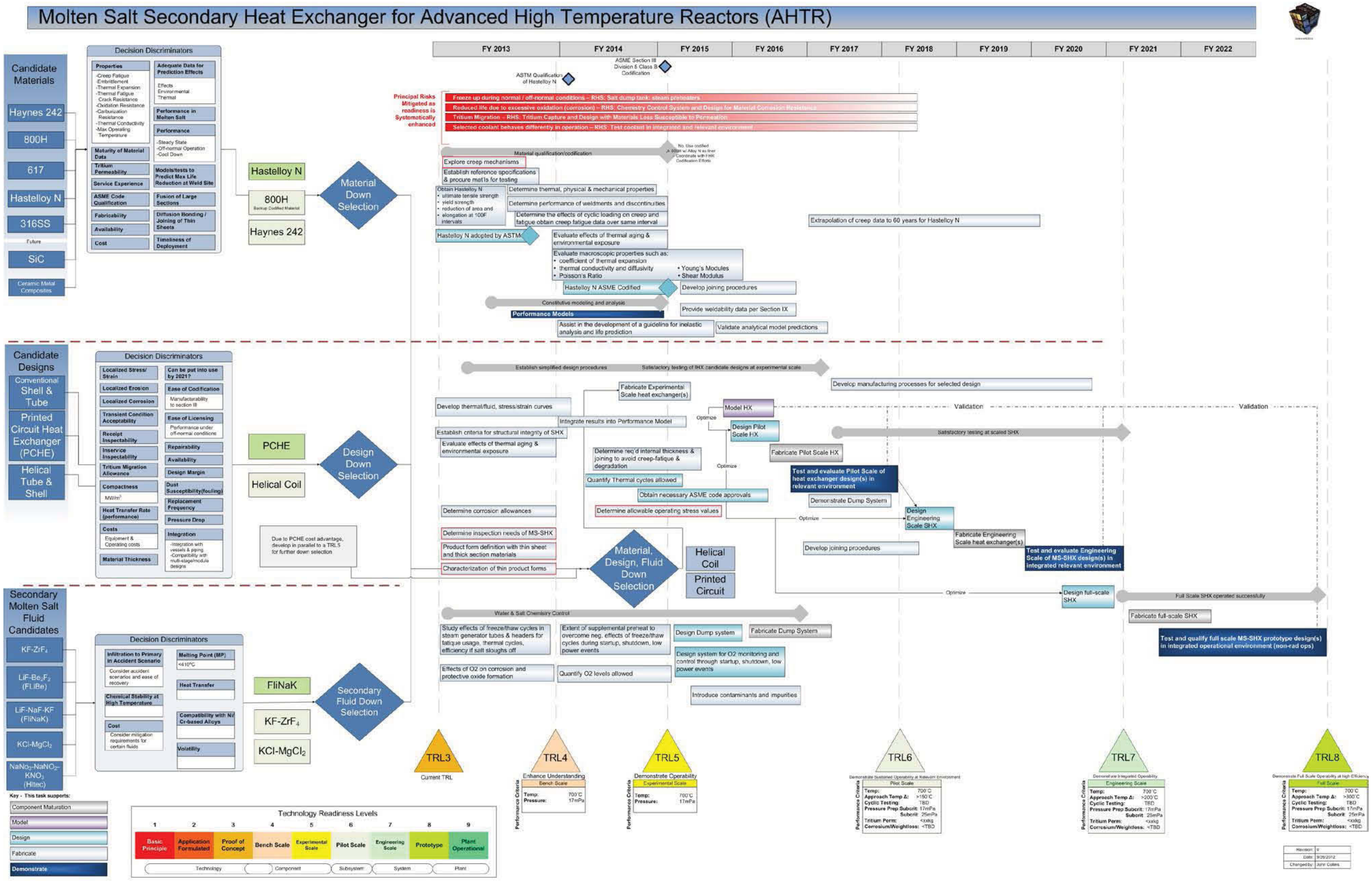


Figure 6-3. TDRM for SHX.

6.1.1.1 Fatigue Testing

The fatigue design curves of ASME BPV Section III, Div 1, Appendix I are not applicable to the expected operating temperature of the SHX. Support data must be generated to develop similar fatigue design curves. However, test data from cyclic loading of the diffusion bonded assemblies under typical operating conditions will be valuable in assessing the performance of these subassemblies as compared to the data obtained from testing material specimens. The cyclic conditions in the full scale units can be generated by the pressure transients, thermal transients, or a combination of pressure and thermal vibrations. Thermal cycles will be imposed on the full-scale units by steady-state variations of temperature along the heat transfer surface because of the temperature differences at the hot and cold ends and by startup/shutdown and other transients, including both load following and upset conditions. For TRL-4, a pressure-induced fatigue testing at typical operating temperatures can provide a relatively quick means of imposing fatigue loads on representative prototype. A separate-effects test that imposes pressure transients on subassemblies that are maintained at constant temperature allows the testing of the subassembly joints under well controlled conditions. Thermal transients would be best imposed on the subassemblies under the following conditions so that the temperature distributions are more typical of the actual installation, as compared to external imposed temperature transients (by ramping a furnace temperature up and down, for instance). Combined pressure and temperature transients will be addressed in TRL-5 or higher testing plans.

6.1.1.2 Pressure Induced Fatigue Testing

The proof pressure and leak testing discussed in Section 6.1.2.1 can identify manufacturing flaws in the subassemblies under static conditions and typically under ambient temperature conditions. Fatigue testing using pressure variations is a simple way to induce cyclic loading and evaluate the fatigue performance in a prototypical configuration. This fatigue testing will provide confirmation of the fatigue curves developed under the materials testing effort in subassemblies more representative of the physical configuration of the SHX. The diffusion welded SHX depends on joining the ribs of the channel side of the plate to the flat of the back of the adjacent plate. This configuration results in sharp corners that can induce stress concentrations. The pressure cycling of the plates will provide separate effects testing of the stresses in these joints to confirm the fatigue data developed in the TRL-3 materials testing and the calculated stresses in the design and analysis modeling of the subassemblies. In this context, the separate effects test describes a test that is intended to isolate a particular phenomenon of interest from other associated phenomena that may complicate the interpretation of the results. For example, by using pressure to impose the cyclic loadings at a constant temperature, the contribution of the thermal gradients in the heat exchanger can be eliminated so that the pressure effects can be studied separately. By testing the subassemblies under elevated temperatures the fatigue strengths can be determined as a function of temperature. It is likely that the test articles would be tested to failure, as indicated by loss of ability to maintain pressure.

6.1.1.3 Thermal Fatigue Testing

Temperature differences between the hot and cold sides of the SHX will impose stress distributions on the diffusion bonded structures and overall thermal transients because the change in operating conditions will also impose thermal loads. These thermal loads will generate stresses in the diffusion bounded plates. A scaled flowing loop will be needed to accurately simulate the thermal conditions in the scaled PCHE accurately.

6.1.1.4 Creep and Creep-Fatigue Testing

The expected operating conditions of the SHX will impose significant stresses at temperatures that are in the creep range for many of the candidate materials. As with the fatigue testing discussed previously, creep testing will need to be performed as part of the future work under the materials R&D effort on standard specimens. Prior to performing creep testing of the subassemblies, a series of tests to better understand the creep performance of the candidate materials under multiaxial stress conditions will provide a better understanding of the material properties and analytical methods.

6.1.1.5 Corrosion Testing

Corrosion testing has been performed at University of Wisconsin under INL subcontract for diffusion welded joints. Corrosion testing, as explained in Section 5.2.4.3, of fabricated subassemblies under typical configurations and at representative velocities, temperatures, pressures, and contaminant concentrations is needed to assess performance of the subassemblies. The physical configuration, methods of fabrication, and flowing fluid of the component in service may result in different corrosion mechanisms or rates than encountered in coupon testing.

6.1.1.6 Thermal-Hydraulic Testing

Thermal-hydraulic performance encompasses the heat transfer and pressure loss characteristics of the compact heat exchangers. For advancement to TRL-4, demonstration of the functionality of the subassembly requires verifying the thermal-hydraulic performance of the subassembly, this demonstration will identify any discrepancies between the design calculations and the actual performance and help validate/benchmark the correlations and also provide uncertainty.

6.1.2 SHX Designs Testing Needs to Achieve TRL-4 and TRL-5

Advancing from a TRL-3 requires successful completion of ASME required material properties development to demonstrate technical feasibility and functionality. SHX tasks to advance to TRL-4 include development of simplified joining and fabrication procedures, structural integrity, product form definition and evaluating the effects of thermal aging, environmental exposure, and corrosion allowance. For a TRL-5, experimental-scale testing, fabrication of the SHXs at experimental-scale, and start of NRC licensing and ASME codification approvals must be complete. Additionally, flaw assessments and leak-before-break tasks must be performed. TRL-5 issuance requires testing and evaluation of SHXs at experimental-scale. The allowable operating stress values and required internal thickness and joining to avoid creep-fatigue and degradation must be determined. Various in-service inspectability tasks also need to be performed.

6.1.2.1 Leak and Proof Pressure Testing

Case Study 2621-1 has been developed for the ASME Section VIII, Division code for use of diffusion bonding for construction of micro channel heat exchangers. Pending development of an ASME BPV Code Section III code case for the diffusion bonded heat exchangers, it is expected that the testing requirements for Section III will be similar to those developed for Section VIII code case and those requirements will be used. The leak and pressure testing for the diffusion bonded heat exchangers will ensure fabrication without significant flaws or leaks. It is proposed that the subassemblies be pneumatically or hydrostatically tested to demonstrate satisfactory performance of the fabrication processes at pressure.

6.1.3 Secondary Fluids Testing Needs to Achieve TRL-4 and TRL-5

Advancing from TRL-3 to TRL-4 requires understanding and developing methods to control water and salt chemistry. To achieve a TRL-4, the constitutive modeling and analysis tasks begin with mechanical single effect tests, corrosion testing, and thermal-hydraulic performance single effect tests. A TRL-4 would be granted only after the material qualification/codification and constitutive modeling and analysis tasks begin. As material (Hastelloy N) testing begins to demonstrate viability towards full codification, a TRL-4 should be considered. As Hastelloy N, a Helical Coil HX, and ($KF-ZrF_4$) are successfully integrated in a low fidelity bench scale test or model, a TRL-4 should be considered.

The effects of freeze and thaw cycles in the SHX tubes and headers will be evaluated. The freeze and thaw cycle effect on fatigue usage, thermal cycles, and thermal efficiency will also be evaluated. The effects of oxygen on corrosion and protective oxide formation will be evaluated. To achieve a TRL-5, the material and bond strength has to exhibit high strength at the required high temperature and pressure with constitutive modeling and analyses. The optimum oxygen levels allowed to achieve passivation and corrosion resistance will be quantified. The extent of supplemental preheat to overcome the negative effects of freeze and thaw cycles during startup, shutdown, and low power events will be determined.

6.1.4 Instrumentation Advancement to TRL-5

While a wide variety of instrumentation is commercially available for high temperature test components and loops, instrumentation should be developed for testing and to support potential application in the heat transfer system test chambers and loops, and perhaps the power plant. Instrumentation requiring development is shown in Figure 6-4 along with the development steps needed to achieve a TRL-5. Following the achievement of a TRL-5, this instrumentation will be ready for integration into the SHX pilot scale demonstration.

Instrumentation suggested in this test plan for further evaluation and development includes:

1. High temperature acoustic sensors and algorithms to detect cracks, detect leaks, locate loose parts in test loops
2. High temperature acoustic sensors and algorithms to locate and identify corrosion at the pressure boundary and in other components
3. High-temperature, low-drift thermocouples or thermocouples whose drift is accurately and reliably quantified
4. Low-drift, high-temperature RTDs with migration-resistance sheath materials
5. Optical measurements of temperature, pressure, and strain
6. High temperature optical windows to accommodate particle imaging velocimetry and other imaging methods
7. Advanced vibration analysis
8. Ultrasonic and fiber-optic based strain detection to understand effects of thermal cycling
9. Alternatives to measuring flow and density/pressure
10. Development of multidimensional displays and associated human factors studies
11. Online condition of materials in the heat transport systems and effects of water chemistry and salt purity
12. Methods of detecting tritium permeation
13. Methods for evaluating the calibration and operation of sensors and transmitters.

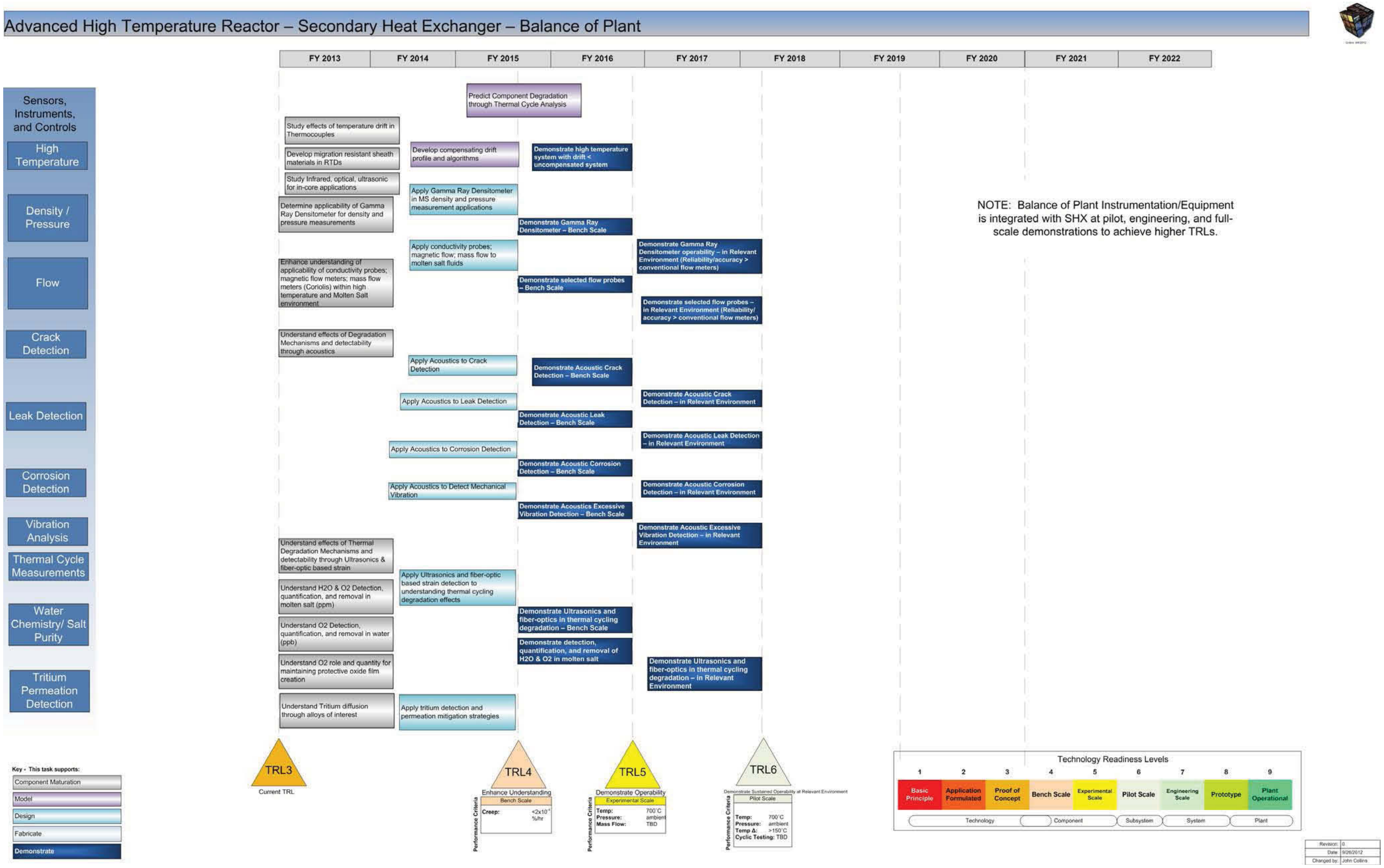


Figure 6-4. TDRM for SHX instrumentation and equipment.

6.2 SHX Scale-up Demonstrations for TRL-6

Technology development tasks for TRL-6 require completion of a pilot-scale SHX, which includes design, fabrication, and testing of the pilot-scale SHX. Modeling will be used to inform and optimize the design. Results from the pilot scale test will be used to validate and improve the model. At this stage, manufacturing processes for the selected design are further developed and tested in the fabrication of the pilot scale demonstration and the molten salt dump system and an oxygen monitoring and control system will be designed, fabricated, and tested prior to the achievement of TRL-6. This test will include the introduction of contaminants and impurities.

This pilot-scale demonstration will be conducted in a relevant environment at 700°C and will demonstrate a temperature differential between the primary and secondary side of 150°C at the anticipated pressure differential between the primary and secondary side (17 or 25 MPa, depending upon Rankine cycle used).

Single effects testing will also be performed to verify tritium permeation and corrosion within tolerances.

6.3 SHX Scale-up Demonstrations for TRL-7

Technology development tasks for TRL-7 require completion of an engineering-scale SHX to be tested in an integrated and relevant environment. Modeling will be used to inform and optimize the design. Results from the engineering scale test will be used to validate and improve the model. At this stage, manufacturing processes for the selected design are further developed and tested in the fabrication of the engineering scale demonstration. This test will include the introduction of contaminants and impurities.

This engineering scale demonstration will be conducted in an integrated and relevant environment at 700°C and will demonstrate a temperature differential between the primary and secondary side of 200°C at the anticipated pressure differential between the primary and secondary side (17 or 25 MPa, depending upon Rankine cycle used).

Integrated into this engineering test will be methods to verify tritium permeation and corrosion within tolerances.

6.4 SHX Scale-up Demonstrations for TRL-8

Technology development tasks for TRL-8 require completion of a full-scale SHX to be tested in an integrated operational and relevant environment. Here again, modeling will be used to inform and optimize the design. Results from the full-scale test will be used to validate and improve the model. At this stage, manufacturing processes for the selected design are further developed and tested in the fabrication of the full-scale demonstration. This test will include the introduction of contaminants and impurities.

This full-scale demonstration will be conducted in an integrated, operational relevant environment at 700°C and will demonstrate a temperature differential between the primary and secondary side of 300°C at the anticipated pressure differential between the primary and secondary side (17 or 25MPa, depending upon Rankine cycle used).

Fully integrated into this full-scale test will be methods to verify tritium permeation and corrosion within tolerances.

7. CONCLUSIONS AND RECOMMENDATIONS

This study will aid in the development and selection of the required heat exchanger for power production and process heat application for an AHTR. This TDRM presents the path forward for deploying large-scale molten salt secondary heat exchangers and recognizing the benefits of using molten salt as the heat transport medium for AHTR.

7.1 Heat Exchangers Design

1. The decision parameters for the selection of the SHX have been established with evaluation goals, alternatives, and criteria. For the same heat duty, the HCHE showed a five times greater overall heat transfer coefficient, along with a much higher secondary pressure drop when compared with the PCHE.
2. The cost analysis of the heat exchangers over 50% cost saving with the deployment of PCHEs compared to HCHE for the three heat exchangers option of 1130 MW each.

7.2 Coolant Fluids

Fuels salts received considerable testing and development in the MSRE program at ORNL during the 1950s through 1970s, but relatively little research has been conducted on coolant salts. The corrosion data for various alloys in FLiBe, FLiNaK, KCl-$MgCl_2$, $NaNO_2$-$NaNO_3$-KNO_3, and KF-ZrF_4 , (the last of which, was recently tested by INL for welded and unwelded Alloy N and found to be adequate) are much too limited for reliable comparisons of corrosion resistance of the various alloys, or the relative aggressiveness of these molten salts. Most of the tests published by the various research groups were screening tests in which parameters were often ill-defined, rather than parametric tests in which parameters, such as temperature and/or contamination levels, were varied systematically to determine the effects on corrosion rate.

1. Presently, FLiBe has been chosen for the AHTR primary coolant, mainly because of its higher heat-transfer performance and lower neutron absorption cross section.
2. A particular concern is the production of tritium gas (mainly because of lithium in the salt), which could permeate through the salt mixture, pipe walls, and heat exchanger walls into the steam generator and possibly escape from the system with the steam or in the industrial process side application. Additional research is needed to better understand and mitigate tritium permeation.

7.3 Materials of Construction

Few specific inferences can be drawn from the existing but limited data on materials of construction. In general, nickel and alloys with dense nickel coatings are effectively inert to corrosion in fluorides, but not so in chlorides.

1. Testing of selected alloys for resistance to intergranular corrosion to determine the relative aggressiveness of the four salts of interest, to identify more closely additional alloys that are resistant to the mechanism is needed.
2. Corrosion rate as a function of contaminant type (e.g., free fluorine, HF, water, metal oxide, dissolved transition metals) is needed.
3. Corrosion rates as a function of alloy composition with respect to chromium and carbon to better define the optimal chromium and carbon composition, independent of galvanic or differential solubility effects is needed.

7.4 Steam Generator and Power Cycle

The efficient transfer of energy for industrial applications depends on the ability to incorporate cost-effective heat exchangers between the nuclear heat transport system and industrial process heat transport system. The heat from the reactor is anticipated to be used for power generation and process heat applications. Given the very high steam generator pressure of the supercritical steam cycle, it is anticipated that water tube and salt shell steam generators will be used in the near term rather than compact heat exchangers.

The coupling to a supercritical steam cycle can likely be simplified by applying lessons from decades of successful operation of fossil supercritical plants. These include the materials of the piping, turbine, and other components, and the components such as condensate demineralizers and deaerators to protect them. Though, potential for solidifying salt is greater in steam cycles (because of lower reactor temperature) supercritical CO_2 cycle should be studied further.

7.5 Balance of Plant

While a wide variety of instrumentation is commercially available for high temperature test components and loops, instrumentation should be developed for testing and to support potential application in the heat transfer system test chambers and loops, and perhaps the power plant. Additional research is needed on:

1. High-temperature, low-drift thermocouples or thermocouples whose drift is accurately and reliably quantified
2. High-temperature, low-drift RTDs with migration-resistance sheath materials
3. Optical measurements of temperature, pressure, and strain
4. High temperature optical windows to accommodate particle imaging velocimetry and other imaging methods
5. Acoustic sensors and algorithms to locate and identify cracking in the test coupons, pressure boundary, and other components
6. Multidimensional displays and associated human factors studies
7. Online condition of materials in the heat transport systems.

A TDRM was developed to identify the research and development activities, modeling, design, fabrication, and scaled testing that must occur to satisfy the requirements of advancing readiness levels. TDRMs provide the framework and structure required to systematically perform decision analysis, reduce risk, and mature technologies in a cost effective and timely manner. The roadmap uses the TRL as a measure of the level of technical maturity of a technology, that is, the ability to design, fabricate, and deploy a component or system. The SHX is currently at a TRL-3 and the challenges addressed in this study must be overcome to mature this technology into a viable and reliable heat transfer system.

8. PATH FORWARD

The AHTR has the potential to provide quality process heat for efficient power production and process heat applications. The development of the intermediate heat exchanger is critical to provide that product. Although the legacy of experience exists for shell and tube heat exchangers combined with steam Rankine power cycles, these do not take advantage of the higher temperature and potential smaller size of the AHTR. Rankine cycles also have steam generator return temperatures that are substantially lower than the freezing point of molten salts, which questions the use of these cycles for power production. Recent optimization studies have shown potential thermal efficiencies of 48% for AHTR reactor outlet temperatures of 700°C when using the supercritical carbon dioxide modified Brayton gas cycle. The potential cost advantage and compact size provides incentive to continue the investigation of PCHE heat exchangers as intermediate/secondary heat exchangers. The development of the shell and tube heat exchanger is also critical due to potential process heat applications where this type of heat exchanger may have an advantage over the PCHE.

8.1 Resources to Advance TRLs

This section contains resources that may be used to advance the TRL for the AHTR secondary heat exchanger.

8.1.1 Diffusion Welding

Diffusion welding is a mature welding process with wide application in many industries. Closely mated surfaces, held together under moderate pressure and temperatures typically exceeding 60% of the absolute melting temperature will eventually, through diffusion processes, eliminate surface contaminants and oxides, and reduce their surface asperities to isolated pores along the bond line which are gradually filled. Grain boundary migration and grain growth dynamics can eventually produce a joint that is micro-structurally indistinguishable from the base materials, see Figure 8-1.

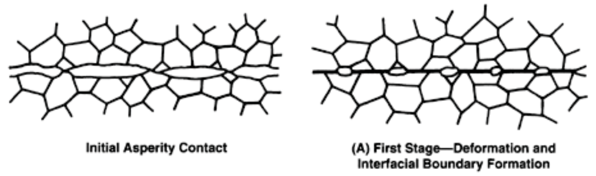
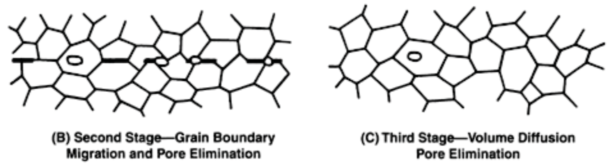
	
(a)	(b)

Figure 8-1. Stages of diffusion welding.

INL has expertise in diffusion welding using the Gleeble System manufactured by Dynamic Systems Inc. (Figure 8-2). The Gleeble is well known for its versatility in many welding metallurgy studies, particularly the rapid thermal cycling and loading typical of fusion welding processes. It is a servo-hydraulic machine that heats specimens by Joule heating. The Gleeble may be used to optimize the procedures needed to develop strong diffusion bonds by varying such parameters as material, pressure, temperature, and time. It can accomplish this with short turnaround times. Diffusion welded samples can then be tested for corrosion in fluids such as molten salts and the high temperature, high pressure gas mixtures typically found in advanced and/or small modular reactors. Diffusion welding is the key welding process in the manufacture of printed circuit heat exchangers, PCHE. PCHEs are very compact and efficient and are under consideration as intermediate/secondary heat exchangers for process heat applications and power conversion units. Diffusion welding may also be used to bond dissimilar metals such as inexpensive low temperature and expensive high temperature alloys.

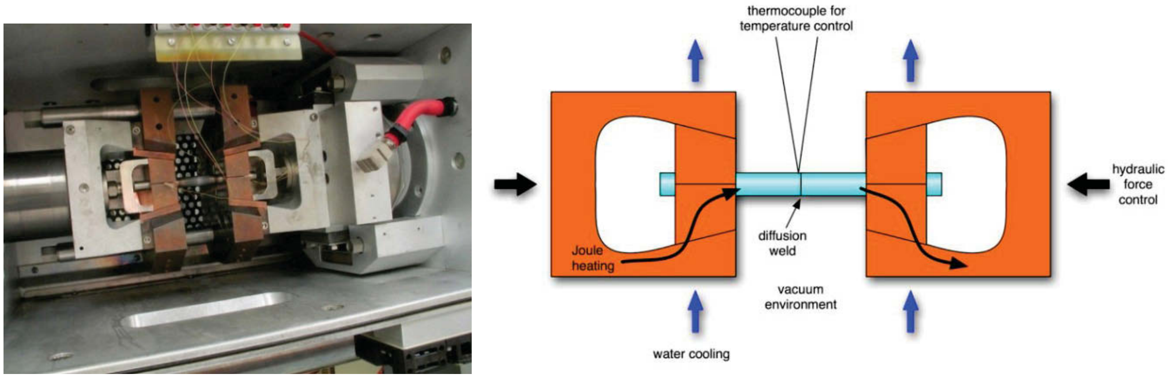


Figure 8-2. Gleeble loaded with diffusion welding specimen and principle of operation: specimens are gripped in water-cooled copper jaws, heated by Joule heating and feedback from welded thermocouple.

8.1.2 Computational Thermodynamic Modeling of Materials

Material tests, including corrosion tests, can be numerous and costly, particularly when developing new codes and standards for high temperature materials. Computational thermodynamic modeling of materials is a means to predict the properties, phase composition, and microstructure of complex, real-life multi-component systems. The thermodynamic properties and phase equilibria in steels, stainless steels, and super alloys which often contain more than 10 components can be calculated. From this, the microstructure and properties of the materials may be accurately predicted. Thus the number of experiments needed for research in areas such as new alloys, fuel and hydrogen cells, and battery material development can be reduced or optimized. This approach can also provide valuable guidance in the design of protective coatings, the effects of heat treatments and in the understanding of aqueous and molten salt corrosion processes. This modeling may be applied to areas such as multi-component phase equilibria and diffusion processes for diffusion welding of super alloys, hot corrosion phenomena in super alloys in molten salts or high temperature gases, and the development of protective coatings. As shown in Figure 8-3, predictions from the models compare well with data from experiments.

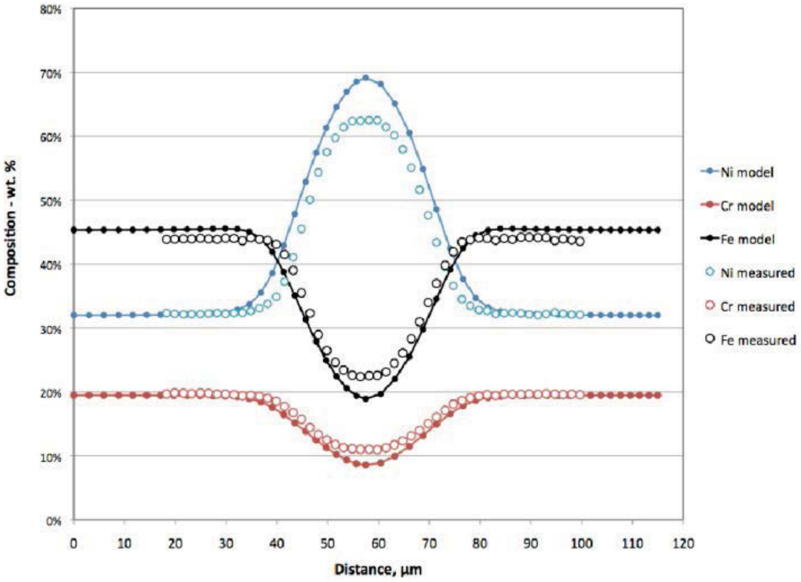


Figure 8-3. Comparison of diffusion modeling of Alloy 800H and measurements from a scanning electron microscope with an energy dispersive spectrometer.

8.1.3 Industrial Process Heat Applications and Economics

The Next Generation Nuclear Plant (NGNP) Project, led by INL, is part of a nationwide initiative to promote the use of nuclear energy and establish a technology for hydrogen and electricity production that is free of greenhouse gas (GHG) emissions. Under this program, many industrial processes requiring heat were modeled to determine whether it is technically and economically feasible to integrate high temperature gas-cooled reactor (HTGR) technology into the industrial processes. To avoid an overly optimistic environmental and economic baseline for comparing nuclear-integrated and conventional processes, a conservative approach was used for the assumptions and calculations. The engineering analyses show that HTGR-integrated processes would sharply reduce carbon dioxide, CO_2 and other GHG emissions, primarily by replacing the heat derived from natural gas and coal with high temperature process heat from the HTGR. Economic analyses for the HTGR-integrated cases were completed to identify the major factors that influence the economics of HTGR-integrated processes of interest. The following processes were analyzed with and without process heat from a nuclear plant:

- Synthetic gasoline production
- Synthetic diesel production
- Ammonia derivatives production
- Steam-assisted gravity drainage for bitumen recovery from oil sands
- Substitute natural gas production from coal
- High temperature steam electrolysis
- Steam methane reforming
- Oil shale recovery
- Power production
- Olefin production from natural gas.

The capability of the HTGR to produce high temperature process heat offers such advantages as:

- Reducing CO_2 emissions by replacing the heat derived from burning fossil fuels, as practiced by a wide range of chemical and petrochemical processes, and co-generating electricity, steam, and hydrogen
- Generating electricity at higher efficiencies than are possible with current nuclear power generation technology
- Providing a secure long-term domestic energy supply and reducing reliance on offshore energy sources
- Producing synthetic transportation fuels with lower life cycle, well-to-wheel (WTW) GHG emissions than fuels derived from conventional synthetic fuel production processes and similar or lower WTW GHG emissions than fuels refined from crude oil
- Producing energy at a stable long-term cost that is relatively unaffected by volatile fossil fuel prices and a potential carbon tax (a price set on GHG emissions)
- Extending the availability of natural resources for uses other than a source of heat, such as a petrochemical feedstock
- Providing benefits to the U.S. economy such as more near-term jobs to build multiple plants, more long-term jobs to operate the plants, and a reinvigorated heavy manufacturing sector.

This legacy of process and economic models and the expertise to perform these analyses, could be adapted to predict the technical and economic feasibility of these industrial processes with other types of nuclear reactors such as molten salt, sodium cooled, or small modular reactors.

8.1.4 Component Test Facilities

8.1.4.1 MISTER

The Mixed Stream Test Rig (MISTER) was assembled in FY 2010 to test high temperature materials within environments of a variety of gas compositions. The test system is designed to provide realistic environments for studying the effects of high temperature gas mixtures upon material samples using two separate gas streams of variable composition within a single furnace, exposing material samples to the gases at temperatures up to 1100°C (see Figure 8-4). Understanding the resulting material corrosion rates will help inform materials selection and qualification to ensure successful future performance.

MISTER is capable of controlling mixtures of CO, CO_2, N_2, Oxygen, Hydrogen and other gases. Many process applications require corrosion testing in high temperature gas mixtures, which MISTER is capable of supplying. In addition to the high temperatures, high pressures exist in many of these process applications. MISTER was thus designed and built so it could, with minor modifications, provide high pressure testing up to 7 MPa. With further modification, it could test materials subjected to mechanical loading or pressure cycling at these high temperatures and pressures for a variety of gas compositions. Testing in these conditions will significantly advance the understanding of materials performance in representative environments for future heat exchangers, steam generators, circulators, seals, and instrument and control components. MISTER will provide the desired environments for material testing through two independent piping systems, one for flammable mixtures (hydrogen, CO, etc.) and another for oxidizing mixtures (oxygen, air, etc.). The flow path for each is a once-through design where the gases are mixed, heated, passed over the samples, and then exhausted by venting to the atmosphere. The gas streams are piped in a configuration that enables gas exposure of different components, specimen configurations or bipolar corrosion measurements during the same experimental run. Bipolar testing refers to the ability to flow different gas compositions on opposing sides of the same sample. The two parallel streams share a collocated gas supply system, and all tube fittings are positioned outside the furnace. MISTER may be used to simulate pressures and temperatures found within the SHX during operation to aid in material testing which will aid the promotion of the technology to TRL 4.

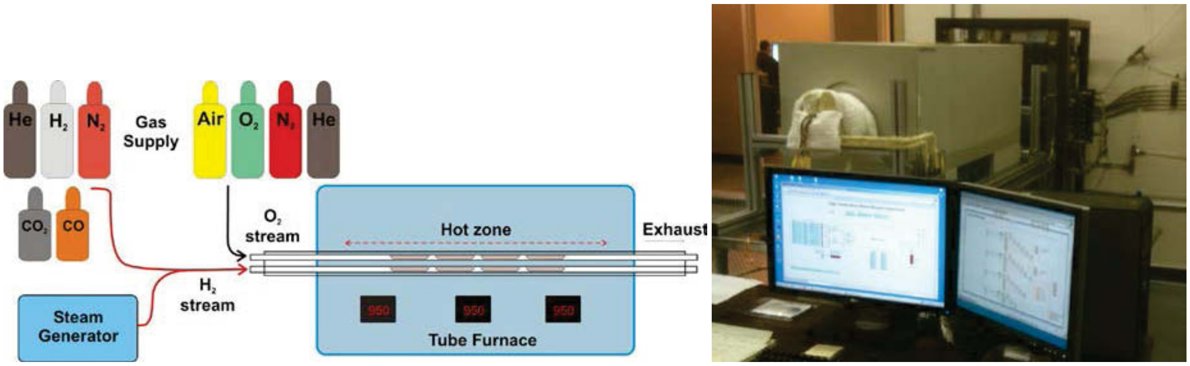


Figure 8-4. Conceptual drawing of MISTER and test facility.

8.1.4.2 SPECTR

The Small Pressure Cycling Test Rig (SPECTR) is used to test mechanical components at high temperatures and pressures in support of the development of fabrication methods for high temperature compact heat exchangers as well as other potential applications. SPECTR consists of a high temperature furnace (capable of operation at temperatures of up to 1200°C and pressures up to 1 MPa), the associated power transformer, furnace coolant circulation system, controls and instrumentation, and a separate test article gas supply and exhaust system (see Figure 8-5). High temperature reactors provide energy for industrial process applications and the generation of electricity. Advanced reactor designs are predicted to operate at temperatures up to 950°C and pressures up to 7 MPa. Part of advancing a reactor concept addresses the research and development necessary to advance the Technology Readiness Levels (TRLs) of the major components of the heat transport system to commercial scale for current designs as well as future higher temperature designs.

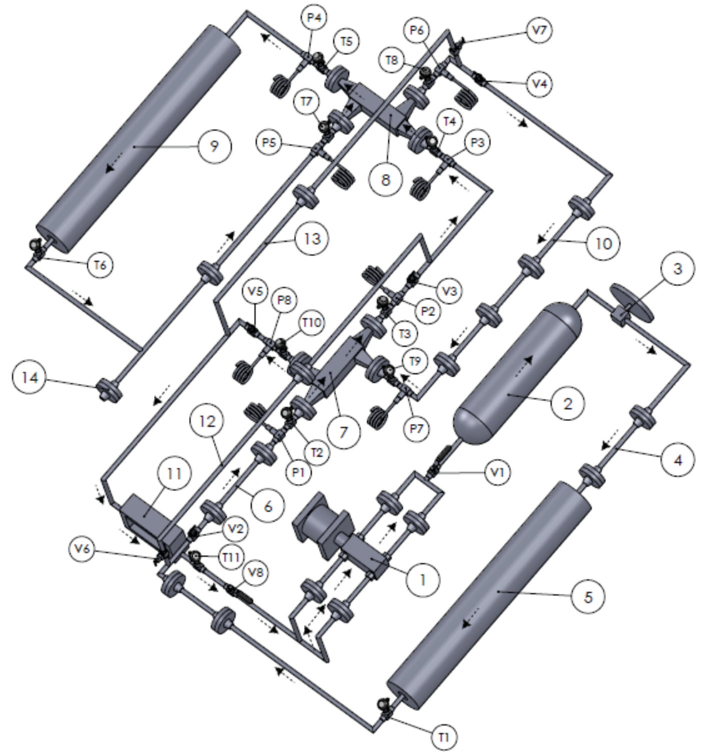
One aspect of the development of the heat transport system is the advancement of the intermediate heat exchanger (IHX) from its current rating of TRL-3 (proof of concept) to TRL-4 (bench scale). That development includes testing of subassemblies of the IHX to assess the fatigue and creep performance of the fabricated parts. The SPECTR supports fatigue testing of the subassemblies at temperatures up to 1200°C and test article internal pressures up to 9 MPa. SPECTR can also be used to perform pressure testing of other test articles. SPECTR provides operating pressures and temperatures for component testing. This type of testing will promote the technology to a TRL 5.

Figure 8-5. SPECTR test facility.

8.1.4.3 Ohio State University's HTHF

The Ohio State University's High-Temperature Helium Test Facility (OSU HTHF) was designed and constructed to test thermal hydraulic performance of high temperature heat exchangers for high-temperature gas-cooled reactors (HTGRs). The HTHF can facilitate performance testing at temperatures and pressures up to 800°C and 3 MPa, respectively. Research-grade helium is used as the working fluid for both the hot and cold sides. Figure 8-6 shows a schematic and photo of the high temperature side of HTHF. Two counter-flow high-temperature printed-circuit heat exchangers (PCHEs) are currently installed in series and have been tested at temperatures and pressures up to 795°C and 2.8 MPa. The total heating power of the facility is 46 kW with a maximum helium flow rate of 45 kg/h, which can be conveniently doubled with addition of one gas booster.

Thermocouple wells (sheathed with 800H alloy) are used for measuring the helium temperatures at various locations in the facility. Three venturi type flow meters measure the volumetric flow rates of helium gas flowing through the loop. A turbine-type flow meter installed on the process chilled water-side of the cooler allows monitoring of the flow rate of the process chilled water (PCW). All measurement and test equipment have calibration information traceable to NIST standards. HTHF has been designed with sufficient flexibility to accommodate testing of heat exchangers with different configurations, fluids (such as, supercritical CO_2), and critical components, such as valves, instruments, gaskets, piping, etc., under high temperature conditions. The HTHF facility can simulate pressures, temperatures and flows to test the SHX and aid in achieving a TRL 5.



Balloon No.	Name
1	Gas booster
2	Surge volume tank
3	Pressure reducing valve
4	Venturi flowmeter 1
5	Pre-heater
6	Venturi flowmeter 2
7	PCHE 1
8	PCHE 2
9	Main heater
10	Venturi flowmeter 3
11	Cooler
12	Bypass 1
13	Bypass 2
14	Blind flange for future use
V1, V8	Ball valves
V2-V7	Needle valves
T1-T11	Thermowells
P1-P8	Pressure taps

(a)

(b)

Figure 8-6. High temperature helium test facility: (a) Schematic and (b) photo of the high temperature side.

8.1.4.4 ASME Codification & Qualification

The design, construction and operation of nuclear and non-nuclear components are based on their ASME-BPV code categorization. INL with their material and code case expertise can help with maturity and qualification of a material as per ASME standard, which would assure that appropriate margins exist in the design for the safe use of the final product.

8.2 Next Steps

The next steps for the advancement of the heat exchangers are as follows:

- Adapt existing process heat and power conversion process models to determine efficiency and economics of integrating AHTRs to process heat applications. This task will determine which process heat applications have the best potential for the economic advancement of the AHTR technology. Also the type or types of heat exchangers may be identified for further development.
- Continue material testing and modeling in molten salts to help qualify the materials and salts for heat exchanger design. Material tests can be performed at design temperatures and pressures with the MISTER facility. Continued material testing with universities such as the University of Wisconsin can help with code qualification of the potential construction materials.
- Component testing at pressure and temperature may be performed using the SPECTR and OSU HTHF facilities to test PCHEs and HCHEs (shell and tube heat exchangers) for use with AHTRs.
- Key components of the modified supercritical CO2 Brayton cycle are the high temperature and low temperature recuperative heat exchangers. PCHEs have been selected as the heat exchanger of choice because of their compact nature. Sandia National Laboratory is working with a manufacturer of heat exchangers within the US in the development of the heat exchangers. However their experience with diffusion welding is limited. Using the INL's Gleeble system, the thermodynamic atomistic modeling experience, and the component testing capabilities, we can support Sandia in the development of the PCHE heat exchangers. The Gleeble system will allow the quick development of procedures to create optimal diffusion welded bonds that can be used by the domestic heat exchanger manufacturer to produce the needed heat exchangers. Atomistic thermodynamic modeling can reduce the number of Gleeble experiments to focus on those procedures which most likely produce the best results. It can also be used to determine corrosion potentials and predict which materials are the best to consider for the heat exchangers. Diffusion welded samples from the Gleeble may be tested in the component test facilities to measure corrosion, pressure and temperature effects.

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