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HX Testing Requirements and Facility Needs for the NHI/NGNP Project

Steven R. Sherman (SRNL)
Yitung Chen (UNLV)

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Savannah River National Laboratory
Washington Savannah River Company
Aiken, SC 29808

http://www.srnl.doe.gov

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ABSTRACT

This document describes the types of tests required and the facilities needed at various scales of deployment (benchtop, pilot, and engineering scale) to test experimentally the heat exchangers and other components that would be used to build the high-temperature heat transfer loops for the Next Generation Nuclear Plant (NGNP). Heat exchanger options are described. Recommendations are provided for pressure/leak testing, cyclic pressure testing, flow testing, heat exchanger testing, and ancillary tests at the various scales. In crafting the recommendations, attention is paid to the NGNP Project's technology readiness goals (i.e. Technical Readiness Levels), and efforts are made to balance the needs for various data with the burden of proof required at each level of development and the relative expense and safety of various tests. This report is not intended to provide detailed experimental procedures for each test or complete facility designs, and further engineering work will be needed beyond this document to implement the recommendations provided here.

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ACRONYMS

ANL	Argonne National Laboratory
ASME	American Society of Mechanical Engineers
BOP	Balance of Plant
CTF	Next Generation Nuclear Plant Component Test Facility
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EPACT	Energy Policy Act of 2005
FY	Fiscal Year
GIF	Generation IV International Forum
HTE	high-temperature electrolysis
HTGR	high-temperature gas-cooled reactor
HTLHX	high temperature heat transfer loop heat exchanger
HTTR	High Temperature Test Reactor (Japan Atomic Energy Agency)
HX	Heat Exchanger
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
NASA	U.S. National Aeronautics and Space Administration
NGNP	Next Generation Nuclear Plant
NHI	U.S. DOE Nuclear Hydrogen Initiative
NQA	Quality Assurance Requirements for Nuclear Facilities
NRC	U.S. Nuclear Regulatory Commission
PHX	process heat exchanger
PICS	Project Information Collection System by Performance Results Corporation
PNP	Prototype Nuclear Plant (Germany)

QAP	Quality Assurance Plan
SHX	secondary heat exchanger
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
THTR	Thorium High-temperature Test Reactor (Germany)
THTR-300	Thorium High-temperature Test Reactor (Germany)
TRISO	Tri-isotopic nuclear fuel particles
TRL	Technical Readiness Level
VHTR	Very High Temperature Gas-Cooled Reactor
UNLV	University of Nevada Las Vegas
U.S.	United States of America

HX Testing Requirements and Facility Needs For the NHI/NGNP Project

1. INTRODUCTION

The Next Generation Nuclear Plant (NGNP) Project and the Nuclear Hydrogen Initiative (NHI) are U.S. Department of Energy (DOE) sponsored programs directed towards the development and demonstration of technologies for the large-scale production of hydrogen and high-temperature heat using nuclear energy. The overall mission of the NGNP Project is the development, design, construction, and operation of an NRC-licensed nuclear plant/hydrogen plant facility, while the NHI's mission is to develop and test the technologies to enable the efficient production of hydrogen from the splitting of water using nuclear energy. The nuclear plant and the hydrogen plant are to be linked by a high-temperature heat transport loop called the System Interface, and the NHI and NGNP Project have overlapping responsibilities in this area. A necessary step in the design of the System Interface is the development and testing of high-temperature heat exchangers and other high-temperature components (e.g., valves, instrumentation, etc.) that can be used for the System Interface. This document describes the types of tests required and the facilities needed at various scales of deployment (benchtop, pilot, and engineering scale) to test experimentally the heat exchangers and other components that would be used to form the System Interface. Attention is paid to the NGNP Project's technology readiness goals (i.e. Technical Readiness Levels), and efforts are made to balance the needs for various data with the burden of proof required at each level of development and the relative expense and safety of various tests. This report is not intended to provide detailed experimental procedures for each test or complete facility designs, and further engineering work will be needed beyond this document to implement the recommendations provided here.

In this section, a general overview of the NGNP Project and NHI are provided. Following this, the operating characteristics and expectations of the System Interface are described, which will establish the need for high-temperature heat exchangers. Some proposed high-temperature heat exchanger types are then discussed, and the case is made for the establishment of dedicated heat exchanger testing facilities in the U.S. Currently, neither the NGNP Project nor the NHI have established laboratories where any high-temperature heat exchanger testing can be performed, and much work will be needed in the near- and longer-term to establish such capabilities in time to support the established program timelines.

1.1. Next Generation Nuclear Plant and NGNP Project

The Next Generation Nuclear Plant is envisioned as consisting of a high-temperature gas-cooled nuclear reactor (HTGR), gas-driven or steam-driven electrical generators, a high-temperature heat transfer loop, and one or more hydrogen production plants. A basic schematic of the plant is shown in Figure 1 and an artist conception of the plant is shown in Figure 2.

The HTGR, or more specifically a VHTR (Very High Temperature Gas-Cooled Reactor), is a helium-cooled, graphite moderated, thermal neutron spectrum nuclear reactor that will operate at a nominal pressure between 5-9 MPa and an outlet temperature between 800-950°C [1]. The development of the HTGR for this application builds upon earlier gas-cooled nuclear reactor experiences including Dragon, Peach Bottom, Fort St. Vrain, PNP, and others [2]. The reactor would employ tri-isotopic (TRISO)-coated uranium fuel and can be constructed using either a prismatic or pebble bed core. The reactor will contain passive safety features, and would be capable of withstanding a postulated long-term, depressurized, loss-of-forced-convection accident without damaging the fuel. The VHTR is one of six reactor concepts recommended by the Generation IV Technology Roadmap for further development [3] and the NGNP is the top priority in the U.S. Generation IV Implementation Strategy [4].

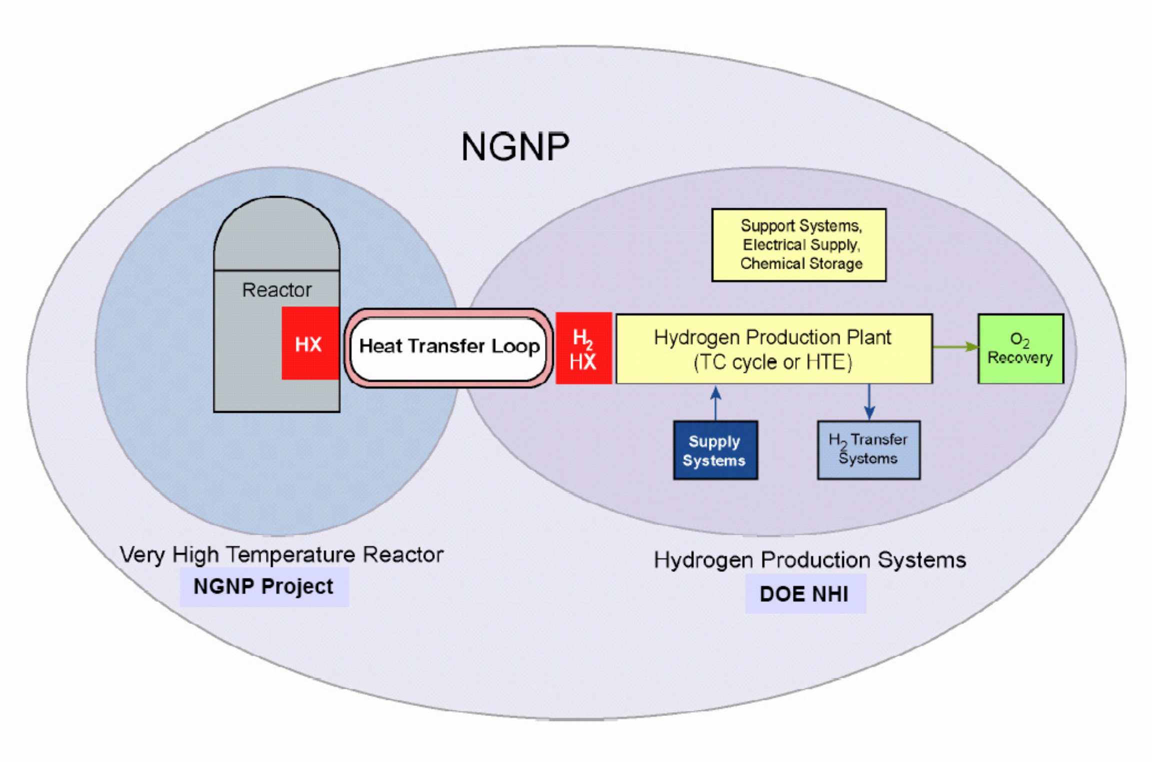


Figure 1. Schematic of Next Generation Nuclear Plant

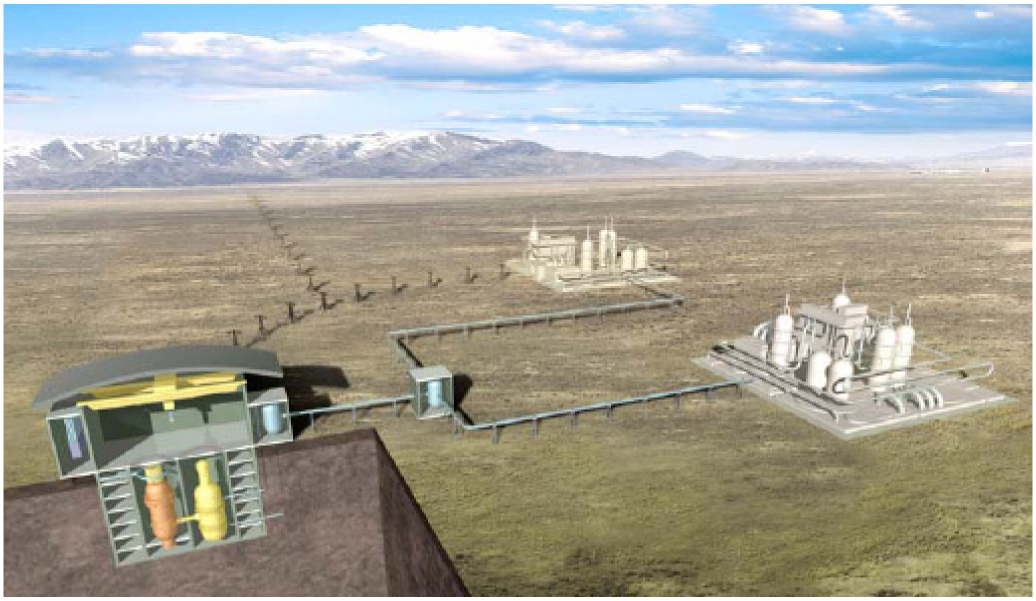


Figure 2. Artist conception of Next Generation Nuclear Plant. The figure shows the HTGR, the system interface, and two hydrogen plants or a hydrogen plant and a chemical processing plant.

In 2005, the U.S. Congress passed the Energy Policy Act (EPACT 2005 [5]) which authorized the creation of the NGNP Project and provided performance targets. In Section 641, the Act states that the Project shall consist of research, development, design, construction, and operation activities for a prototype plant that includes a nuclear reactor supported by the Generation IV Nuclear Energy Systems Initiative, that produces electricity or hydrogen or both, and that start-up of the prototype will occur no later than the end of FY 2021 (September 2021). The Act calls for placement of the NGNP at the Idaho National Laboratory (INL). Major program elements described in the Act include

- High-temperature hydrogen production technology development and validation
- Power conversion technology development and validation
- Nuclear fuel development, characterization and qualification
- Materials selection, development, testing and qualification
- Reactor and balance-of-plant (BOP) design, engineering, safety analysis, and qualification.

As a result of this Act, the U.S. DOE selected the INL to lead the development of the NGNP by integrating and coordinating all necessary research and development activities, and by coordinating project efforts with industry and other Project participants. The nuclear reactor that is part of the NGNP will be licensed by the U.S. Nuclear Regulatory Commission (NRC) under a commercial license.

Due to its historic origins as a component of the U.S. DOE Generation IV program, research and development activities under the NGNP Project had been limited traditionally to the nuclear reactor itself and did not extend beyond the intermediate heat exchanger, which is the entry point into the System Interface. The NGNP Project, however, is responsible for deployment of the NGNP and not just for the nuclear reactor part of the plant, and the System Interface, energy conversion areas, and ultimately the hydrogen production plant, are within its domain of responsibility. This is symbolized by the larger ellipse in Figure 1.

1.2. U.S. DOE Nuclear Hydrogen Initiative (NHI)

The NHI is responsible for performing research and development activities leading to the demonstration of nuclear hydrogen production technologies at scales ranging from the laboratory or benchtop scale to full-sized deployment.

Work under the NHI is divided into four areas: thermochemical hydrogen production, high temperature electrolysis, system interface, and technical integration (i.e., system studies, economic modeling, etc.). In the thermochemical area, research has primarily been performed on the Sulfur-Iodine cycle [6] and the Hybrid Sulfur cycle [7], both of which require thermal energy input at temperatures exceeding 800°C at the present time. Some screening work is also taking place on alternative lower temperature methods, and down-selects have been made to do more work on the Argonne National Laboratory-modified Ca-Br cycle [8] and the $CuCl_2$ cycle [9]. In the high-temperature electrolysis area, solid oxide fuel cells are operated in reverse to split water into hydrogen and oxygen at a temperature of 800-850°C and experiments are ongoing at the INL [10] to adapt this technology for large-scale production. The System Interface and Support Systems area is concentrating on development of high-temperature heat exchangers, fluid conduits, and system models and designs to enable the transfer of high-temperature thermal energy from the nuclear reactor to the hydrogen production plants. The results and information from the technical areas are integrated under the technical integration function of the project in order to put it in the context of economics, efficiencies, and the larger energy-related markets.

The NHI, though managed by DOE’s Office of Nuclear Energy (NE), is closely aligned with DOE’s larger hydrogen program that is managed by DOE’s Office of Energy Efficiency and Renewable Energy (EERE). The larger program is concerned with all aspects of the coming hydrogen economy including production, transportation, storage, and use.

The NHI was formed in 2004, and has proceeded in parallel with the Generation IV Nuclear Energy Initiative and, more recently, the NGNP Project. The NHI shares responsibility with the NGNP Project for the System Interface and Supporting Systems (e.g., heat exchangers, power conversion equipment, etc.). Though the NGNP Project is ultimately responsible for deployment of the NGNP, the NGNP Project and NHI are managed as separate programs by DOE’s Office of Nuclear Energy (NE-33).

1.3. System Interface Operational Characteristics

In its simplest configuration, the System Interface consists of one transmission heat exchanger, a hot transmission pipe, one receiving heat exchanger, and a colder return pipe (see Figure 3). A fluid circulator is used to move fluid through the loop, and heat transfer is performed though conductive and forced convection mechanisms. The transmission heat exchanger, also called the intermediate heat exchanger (IHX), receives thermal energy from the nuclear reactor and transmits it into the fluid circulating through the heat transfer loop. The receiving heat exchanger, also known as the process heat exchanger (PHX), receives thermal energy from the fluid circulating through the heat transfer loop and transmits it to the hydrogen production process. The hot transmission pipe and the colder return pipe are part of a closed fluid loop through which a heat transfer fluid (gas or liquid) is circulated. Radiation loss from the hot temperature surface needs to be carefully studied and reduced by using thermal insulation especially for the large diameter of the helium supply pipe.

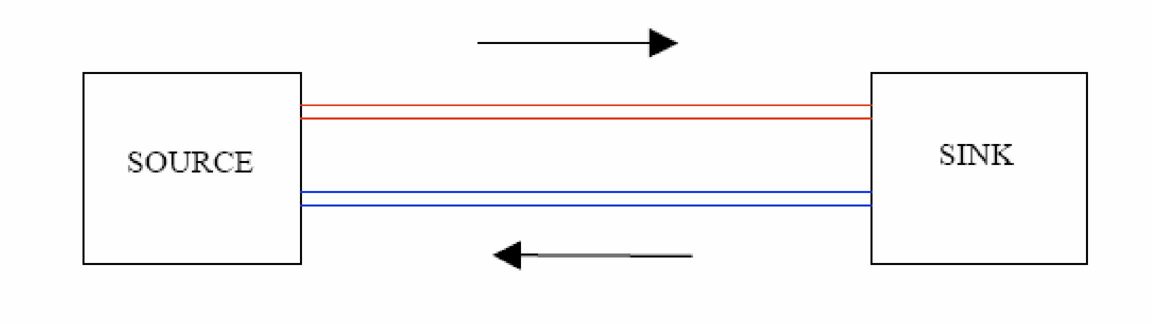


Figure 3. Simple System Interface showing the fluid flow from the nuclear reactor (source) to the hydrogen production plant (sink).

More complex interfaces can be designed that employ multiple heat exchangers, multiple parallel or concentric heat transfer pipes, and multiple loops. Figure 4 shows one such arrangement.

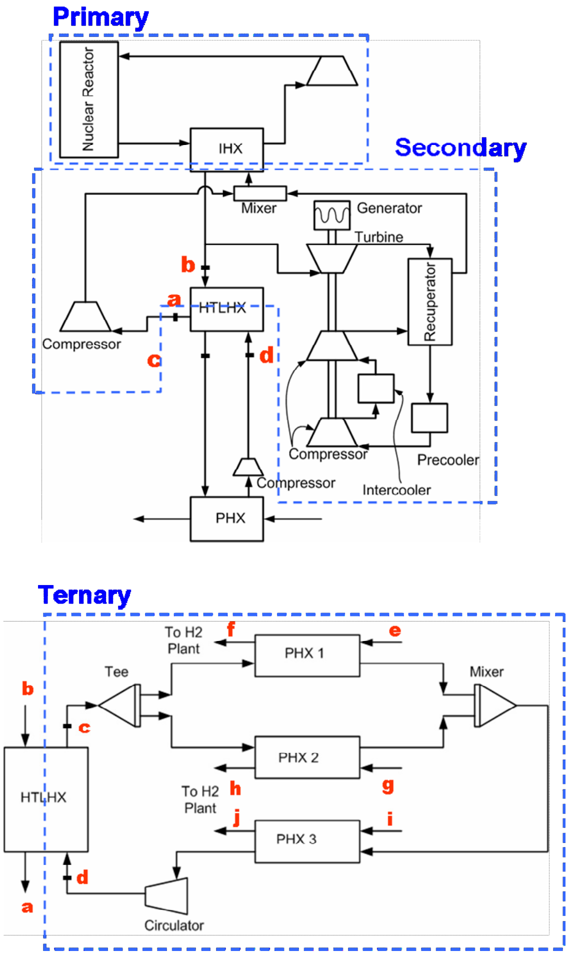


Figure 4. A more complex System Interface arrangement using a secondary loop with electrical generation and a tertiary loop to provide thermal energy to a high-temperature electrolysis plant.

In this more complex arrangement, an intermediate heat exchanger (IHX) is used to transmit the full power of the nuclear reactor's primary heat transfer loop to a secondary heat transfer loop. In the secondary heat transfer loop, heat transfer fluid is divided between an electrical power conversion unit (gas-driven or steam-driven electrical turbines) and another IHX, called the high-temperature loop heat exchanger (HTLHX). The HTLHX then transmits thermal energy to a tertiary loop, where thermal energy is distributed to three different hydrogen process heat exchangers (PHX 1, PHX2, and PHX3) [11].

The NGNP's System Interface may be expected to transmit 5 to 65 MWt at a nominal temperature range of 500-950°C depending upon which heat transfer fluid is selected (steam, supercritical carbon dioxide, helium, helium/nitrogen, and perhaps liquid salt). Commercial variations of the NGNP may be expected to provide up to 100% of the reactor thermal output (600 MWt) to the System Interface [12] with no concomitant electricity generation. The pressure of the System Interface will most likely be set to match the pressure of the nuclear reactor – 5 to 9 MPa – in order to reduce the mechanical stresses on the intermediate heat exchanger(s). Since it is unlikely the hydrogen production process will operate at pressures as high as 5 MPa, the process heat exchanger must be able to absorb a steady-state pressure drop across the heat exchanger at high temperature without damage, and the intermediate heat exchanger must also be designed to handle a transient pressure drop across the heat exchanger in case of a loss of fluid in the System Interface. The heat exchangers, pipes, valves, and other components that compose the System Interface will also be expected to operate at the expected pressures within the nominal temperature range.

1.4. Heat Exchanger Types Under Consideration

Heat exchangers are the key energy conversion components for thermally-driven hydrogen production plants and other downstream users of high-temperature heat from a HTGR. Heat exchangers are used in many commercial applications, and numerous types of heat exchangers can be purchased from a large number of manufacturers. The performance requirements and component designs for these commercial applications are straightforward. However, commercial units and standard designs will almost certainly be inadequate for the high temperatures and aggressive chemical environments anticipated in the System Interface and the processes required for nuclear hydrogen production. Containing reactive and corrosive chemicals at very high temperature, and high pressure, will require specialized materials and fabrication processes to ensure safety and durability over long periods and many process cycles.

The requirements for high-temperature high-power reliable service drive the design choices that must be made for the heat exchangers in the NGNP System Interface. For the IHX, the choice of which designs to use is also limited by the need to use ASME NQA-1 approved materials and heat exchanger designs because the heat exchanger will form part of the nuclear boundary. For the PHXs, the choice of heat exchanger materials and designs is more open because the hydrogen plant will be non-nuclear, but the PHXs have the added burden of needing to absorb a large pressure drop (5 to 9 MPa) across the heat exchangers at high temperature, and must be made resistant to corrosion, pitting and cracking by the chemicals that will be used in the hydrogen production plant.

For the NGNP IHX, tubular and compact plate heat exchangers are being considered. At this time, the IHX will most likely be composed of a high-temperature alloy such as Inconel 617® or Haynes® 230®, but ceramic heat exchangers are not out of the question once a suitable ceramic material and design has been ASME NQA-1 approved. The joint connection between metal and ceramic materials needs to be carefully designed in order to avoid failure caused by the large mechanical and thermal stresses due to expansion and contraction.

For the process heat exchangers, metals or ceramics may be deployed depending upon the hydrogen production process. Sulfur-based hydrogen production methods require that the H_2SO_4 decomposer be made of SiC, while high-temperature steam electrolysis methods can use metals. Tubular heat exchanger designs are favored for the process heat exchangers, though compact or plate designs might be used in some applications. More specific information on tubular or plate heat exchangers is provided below.

1.4.1. Tubular Heat Exchangers

The most commonly deployed heat exchangers are tubular heat exchangers. In a tubular heat exchanger, thermal energy is transferred laterally into or out of a tube or multiple tubes through which a fluid or fluidized medium is flowing. A separate fluid or fluidized medium flows over and around the tube or tubes in a co-current, cross-current, or countercurrent fashion in order to deliver or receive thermal energy from the tube or tubes. The tube walls serve as a thermally conductive barrier that prevents the intermixing of hot and cold fluids while allowing for the flow of thermal energy by conduction through the tube walls and convection from the tube surfaces to the fluids or fluidized mediums flowing around and through the tube or tubes.

The simplest construction of a tubular heat exchanger is a pipe-within-a-pipe or double-tube, shown graphically in Figure 5. In this design, one fluid flows through a central tube, while another fluid flows through an annulus around the central tube in either a countercurrent or co-current direction. The heat transfer surfaces are the exposed areas of the inner and outer surfaces of the central tube, and the outside of the heat exchanger is usually insulated to eliminate heat losses. The power of the heat exchanger is directly related to the heat exchanger surface area, and power is increased by lengthening the heat exchanger, and thus increasing the exposed surface area of the central tube. Though a tubular heat exchanger can be made of any length, the practical upper limit in surface area for a double-tube heat exchanger is approximately 9-14 m^2, and beyond that multiple tube banks or other heat exchanger designs may be needed to increase the power of the heat exchanger [13] while still economizing on construction materials.

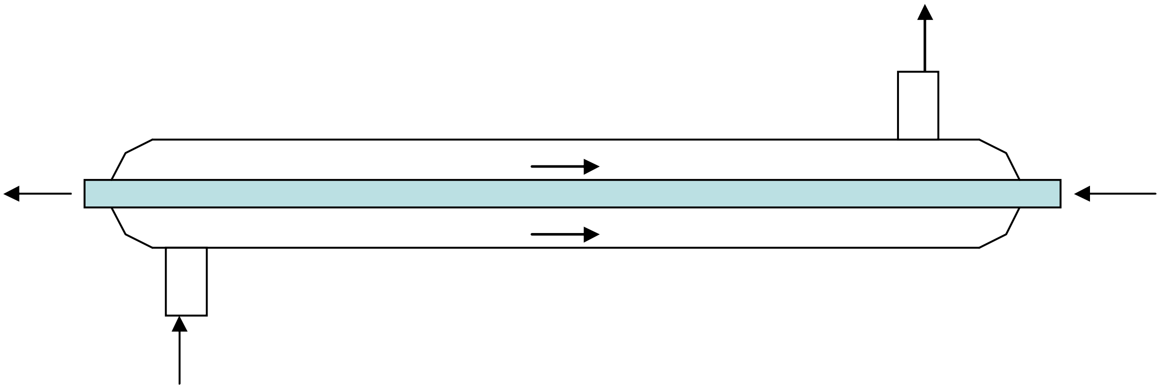


Figure 5. Simple countercurrent tubular heat exchanger.

Larger heat exchanger surface area and better capacity to handle higher fluid velocities can be realized by deploying shell-and-tube heat exchanger designs. In a shell-and-tube heat exchanger, the diameter of the outer tube is greatly increased, and a bank of tubes rather than a single central tube is used, as shown in Figure 6. Fluid is distributed to the tubes through a manifold and tube sheet.

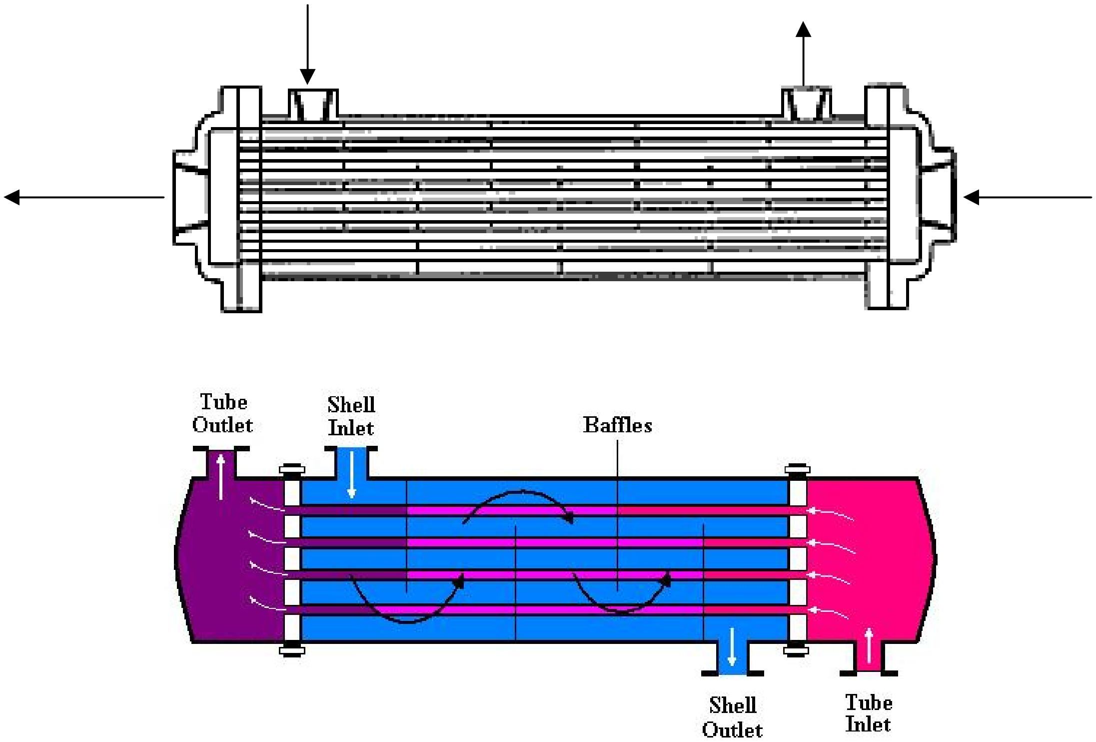


Figure 6. Straight tube fixed bundle shell-and-tube heat exchangers with baffles [14].

To increase heat transfer efficiency, further modifications to the flow paths of the outer and inner fluids can be accomplished by adding baffles to the shell to increase fluid contact with the tubes, and by creating multiple flow paths or passes for the fluid flowing through the tubes. Heat exchangers having hundreds of meters of surface area can be realized with these designs. Shell-and-tube heat exchangers are the most commonly deployed type of heat exchangers in industry, and there is a sophisticated body of standards established for their construction [15].

Other variations of tubular heat exchangers exist including helical coil heat exchangers and hairpin heat exchangers. In a helical coil heat exchanger, the configuration of the shell is similar to a shell-and-tube heat exchanger, but the tube or tube bank is formed into a compact helical or corkscrew arrangement, with the longitudinal axis of the shell aligned with the axis of the tubular helices. This is done in order to increase the exposed surface area of the tubes per unit volume of the shell, to increase fluid contact with the walls inside the tubes, and to create a more robust design that can better handle thermal expansion of the helical tubes. The helical coils may be piped individually, as in a simple tubular heat exchanger, or fluid may be provided to the helical tubes using a manifold, as is done in a shell-and-tube heat exchanger. Helical coils are often used in steam generators, where the hot fluid flows through the helical coils, and the water to be boiled flows through the shell.

In a hairpin heat exchanger, a 180° bend is deployed, which allows the headers for the cold and hot fluids to be placed in the same location (Figures 7 and 8). The hairpin design can also be used with a bank of internal tubes, in which case the hairpin heat exchanger resembles a straight tube shell-and-tube heat exchanger. Alternatively, a two-pass, four-pass, or 2*n* (*n* equals the number of 180° turns) pass shell-and-tube heat exchanger could be deployed that allows for the grouping of hot and cold inlet and outlet flow channels.

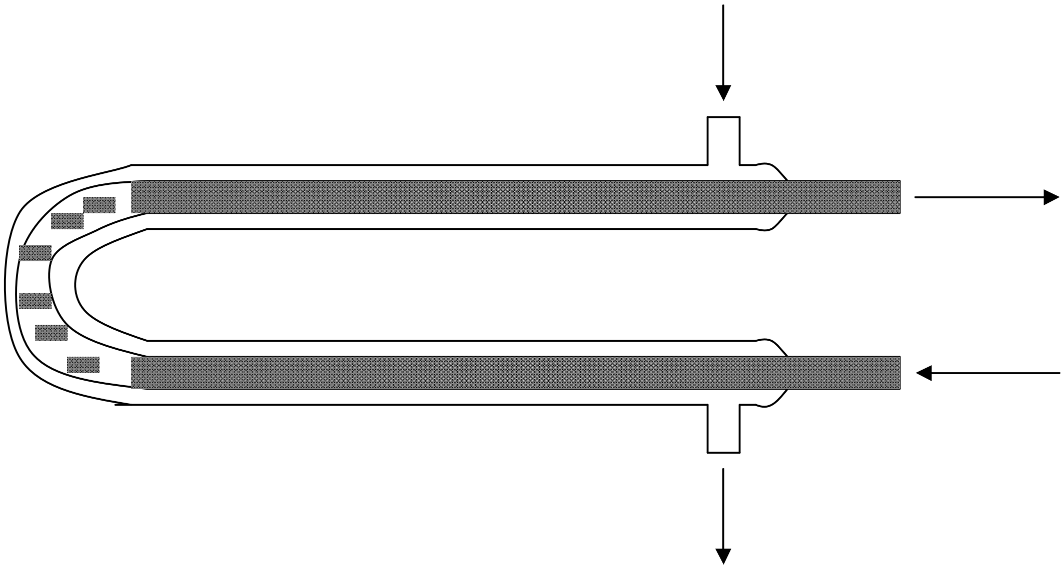


Figure 7. Schematic of a hairpin simple tubular counterflow heat exchanger.

Figure 8. Hairpin heat exchangers manufactured by Brown Fintube France S.A.

The heat transfer performance of tubular heat exchangers may be enhanced, when needed, by adding fins to the outer surfaces of the inner tubes. Fins may be arranged in a longitudinal or lateral fashion, and serve to increase the heat transfer area of the tubes. Increased performance may also be realized by placing static mixers or other mechanical flow adjusters inside the tubes to create turbulence or increase fluid contact with the internal tube surfaces. Adding fins or static mixing devices to the flow channels comes at a price, however, and higher pressure drop across the hot or cold flow paths may result.

Tubular heat exchangers, particularly the shell-and-tube and helical varieties, are the leading concepts for use as an IHX in the NGNP. The THTR-300 program in Germany built a helium/helium IHX device that was designed to operate at the 10 MWt scale and at 950°C [16, 17]. JAEA's High Temperature Test Reactor (HTTR) has deployed a 10 MWt helium/helium helical tubular IHX and has successfully tested it up to 950°C for short time intervals [18]. There are existing shell-and-tube heat exchanger designs deployed in current nuclear plants, and a pathway towards getting the select high-temperature alloys ASME NQA-1 approved has been defined.

A tubular heat exchanger/chemical reactor based on the hairpin concept is under study by the NHI to perform the H_2SO_4 decomposition step in the SI hydrogen production process. The heat exchanger/chemical reactor, shown in Figure 9, is composed of an external electrical heating mantle, a SiC outer tube that is closed at one end, and an internal SiC tube that is open at both ends. Sulfuric acid flows through the outer annulus from the bottom of the unit and enters the heated zone. Once in the heated zone, heat transfer occurs from the outside of the bayonet to the outer annulus, and the H_2SO_4 is boiled into a vapor. Traveling further up the bayonet, the H_2SO_4 vapor becomes superheated, and it decomposes spontaneously into SO_3 and H_2O. The SO_3 and H_2O continue upward through the outer annulus until they reach the catalyst bed at the top of the bayonet where the SO_3 decomposes endothermically into SO_2 and O_2. After the catalyst bed, the flow of SO_2, H_2O, and O_2 goes around a hairpin turn and flows back down the bayonet through the inner SiC tube to exit the heat exchanger/reactor. The inner SiC tube is not insulated, and it acts as a recuperator, transferring thermal energy back into the outer annulus. This design allows for a large temperature variation along the length of the bayonet such that the top end of the bayonet can be maintained at 800°C while the other end can be maintained below 250°C, which is needed to allow for the use of polymeric gasket materials in the base of the bayonet. In a larger scale design, the electrically heated mantle would be replaced by a shell, and a hot fluid would be used to heat a single bayonet or multiple bayonets. In the NGNP, the hot fluid flowing through the shell would be supplied by the System Interface.

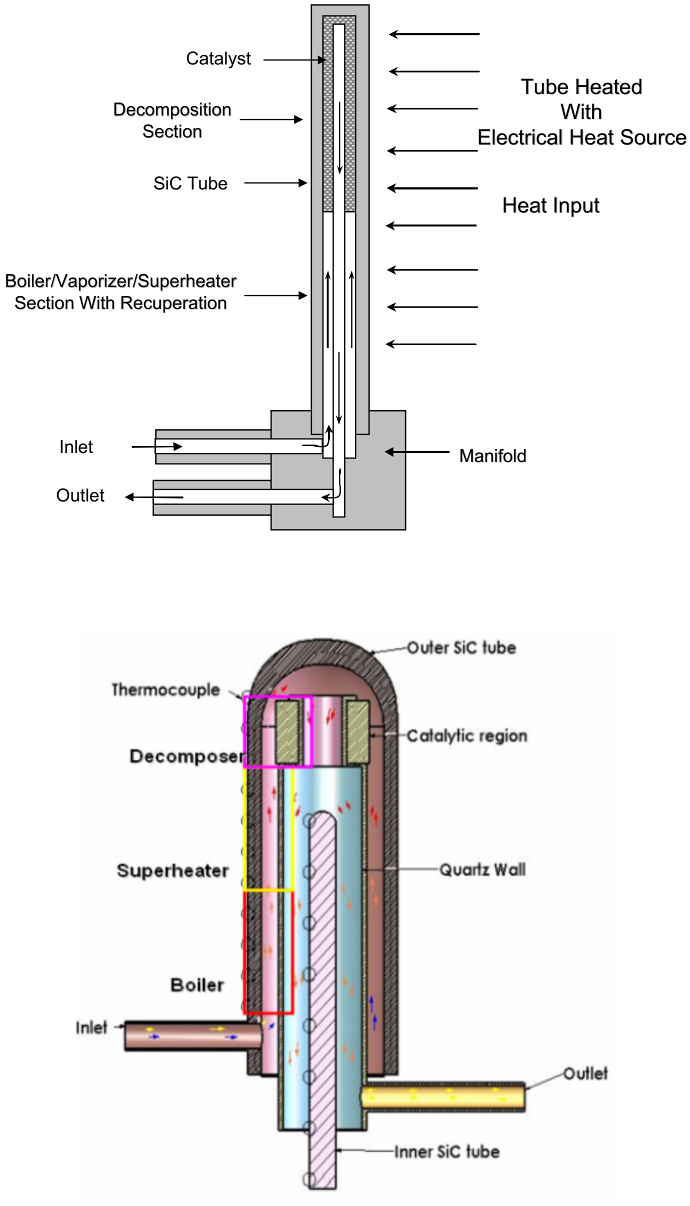


Figure 9. Lab-scale bayonet H_2SO_4 decomposer (Sandia National Laboratories).

1.4.2. Plate Heat Exchangers

In a plate heat exchanger, plates or planer heat transfer surfaces are the fundamental heat transfer surfaces rather than tubes. Common plate heat exchangers deploy metal plates arranged in a stack-wise fashion and sealed with gaskets, welds, brazing, or diffusion bonding (Figure 10). Plate heat exchangers offer more compact designs with higher surface areas for a given heat exchanger volume and are best used in situations where there is little probability for encountering particle debris or solids in either the hot or cold streams due to the close spacing of the plates (usually less than 1 cm). Counter flow, cross flow, and co-current flow can be arranged by altering the design of the supply manifolds to the heat exchanger. Plate heat exchanger may be composed of a single plate, where the plate serves as the sole heat transfer surface and fluid separator for the heat exchanger, or they may be composed of hundreds of plates.

Due to the high temperature requirements of the heat exchangers and the relatively high cost of the materials of construction needed at high temperatures, compact plate heat exchangers are receiving attention as an alternative to tubular heat exchangers for the NGNP System Interface. Compact heat exchangers, such as those manufactured by Heatric [19], have higher heat transfer surface area per unit volume than their tubular counterparts and so have smaller size, footprint, lower fluid inventories, and reduced material costs (at least for the heat exchanger itself). The channels in compact heat exchangers are small, having effective diameters less than 1 cm, and are formed into the plates by etching or pressing. The plates are then brazed or diffusion bonded to form a block (Figure 11). Manifolds, fluid nozzles and other structures are then welded to the block and the heat exchanger. Variations of the basic compact design include plate-fin heat exchangers, in which plates are separated by corrugated spacers to increase the contact surface area between plates (see Figure 12). The compact design allows for the construction of high efficiency heat exchangers using less material than a shell-and-tube heat exchanger.

There are some practical limitations to the size and shape of compact heat exchangers [20], as determined somewhat by the heat exchanger aspect ratio. The aspect ratio of the compact heat exchanger (ratio of heat exchanger length to heat exchanger height or width) is related to the volume of the heat exchanger, the heat transfer surface area, the channel length, and other geometric factors. Increasing the aspect ratio implies an increase in the length of the heat exchanger for a given width or height, or cross-sectional area). At smaller sizes, there is no established upper limit to the aspect ratio, but achieving even heat transfer performance across the face of the longer cross-section becomes more difficult in a cross-flow configuration. At larger sizes, the limit on aspect ratio becomes more firm. The largest commercially available compact heat exchanger from Heatric has approximate dimensions of 1.5m x 0.6m x 0.6m, which has an aspect ratio of 2.5. Because of this limit, multiple heat exchangers may be needed to perform the job of the ideal heat exchanger, and the cost of additional hardware (e.g., manifolds, support equipment) to support multiple heat exchanger modules will be greater than needed for a single larger heat exchanger.

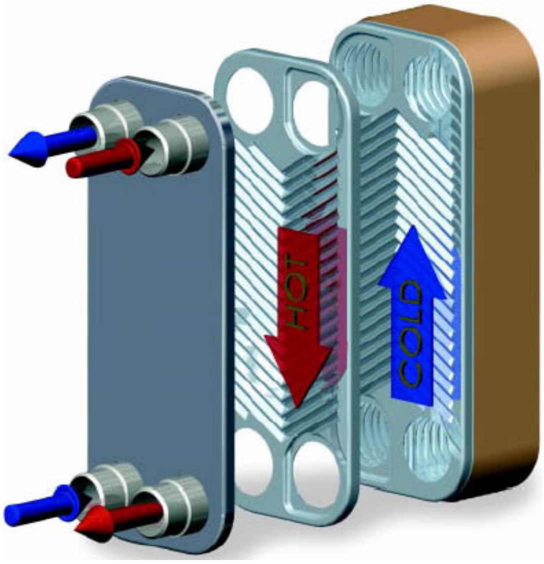


Figure 10. Flat plate heat exchanger.

Figure 11. Heatric diffuision-bonded compact plate heat exchanger block.

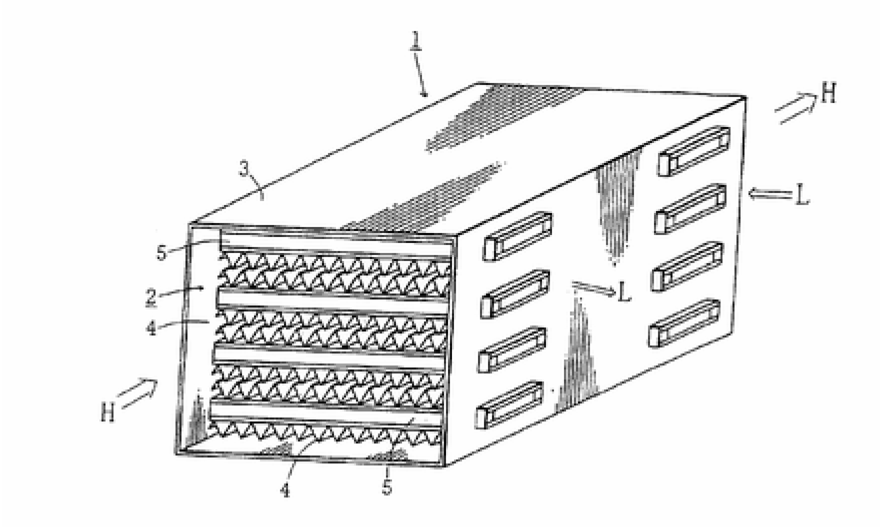


Figure 12. Plate-fin heat exchanger schematic from U.S. Patent 6,910,0528 [21].

In the longer term, it may be possible to qualify and deploy ceramic plate heat exchangers. Ceramics such as SiC or C/SiC composites are used for certain very high temperature applications (up to 1000°C) in the aerospace and gas turbine industries because of their high strength and creep resistance at high temperatures. The production of ceramic plate heat exchangers would require the production of ceramic plates and the bonding of plates into stacks, and such capabilities could be adapted from existing ceramic component manufacturing industries. On a production scale, ceramic disc brakes are being produced for airplane and automotive braking systems by several companies including Starfire Systems Inc. (US), Honeywell International (US), DACC (Korea), and SGL Carbon (Germany). Figure 13 shows a StarBlade™ disc rotor produced by Starfire Systems Inc.

Figure 13. C/SiC disc rotor produced by Starfire Systems Inc.

Under the NHI, two types of ceramic plate heat exchangers have been discussed – the C/SiC offset fin plate heat exchanger, and the compact shell and plate heat exchanger. The offset fin plate heat exchanger, conceived by Dr. Per Peterson and his group at the University of California, Berkeley, involves stacked C/SiC plates with flow channels optimized for the countercurrent flow of high-temperature helium and molten salt (see Figure 14). This design was offered as an alternative for an IHX employing helium on the hot side and a molten salt such as FLiBe on the cold side. . UNLV has developed a three-dimensional numerical model to predict the overall performance based on the UC-Berkeley design. The offset strip-fin, hybrid plate, type compact heat exchanger concept is chosen, and is manufactured from a liquid silicon impregnated carbon composite material. The offset strip-fin is chosen as a method of heat transfer enhancement due to the boundary layer restart mechanism between the fins that has a direct effect on heat transfer enhancement. The effects of the fin geometry on the flow field and heat transfer are studied in three-dimensions using Computational Fluid Dynamics (CFD) techniques. Fin dimensions need to be chosen that optimize heat transfer and minimize pressure drop. The UNLV study is conducted with helium gas and the molten salt FLiNaK as the working fluids for baseline heat exchanger design geometry. Comparisons of the overall performance between the rectangular and curved fin geometry were performed. The UNLV has also studied temperature dependent physical properties and unsteady state performance during start-up or shut-down process.

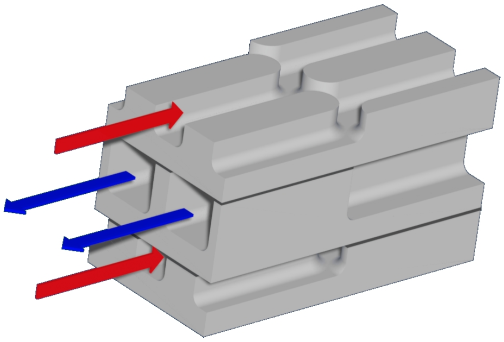


Figure 14. Off-set fin ceramic heat exchanger. Small channels are for helium and large channels are for molten salt.

A ceramic heat exchanger/sulfuric acid decomposer design has been offered by Ceramatec, Inc. for use in either the S-I process or the Hybrid Sulfur process. In the Ceramatec design (Figure 15), SiC plates impregnated with Pt catalyst are bonded together into stacks, and the stacks are assembled into modules, which are then packaged into an insulated shell. The UNLV has developed the detailed three-dimensional analysis on fluid flow, heat transfer and chemical reaction of the decomposer. The numerical model has been validated by comparisons with experimental and calculation results from other researchers. Several new designs of the decomposer plates have been proposed and evaluated to improve the uniformity of fluid flow distribution in the decomposer. To enhance the thermal efficiency of the decomposer, several alternative geometries of the internal channels such as ribbed ground channels, hexagonal channels, and diamond-shaped channels are proposed and examined. It was found that it is possible to increase the thermal efficiency of the decomposer from 89.5% (baseline design) up to 95.9% (diamond-shaped channel design). The calculated molar sulfur trioxide decomposition percentage for the baseline design is 63.8%. The percentage can be increased significantly by reducing reactants mass flow rate and with increasing channel length and operation pressure. The highest decomposition percentage (~80%) for the alternative designs was obtained in the diamond-shaped channels case. Beside the numerical analysis on fluid flow, heat and mass transfer, the thermal/mechanical stress analysis of the decomposer ceramic part has also been performed, and the results show that all of the investigated designs are safe under the proposed operating conditions. The design of connection joint between metal and ceramic materials needs to be carefully investigated because failure of connecting component may be occurred due to thermal or mechanical stresses.

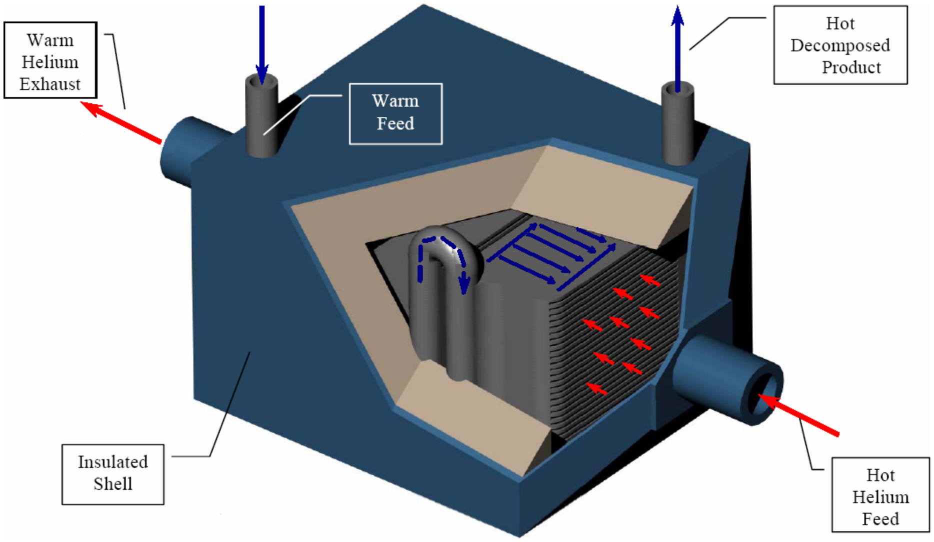


Figure 15. Ceramatec ceramic sulfuric acid decomposer concept.

Spiral plate heat exchangers are a variant of the flat plate heat exchangers that can be used for services that may encounter heavy fouling, and may be considered for certain applications in the hydrogen production plant. Figure 16 shows a drawing of a spiral heat exchanger. The channel sizes are much larger than those found in compact heat exchangers and are much less likely to get plugged by fouling or debris, and the tangential flow pattern of the hot and cold fluids helps keep the flow surfaces clean. Fluid inlet and outlet points are located at the center and the outer edge of the heat exchanger, and countercurrent flow is usually performed for maximum heat transfer performance.

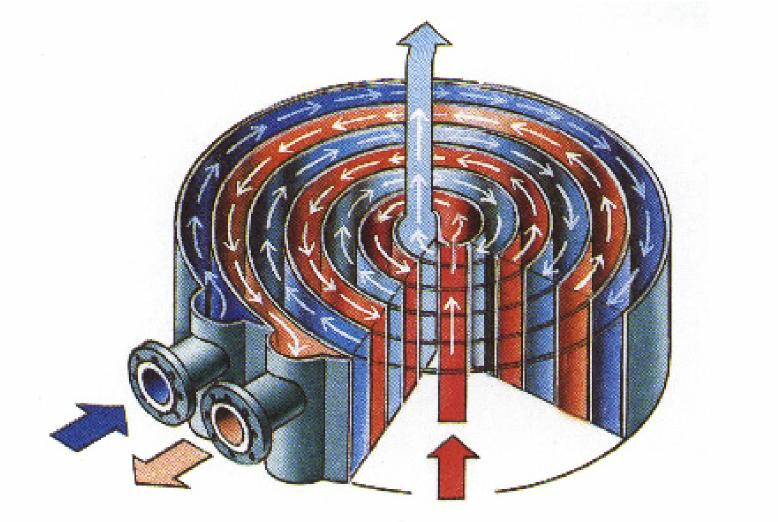


Figure 16. Spiral plate heat exchanger with counterflow arrangement [22].

1.5. Need for HX Testing and Test Facilities

The operating conditions of the System Interface are on the outer edge of the state of the art for industrial heat transfer systems, and the limits are mainly due to materials. Metals become increasingly soft at higher temperatures, and above 700°C, there are very few metals or alloys that retain significant mechanical strength and resistance to creep. Figure 17 shows the relationship between temperature and creep rupture strength for Alloy 800, a high-temperature nickel-based alloy. Similar curves can be obtained for other high-temperature alloys too, such as Inconel 617® or Haynes® 230®. In all cases, failure of the material depends upon the applied stress, the temperature, and the length of time the stress is applied to the material. For example, a component made of Alloy 800 may be expected to last 10 000 hours at 800°C under a stress of 50 MPa, but the stress must be reduced to no more than 20 MPa if the component is expected to last 100 000 hours before failure.

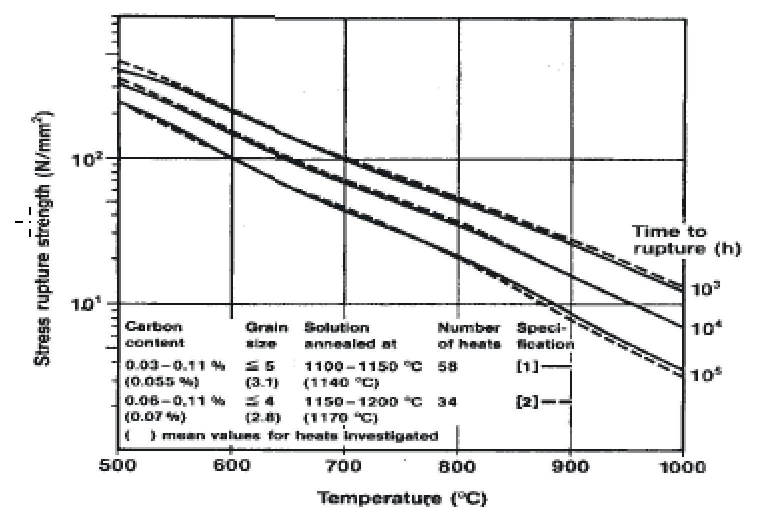


Figure 17. Creep rupture strength of Alloy 800 [23, 24].

Because of the these limitations, industrial processes tend to operate either at lower temperature if the process must operate at high pressure, or, if the system must operate at high temperature, the pressure or stresses of the system are minimized. For example, in the hot zone of a coal-fired steam boiler, the temperature of the furnace can reach as high as 1100-1650°C, but the furnace is operated at atmospheric pressure and the walls of the furnace are protected by the use of refractory materials. The furnace is used to heat steam, and the steam tubes are heated and pressurized up to 600°C and 25 MPa. Though the steam tubes contain high-temperature high-pressure steam, the tubes operate below the creep rupture limit of many steels and nickel alloys [25]. As another example, residuum crackers used in petroleum processing operate at temperatures up to 860°C, are made of metal, but operate near atmospheric pressure (10-30 psig) [26] so as not to exceed the stress and creep limitations of the structural materials. The gasification of coal in South Africa is carried out at a pressure of approximately 3 MPa and at temperatures as high as 1200°C in the combustion zone [27], but the gasification vessels are actively cooled with water to prevent damage to the reactor vessels (see Figure 18). Coal gasifiers of this type have operated at pressures up to 10 MPa, though all with active water cooling to protect the vessel integrity.

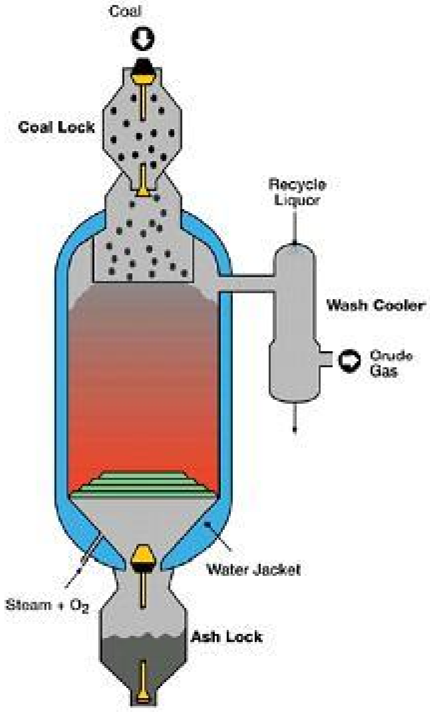


Figure 18. Sasol-Lurgi Fixed Bed Dry Bottom Gasifier.

There is some limited experience in constructing and operating high-temperature high-pressure metallic heat exchangers. Under the HTTR program at JAEA, a 30-MW helical heat exchanger constructed of Hastelloy XR is designed to operate at temperatures up to 950°C, but at a pressure differential between the hot and cold sides of less than 0.015 MPa [28]. The heat exchanger itself is packaged within a pressurized shell that is maintained at the same pressure as the hot fluid, so as to reduce the mechanical stresses between the hot and cold sides of the heat exchanger. The HTTR heat exchanger design developed in parallel with German designs under their THTR program, and a 10-MW helical coil heat exchanger composed of Material 2.4663 (Inconel 617®) was built and tested [29]. Designs involving U-tube heat exchangers were also developed, and scale-up to 170 MW was envisioned.

Ceramic materials such as SiC are known to have much better high-temperature performance, and retain much of their strength at high temperature. SiC, for instance, retains its room temperature flexural strength to temperatures beyond 1200°C [30], and is stronger than most metals. Ceramics are more brittle than metals, and the failure of ceramic components depends upon the strength of the material and the presence or absence of flaws (cracks) in the component. Failure of ceramic components is statistically based, and the larger the component, the more likely there will be a significant flaw in some portion of the component that could lead to failure. The construction of large ceramic components depends partially on the skill of the manufacturer to construct large components using smaller ceramic building blocks (e.g. carbon fiber composites, Space Shuttle heat-resistant tiles) in which the number of flaws and the propagation of cracks can be limited. Careful attention must be paid to which binder materials are used also, as the binding material may have different physical or chemical characteristics than the ceramic, and could degrade or fail at lesser conditions than the ceramic. Joint connections between metal components or pipes and ceramic materials also needs to be carefully designed.

High-pressure high-temperature processes are used to produce synthetic diamonds. Pressures up to 15 GPa and temperatures up to 2000°C, induced by electrical heating, are used to compress graphite into diamonds. The pressure is induced by placing graphite between two anvils, and is imposed as a compressive force [31]. The time scales involved in these processes are not long (hours) compared to the required operating time for the System Interface components (10^5-10^7 hours), and the system volumes are small, and so the operating experiences with diamond processing are less relevant to high-temperature component design for the NGNP.

The System Interface must operate at high temperature and high pressure (see Section 1.3) for a sustained period of time, and such conditions are not where industrial systems usually operate, and where there is an extensive domain of knowledge on how to operate. Heat exchangers and other equipment can be designed to operate at such conditions, but they will need to be tested before they are deployed in the NGNP. Testing provides data that can be used to adjust heat exchanger models, and provides information on the factors that can't be modeled well, such as the adequacy of the component's construction methods, wear and tear by corrosion, erosion or creep and fatigue mechanisms, and responses to due to cycling or singular dynamic events (e.g., sudden depressurization of the hot or cold side). High-temperature testing is also needed of supporting equipment such as instrumentation and valves in order to verify their ability to operate as expected at such conditions.

At higher temperatures, heat transfer by radiation becomes increasingly important, and heat transfer models that are accurate at lower temperatures may be increasingly inaccurate at higher temperatures if they do not account accurately for radiation heat transfer effects. Multi-mode heat transfer software has been developed for designing coal-fired burners and other high-temperature operations where radiation is the dominant heat transfer mechanism, and such models should be examined and compared to nuclear thermal-hydraulics codes and to data measured in the laboratory for prototype heat exchanger designs in order to determine which codes will work best at the conditions of interest, and which ones will need adjustment.

The NGNP Project is adopting a classification system for assessing the technical readiness of components, processes, and technologies, and use of this system reinforces the need to perform testing as the arbiter of technical readiness. In the NGNP system, a component or process is assessed and assigned a Technical Readiness Level (TRL), and higher TRLs are associated with higher levels of technical maturity. The NGNP Project's TRL system (shown in Appendix) is based upon the systems adopted by the U.S. Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) [32]. The DoD and NASA systems assign a TRL number between 1 and 9 to an individual component, sub-system, or system. A TRL of 1 implies "basic principles observed or reported", meaning the concept or idea appears possible based on physical observations of relevant phenomena, while a TRL of 9 implies "actual system 'flight proven' through successful mission operations." At increasing TRLs, the component, sub-system, or system must be tested in the "relevant environment" and at increasing levels of fidelity and robustness. These technical readiness level systems recognize that modeling by itself is insufficient to prove component or system designs, and that components, sub-systems, or systems must be tested the expected conditions on interest to reach technical maturity.

TRLs must be assessed for the actual application of interest. For example, metallic shell-and-tube heat exchangers are commonly deployed in the chemical and petrochemical industries, and would be rated at TRL 9 ("mission proven") for most applications. However, the operating experience of using a metallic shell-and-tube heat exchanger for an IHX is less well-established, is not available from vendors as an off-the-shelf component, and so would likely be rated no higher than a TRL of 7 ("system prototyping demonstration") for the NGNP application, given the background experience with the German and Japanese reactor programs.

Implied in the TRL rating system is the assumption that the reliability of a component, sub-system, or system for a given application is proportional to the investment or development costs. Reliability here is defined as the ability of a component, sub-system, or system to perform and maintain its functions in routine circumstances as well as hostile or unexpected circumstances for an expected period of time. The probability of failure is the inverse of reliability, and has units of probability or the number of failures per unit time. Figure 19 shows this relationship between the TRL, the probability of failure, and the investment costs. Using this development model, the investment in any one component, sub-system, or system at lower TRLs is purposely kept to a minimum in order to reduce costs because the probability of failure is assumed to be relatively high. The design-and-test cycle used in the TRL system is an optimization process, and only successful tests lead to higher TRLs. Minimum cost occurs when all tests are successful, and failed tests either lead to lost investment (cost with no benefit) if a design is rejected, or greater cost if designs must be adjusted and tests repeated in order to achieve a successful test. More expensive testing (i.e., representative environments, larger sizes) can be tolerated at higher TRLs because the component reliability is greater and the risk of losing the investment or incurring extra testing costs is decreased.

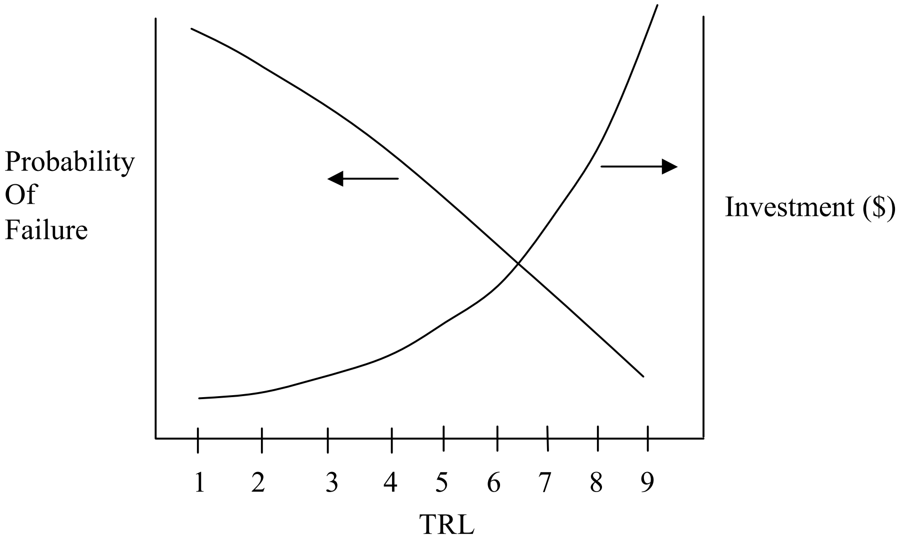


Figure 19. Relationships between TRL, probability of failure, and investment costs.

It is possible to skip lower level testing in order to save up-front development costs, but skipping steps should only be done if the component's probability of failure or reliability, as measured by its TRL, is well understood and appropriate for the level of testing. There are two components to the assessed reliability of a component – inherent reliability, and the developer's degree of knowledge about the component's inherent reliability. At the lowest TRLs, knowledge of a component's inherent reliability is almost non-existent, and so the probability of failure must be assumed to be relatively high until otherwise indicated by test results. As more tests are performed, information about a component's inherent reliability is revealed, and this allows the developer to select and test changes to designs to increase reliability, and this leads to higher TRLs. If the initial testing steps are not performed and knowledge of the component's inherent reliability is incomplete, then there is a risk of losing a greater investment or incurring higher costs than would have otherwise incurred if the level of testing were scaled appropriately to the actual TRL of the component.

At the present time, there is no readily accessible laboratory in the U.S. for operating at the high temperatures, pressures, and flow conditions needed to test components for the NGNP System Interface. At the lab scale, the capabilities needed to perform high temperature heat exchanger testing are not unique, and a dedicated testing laboratory could be established, with some investment, at almost any university or national laboratory. Capabilities for heat exchanger testing also exist in industry, but such facilities are generally closed to outsiders, or are linked to certain commercial products. If a commercial space were used, extra care would need to be taken to protect the intellectual property of the NGNP Project or its investors.

At larger scales, such as at the pilot-scale and engineering-scale, the facility size and power requirements become more problematic, and the choice of possible sites that could be controlled by the NGNP Project and that can meet the physical requirements becomes more limited. At the pilot-scale, high-bay facilities capable of providing up to 1-2 MW of electrical power may be needed, and such facilities could be made available at national laboratories and some universities. At the engineering-scale, there is only one of two planned facilities where components could be tested at the conditions of interest – the NGNP Component Test Facility (CTF) and the NGNP itself.

Though the NGNP CTF and the NGNP are undergoing extensive design efforts, minimal planning has been performed to establish high temperature testing capabilities at the prerequisite laboratory-scale and pilot-scale. This document is intended to initiate the planning process for smaller-scale laboratories, so that technologically immature heat exchangers and other components may be advanced in maturity far enough along to be made available for the NGNP CTF and the NGNP when those facilities come on-line. The NGNP CTF and the NGNP are expected to be available for service by the 2013-2015 and the 2018-2021 time frames.

2. BENCHTOP TESTING REQUIREMENTS AND FACILITY NEEDS

Tests at the benchtop scale are performed to screen prototypes and to collect data sufficient to advance concepts to higher technical readiness levels, specifically to **NGNP Project TRL 4** or **5**. The testing of components and heat exchangers required by the NGNP Project will rely, in part, on adaptations of conventional heat exchanger and component designs. Determination of heat transfer behaviors in laboratory prototypes as well as effective assessments of laboratory data in comparison to models will be required. These aspects can be pursued at the benchtop scale in conjunction with analytical and computational fluid dynamics (CFD) modeling. Initial high-temperature testing of heat exchanger and component prototypes are performed, and the data generated by such testing is used to improve models and to gather performance information that can be used to improve component designs. Lower cost and more rapid testing is emphasized since it is likely that multiple components will need to be tested at this scale in order to generate data sufficient to perform technology downselects and to better plan larger-scale tests.

2.1 Pressure/Leak Testing

Prototype heat exchangers and other fluid-containing components must be pressure tested and may require leak testing. Pressure testing involves pressurizing the component in a controlled fashion and watching for component failure, component damage, or leaks. Leak testing is an extension of pressure testing, and is carried out in order to quantify leak rates. The purposes of pressure and leak testing in the NGNP Project component testing program are to first determine whether the prototype designs and as-constructed components are safe enough to be pressurized to the working pressures of interest without damage and risk of harm to workers, and second to quantify the average leak rates of certain design/material combinations. The average or characteristic leak rate of a component is also known as conductance [34], and is important to know when attempting to determine the steady-state (steady pressure) leak rate of material out of a pressurized component and into the atmosphere, or across heat exchanger surfaces. Perfectly sealed metallic surfaces would have no conductance, while imperfectly sealed heat exchanger plates or porous ceramic surfaces may have measurable conductance. Knowing the component conductances is important when seeking to determine the potential for cross-contamination of process streams or for calculating the expected cooling fluid loss rate.

The ASME Boiler and Pressure Vessel Code [35] provides information on how to perform pressure testing at room temperature. Pressure tests can be performed hydrostatically or pneumatically. In a hydrostatic test, water is used as the pressurized fluid, while pneumatic tests use pressurized gas (air, helium, nitrogen). Components are pressurized up to 1.5 times the Maximum Allowable Working Pressure (MAWP) and the systems are checked for leaks by watching for a decay in system pressure after system isolation or by using leak detection measures (e.g., soap, helium sensors) to discover leaks.

For the NGNP Project benchtop prototypes, pressure testing can be carried out initially using water as a screening tool, but pressure testing will need to be performed pneumatically in a heated environment in order to reach the temperatures of interest (up to 900°C). Helium, air, or other inert gas can be used as the pressurizing fluid. A pressure test rig involving a gas cylinder or compressor and gas booster and an instrumented kiln or furnace is needed to perform such a test (see Figure 20).

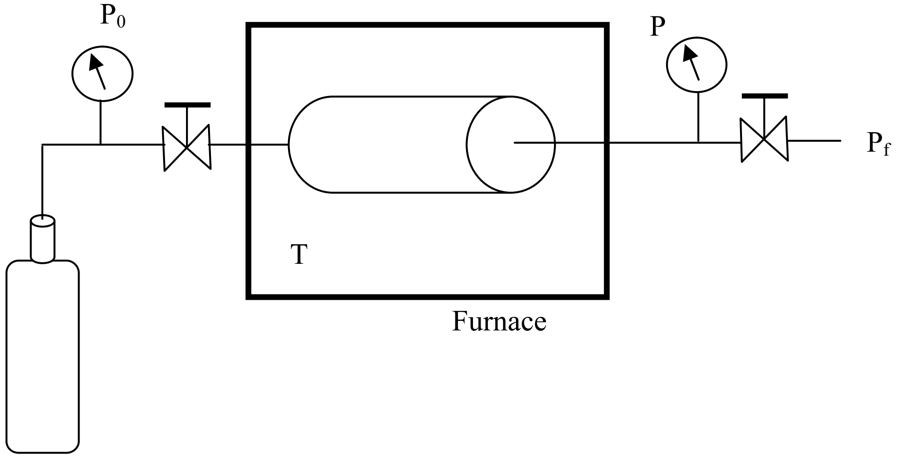


Figure 20. Simplified high-temperature pressure testing apparatus.

The kiln or furnace inner surfaces must be protected against shrapnel in case of catastrophic component failure, and the kiln or furnace should be placed behind a barrier or at a safe distance and orientation relative to the experimenter. Instrumentation is used to determine whether leaks are present because direct examination of the heated component for leaks is not practical for safety reasons. Leak testing must be performed at the temperature of interest because thermal expansion of the component may change component reliability or leak rates.

Leak testing [34] is a refinement of static pressure testing and is performed once the pressure integrity of the prototype component is accepted, thus indicating there are no gross leaks from the component and the component will not immediately fail upon pressurization. Leak testing is performed by pressurizing the component, sealing off the system, and then monitoring the pressure inside the component or sub-section of a component versus time. Leaks are indicated by a measured decay in the pressure after system isolation, and multiple pressure readings versus time are used to determine a pressure decay curve. A chemically inert fluid must be used, otherwise the reaction of the fluid with the component may cause changes in the internal pressure which may mask or magnify the pressure decay curve. Large leaks will be detected relatively quickly on a time scale of seconds to minutes, but slower leaks may express themselves over many hours. Leaks may be caused by defects in the installation of the component, defects in the assembled component itself (e.g., cracks, corrosion damage, gaps due to thermal expansion, etc.), or the inherent permeability of the component material(s). The leak rate of the test system itself must be measured prior to testing components to establish a baseline.

The leakiness of a component is characterized by a conductance factor C, defined in Equation 1, and is measured as a function of pressure during a pressure decay test. Conductance has units of volume/time.

$$P = \left[\frac{1}{P_f} - \left(\frac{\frac{P_0}{P_f} - 1}{P_o} \right) \exp\left(-\frac{C}{V} t \right) \right]^{-1} \tag{1}$$

In Equation 1, P_o and P_f are the initial and ambient pressures, V is the volume of the system, t is time, and C is the conductance of the system. Conductances are functions of the pressure difference (P_0-P_f) and of temperature T. The conductance is used to estimate a steady-state leak rate or volumetric loss by applying Equation (2).

$$Q_{loss} = C[P,T]\left(\frac{P_0}{P_f} - 1 \right) \tag{2}$$

In Equation 2, $C[P,T]$ is used to indicate that C is a function of P and T, and correlations for C can be determined by fitting simple algebraic models to conductance data at different temperatures and pressures. Equations 1 and 2 are based on the ideal gas law and may need to be re-derived using a suitable Equation of State (van der Waals, Peng-Robinson, etc.) if the conditions of the gases are far removed from the ideal gas state. See [34] for information on the derivation of Equations 1 and 2.

Measuring the leakage rates of a heat exchanger is more complicated because the hot and cold sides of the heat exchanger may operate at different pressures and at different average temperatures and may have different leak rates, and internal leaks can occur between the hot and cold sides (i.e., cross leakage). Multiple decay tests are needed at different pressures and temperatures in order to most accurately separate and determine the various leak rates.

For illustrative purposes, a prototype heat exchanger is assumed to operate with a hot inlet channel temperature and pressure of 200°C and 7 MPa, and a cold inlet channel temperature and pressure of 100°C and 6 MPa. The outlet temperatures of the hot and cold channels are 160°C and 120°C, respectively. The difference in pressure between the hot and cold sides is maintained at 1 MPa.. It is desired to determine the steady-state external leak rates of the hot side, cold side, and the cross channel leak rate using pressure decay testing.

Since the leak rates depend upon temperature and pressure, the hot side, cold side, and cross channel leak rates will each need to be measured at different pressures and temperatures in order to more closely match the desired operating conditions of the heat exchanger. The cross channel leak rate will need to be measured at differential pressure of 1 MPa and at a temperature between 100 and 200°C. The external leak rate of the hot side will need to be measured at a pressure of 7 MPa and a temperature between 160 and 200°C. The cold side leak rate will need to be measured at a pressure of 6 MPa and a temperature between 100 and 120°C.

To measure the cross channel leak rate, the temperature of the furnace is set to the average calculated temperature of the heat transfer surfaces separating the hot and cold fluids in the heat exchanger. The system's temperature is then allowed to equilibrate. The hot channel is pressurized to 1 MPa in this example while the cold side is maintained at ambient pressure, and the pressure of the hot side is measured over time. Equation 3 shows the leak terms involved in this test.

$$Q_{hot,external} + Q_{cross} = Q_{hot,observed} \tag{3}$$

In Equation 3, $Q_{hot,external}$ is the leak rate of gas from the hot side of the heat exchanger to the outside environment, Q_{cross} is the leak rate from the hot side of the heat exchanger to the cold side of the heat exchanger, and $Q_{hot,observed}$ is the total observed leak rate from the hot side of the heat exchanger. The test is then repeated in a similar manner, except the cold side of the heat exchanger is pressurized to 1 MPa and the hot channel is opened to atmosphere. Equation 4 shows the leak terms involved in this second test.

$$Q_{cold,external} + Q_{cross} = Q_{cold,observed} \tag{4}$$

The cross-leakage term Q_{cross} is assumed to be equal in Equations 3 and 4 if the test conditions for both decay tests are symmetrical, and the sign of Q_{cross} in Equation 3 or 4 simply depends upon whether the pressure is higher in the hot channel than in the cold channel, or vice versa. A third test is performed, where both the hot and cold sides of the heat exchanger are connected to each other, and the entire heat exchanger is pressurized to 1 MPa. Equation 5 shows the relationship between the leakage rate terms in this third test.

$$Q_{hot,external} + Q_{cold,external} = Q_{external,observed} \tag{5}$$

With the pressures equalized, the cross term is equal to zero because there is no driving force for a cross leak. The three observations allow for calculation of the cross-leakage rate, and this is accomplished by using Equation (6), which was determined by substituting the terms in Equation 5 with their equivalents from Equations 3 and 4 and then separating Q_{cross}.

$$Q_{cross} = \frac{1}{2}\left[Q_{hot,observed} + Q_{cold,observed} - Q_{external,observed}\right] \tag{6}$$

Therefore, three pressure tests can be used to measure the cross leakage rate Q_{cross} and cross conductance C. Physically, the cross-leakage rate, which is an absolute value, must be greater than or equal to zero, but it is possible that a negative rate would be calculated using Equation 6. In that case, a statistical examination of the data should be performed in order to determine whether the finding is statistically different than a zero rate. If it is a statistically significant result, then there was a change in one of the rates, and the measurements may need to be repeated.

The Q_{cross} term determined this way is a constant. If Q_{cross} is needed at temperatures much different than the average temperature of the interface between the hot and cold channels, then the set of three measurements should be repeated at multiple temperatures, and the cross-channel capacitance can be determined as a function of temperature (see Equation 2).

Once Q_{cross} is known, two more pressure decay tests are performed. First, heat exchanger is heated to the average external temperature of the hot side of the heat exchanger. Then, the hot and cold sides are pressurized to the hot side pressure setting but are not connected to each other. Then, the leakage rate and conductance of the hot side is measured directly. Under this condition, the cross leakage is minimized because the pressure differential is reduced or eliminated, and Q_{cross} in Equation 3 is approximately zero. The test is then repeated at the average external temperature of the cold side and the two sides are set to the cold side pressure to find the cold side leakage rate.

As with any experiment, multiple trials may be conducted to gather statistical information about the various conductances and leakage rates, or to determine the functional dependence of the conductances with temperature.

2.2 Cyclic Pressure Testing

Information on the durability of a component may be collected by pressurizing and depressurizing a component multiple times in order to place the component under stress and to create fatigue. In such a test, the component is heated using the same furnace or kiln used for the pressure and leak testing, and is then pressurized to the desired pressure. The component is held at the desired pressure for some period of time, and then the pressure is released. The process is repeated multiple times. At the end of cyclic testing, the component is examined in some manner to characterize any changes that may have occurred in the component, and the information is used to design better more fatigue-resistant versions of the component.

The cyclic pressurization testing should be done remotely and using automated fill and depressurization valves. It is possible that a component may fail upon pressurization, especially after having undergone multiple pressurization/depressurization cycles, and the material barriers used for static pressure testing should remain in place for the dynamic tests.

For other indications of change, pressure decay measurements (See Section 2.1) may be obtained during the course of a pressurization cycle in order to compare component integrity from run to run. Increases in pressure decay rates would indicate larger leak rates, and may be an indication of pending component failure.

2.3 Similitude

The truest testing of high-temperature heat exchangers and other components for the NGNP System Interface would be performed at the actual conditions of interest using components having actual geometries. This means that components having final shapes and forms would be tested at 5-9 MPa and 750-900°C in a flowing helium or steam environment. For heat exchanger testing, a second high-pressure helium loop or steam loop would be required to receive the heat from the high-temperature loop and to balance the pressure across the heat exchanger. Prototypes that perform well at the laboratory scale under such conditions could be easily scaled to larger sizes, and the confidence in the TRLs of the components would be greatly increased.

There are some disadvantages to working with high-temperature high-pressure test loops at the laboratory scale. Tests performed at this scale would be relatively expensive since the test loops must be made of the same high-temperature materials and use the same types of valves, fluid motivators, and instrumentation as would be used on larger test loops, and so the volume/cost ratios would be higher. The technical risks are greater because the test loop itself include items that must be advanced in technical maturity along with the articles that must be tested, and successful testing of prototypes depends upon having a reliable and controllable test bed. There are also increased safety risks too, because prototypes will be tested for the first time at high temperature and pressure, and it is possible, due to technical immaturity of designs or the manufacturing methods, that prototypes may have flaws that lead to component failure and sudden loss of loop fluid.

As a lower-cost alternative, much useful information can be collected at less cost and increased safety and reliability by carrying out multiple reduced-condition tests on prototype components. A reduced-condition test eliminates one or more of the hazardous test conditions in order to reduce the cost and increase the safety of any particular test, while still allowing for the collection of data relevant to model validation. For example, a pressure-drop measurement could be performed at similar flow rates and fluid temperatures but at near-atmospheric pressure. High-temperature high-pressure testing would still be performed, but would be delayed until the component has proven reliable at reduced conditions and larger test loops have been implemented at the pilot-scale or engineering-scale. The leakage rate may not be the same when a pressure-drop test is conducted based on similitude design.

Costs can be reduced still further by eliminating the closed test loops and deploying water, steam, and/or air in once-through test beds. Water and air are available at much less cost than helium, and can be obtained from laboratory utilities. Steam can also be produced locally with a boiler or obtained from a building steam source.

The properties of water, steam, and air are different than high pressure helium, but the conditions of the experiments can be changed to correspond to fluid conditions that are similar to what would have been realized had hot high-pressure helium been used instead. Though the individual properties of fluids will differ (density, viscosity, thermal conductivity, etc.), different fluids will behave in similar ways when certain dimensionless combinations of their fluid properties and the system geometries are similar. This similarity is called *similitude* [36]. In fluid and heat transfer systems, similarity is indicated by matching dimensionless numbers – Reynolds number (Re), Prandtl number (Pr), Graetz number (Gz), Stanton number (St), Nusselt number (Nu), and others. Testing of devices under similar conditions has been discussed by Kline [37], Bardet and Peterson [38], and Ingersoll et al. [39]. Careful attention must be paid to the leakage rate and fatigue because different fluids may be used for tests using the same pipe. Also, the mass diffusivity and permeability of helium and air are different.

Of the large number of dimensionless numbers usually used in fluid and heat transfer studies, the Re, Pr, and Nu are the most important for the forced convection tests described here [40]. Re is calculated (Equation 8) by multiplying the characteristic diameter of the flow channel times the fluid velocity times the density of the fluid, and dividing by the fluid viscosity, and provides a measure of whether the fluid is flowing in the laminar, transition, or turbulent regimes.

$$\mathrm{Re} = \frac{\mathrm{D} v \rho}{\mu} \tag{8}$$

Two fluids flowing through channels of differing characteristic flow channel diameters (D) may have the same Re if the fluid viscosities (μ), fluid densities (ρ), and fluid velocities (v) are adjusted to compensate. Pr is calculated (Equation 9) by multiplying the fluid heat capacity (c_p) by the fluid viscosity (μ) and dividing by the thermal conductivity of the fluid (k).

$$\mathrm{Pr} = \frac{c_p \mu}{k} \tag{9}$$

The Pr is correlated with the behavior of the hydrodynamic and thermal boundary layers of the fluid and is similar for most gases. The Nu is defined by Equation 10 and relates the heat transfer film coefficient to the thermal conductivity of the fluid.

$$\mathrm{Nu} = \frac{h_i \mathrm{D}}{k} \tag{10}$$

The heat transfer film coefficient, contained within the Nu, is needed to determine the overall heat transfer coefficient (U) of a heat exchanger. From that, heat transfer area can be determined for a given power level and fluid temperatures, and heat exchanger designs can be examined.

The Nu is related to the flow conditions (Re) and the properties of the fluid (Pr) through two other dimensionless groups, the Gz, shown in Equation 11, and the St, shown in Equation 12.

$$\mathrm{Gz} = \frac{\pi}{4} \mathrm{Re}\,\mathrm{Pr} \frac{\mathrm{D}}{\mathrm{L}} \tag{11}$$

$$\mathrm{St} = \frac{h_i}{c_p v \rho} = \frac{h_i}{c_p \mathrm{G}} = \frac{\mathrm{Nu}}{\mathrm{RePr}} \tag{12}$$

In Equation 11, L is the length of the flow channel. In Equation 12, G is the mass velocity. Depending upon whether the flow conditions are laminar or turbulent, there are a number of correlations that use the Re, Pr, Gz, or St to calculate the Nu and, as a result, the heat transfer film coefficient. Texts on heat transfer should be consulted in order to determine which correlations are applicable to the test conditions of interest (e.g., laminar flow, turbulent flow, tubular versus planer geometries, etc.).

Table 1 shows a comparison of some of the properties of air, water vapor, and helium at 100°C. In order to match the fluid conditions in a test article using air to those that would be experienced in a test article using helium, the Re and Nu can be made to match by altering the fluid channel diameter and the fluid velocity in a prescribed manner. Equation 10 is used to adjust the fluid channel diameter, $D_{air}=D_{He}(k_{air}/k_{He})$, in order to match Nu numbers. After adjusting the fluid channel diameter, the Re must also be adjusted using Equation 8, and this can be accomplished by increasing proportionally the air velocity to compensate for the decreased fluid channel diameter. The Pr and μ are already similar and the density of the two gases is assumed to be roughly the same at the sample conditions of interest. In this manner, a test using air at 100°C could be performed, and direct inferences of about how a similar system using helium would behave could be drawn from the results.

Table 1. Sample Fluid Properties at 100°C and 1 atm

Fluid	Pr	k (Btu/ft·h·°F)	μ (cP)
Air	0.69	0.0184	0.021
Helium	0.71	0.0988	0.022
Water Vapor	1.06	0.0136	0.013

Exactly matching fluid conditions is not required at the laboratory scale for the NGNP System Interface components because it is assumed that larger-scale testing will be performed using actual high-temperature high-pressure circulating loops. Data collected from the benchtop tests will be used to adjust heat exchanger models, which in turn will be used to develop more mature component prototypes and to set up the test conditions at larger scales. In the interest of cost and time, laboratory scale tests should be performed at scaled conditions that approach the actual conditions of interest without going to extreme lengths in cost and effort to achieve perfect similitude.

When possible, the flow conditions, system geometries, and system temperatures should be varied from test to test so that the flow and heat transfer conditions tested span the conditions of interest. For example, if the actual heat exchanger is expected to operate with a Re = 1000, test conditions should be varied so that tests are performed using Re numbers that are less than and greater than this number. This may allow for more accurate adjustment of flow and heat exchanger models because the models could be used in an interpolative rather than extrapolative manner.

2.4 Flow Testing

Component testing under flow conditions is used to determine component friction factors as a function of changing fluid conditions. The data measured during flow testing is compared to system models, and adjustments are made to the models and component designs to improve the correlation of the models with the physical data and to improve overall component performance under the conditions tested.

Components are tested using a single-phase fluid, preferably air, nitrogen, water, or steam. Tests can be carried out at near ambient up to high pressure, depending upon the design of the flow system and the fluid source. If air, nitrogen, or other inert gas is used, gas could be supplied at 5-9 MPa if obtained from high-pressure cylinders, while steam supplied from a laboratory steam generator may be available only up to 90 psi (0.6 MPa).

An idealized flow test apparatus is shown in Figure 21. In the flow test apparatus, component is insulated to prevent the flow of thermal energy into or out of the system during the test. A pre-conditioned gas having the desired temperature T_1, pressure P_1, and fluid velocity v_1 is introduced into the component, and the temperature T_2, pressure P_2, and exiting velocity v_2 are measured at the fluid outlet from the component. The component must be allowed to reach steady state after flow is introduced in order for the test to provide the proper information.

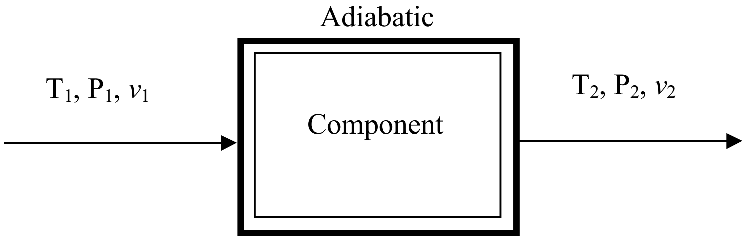


Figure 21. Idealized flow test apparatus.

A mechanical energy balance on the component is used to extract information about the frictional losses in the component. A general mechanical energy balance equation [41] is shown in Equation 13.

$$\Delta \frac{1}{2}\frac{v_m^3}{v_m} + \Delta\Phi + \int_{P_1}^{P_2} \frac{dP}{\rho} + W + E_v = 0 \tag{13}$$

In Equation 13, $v^3{}_\mathrm{m}$ is the cube of the velocity averaged over the cross section of flow (3rd raw moment), v_m is the velocity averaged over the cross section of flow (1st raw moment), Φ is the potential energy per unit mass of the fluid at the inlet or the outlet, ρ is the fluid density, W is the work expended by or performed on the fluid while in the system per unit mass, and E_v is the friction term per unit mass. In the case that the fluid is in the turbulent regime, the $v^3{}_\mathrm{m}/\ v_m$ term approaches $(v_\mathrm{m})^2$ and the square of the average velocity can be substituted into Equation 13. The Δ symbol is used to show that a difference is taken between the final and initial conditions for the velocity and potential energy terms.

For the idealized flow system, the potential energy term and the work term are set to zero, and the changes in fluid velocity, pressure, and temperature are used to determine the friction losses.

Once the friction losses are known, physical information about the component, such as channel diameter D, channel length L, calculated average fluid velocity per channel v_m, and the number of flow channels in the component, may used to determine friction factors f_F for the component using Equation 14.

$$E_v = \sum 2 f_F \frac{L}{D}\frac{v_m^2}{g} \tag{14}$$

In Equation 14, g is the gravitational constant. The friction losses for each flow channel in the component are added to give the overall observed friction loss. Since friction factors are independent from the component dimensions, having knowledge of the friction factors would aid in the analysis and design of larger components. The friction losses are also known as friction head losses.

As a check of the observed friction factors, friction factors can also be calculated using information about the Re in the flow channels and the surface roughness (e/D). If the flow is laminar (Re<2300) in a flow channel, the friction factor can be determined by applying Equation 15, which is obtained from the Hagen-Poiseuille equation for incompressible, laminar, conduit flow [41, 42].

$$f_F = \frac{16}{\mathrm{Re}} \tag{15}$$

If the flow is in the transition region, then an empirical relation by Colebrook can be used to determine the friction factor, shown in Equation 16.

$$\frac{1}{\sqrt{f_F}} = 4\log_{10}\frac{D}{e} + 2.28 - 4\log_{10}\left(4.67\frac{D/e}{\mathrm{Re}\sqrt{f_F}} + 1\right) \tag{16}$$

If the flow is in the turbulent regime (Re>3000) and the pipe is smooth ($(D/e)/(\mathrm{Re}\sqrt{f_F}) >= 0.01$), then the friction factor can be determined by using Equation 17.

$$\frac{1}{\sqrt{f_F}} = 4.0\log_{10}\left[\mathrm{Re}\sqrt{f_F}\right] - 0.40 \tag{17}$$

Otherwise in the turbulent regime, if the pipe is considered rough ($(D/e)/(\mathrm{Re}\sqrt{f_F}) < 0.01$), Equation 18 is used to calculate the friction factor.

$$\frac{1}{\sqrt{f_F}} = 4.0\log_{10}[D/e] + 2.28 \tag{18}$$

Exact agreement between observed and calculated friction factors may not be obtained, but a statistical match is desired. If the observed and calculated friction factors do not match, then there is opportunity to improve upon the models or the assumptions used in the models in order to improve the comparison.

In non-circular flow channels, and equivalent diameter is used in the fluid calculations. The equivalent diameter of channel *i* is shown in Equation 19.

$$D_{eq,i} = \frac{A_i}{P_i} \tag{19}$$

In Equation 19, A_i is the cross-sectional area of flow of channel *i*, and P_i is the wetted perimeter of channel *i*.

In some cases, the geometry of a component such as a valve, elbow, or other fitting that involves changes in flow direction or flow cross section affects the friction behavior, and friction losses tend to be somewhat independent of the Re. In these cases, a friction factor *K* is calculated directly from the measured friction loss or friction head loss. This calculation is shown in Equation 19.

$$E_v = K\frac{v_m^2}{2g} \tag{19}$$

An actual test apparatus would require additional equipment to create and control the temperature, pressure, and flow conditions needed to perform a steady-state measurement of frictional losses. A pressurized gas source, pressure regulators, back-pressure regulators, and relief valves will be needed to operate at elevated pressure. Gas heaters such as those shown in Figure 22 or a steam generator such as that shown in Figure 23 will be needed to heat the feed gas to the desired temperature. Custom-made externally heated gas heaters may also be constructed using electrical heating tape or sections of finned tubing placed into a kiln or furnace.

Temperature, pressure, and flow instrumentation will be needed to collect data from the test apparatus. Pressure, temperature, and flow controllers may be needed to control the experiment set points. A fluid cooler (air-cooled, water-cooled) may be needed to chill the fluid at the end of the test apparatus before the fluid is vented. An equipment control and data acquisition system will be needed to control the system and collect laboratory data. Customized components may also be deployed that have additional instrumentation installed (thermocouples, pressure taps, etc.) in order to provide a greater degree of understanding of what is happening in different parts of the component during the flow test.

Figure 22. In-line air heaters operate up to 700°C and 120 psig (Heat Torch™ 200 by Farnum Custom Products, Inc.).

Figure 23. Sussman® low-capacity electric steam generator (27 lb/h, 0-90 psi steam).

2.5 Heat Exchanger Testing

Heat exchanger testing is performed on prototype heat exchangers in order to measure heat exchanger performance and, consequently, overall heat exchanger coefficients (*U*). The local overall heat exchanger coefficient [13] is defined in Equation 20.

$$\frac{dq}{dA} = U\Delta T = U\left(T_{hot} - T_{cold}\right) \tag{20}$$

In Equation 20, q is the rate of heat transfer for a localized area of the heat exchanger (usually measured in W or Btu/hr), U is the overall heat transfer coefficient (W/m^2·K), A is the localized heat exchanger area, and ΔT is the temperature difference between the bulk hot and cold fluids at that localized area. It is referred to as a local coefficient because it applies to a localized section of the heat exchanger where temperature and fluid conditions are time invariant, and overall because it accounts for the heat transfer resistances in the films on the hot and cold sides of the heat exchanger and for the thermal conductance of the heat exchanger material.

Equation 20 can be integrated over the entire surface of the heat exchanger to obtain the overall heat exchanger coefficient if certain conditions are met. These conditions are: 1) The overall heat exchanger coefficient is constant (same conditions apply to entire heat exchanger surface), 2) the heat exchange system is adiabatic, and 3) flow is steady in either parallel or counter-current arrangement. In this case, Equation 20 becomes Equation 21.

$$U = \frac{q_T}{A_T \overline{\Delta T_L}} \tag{21}$$

In Equation 21, q_T is the rate of heat transfer in the entire heat exchanger, A_T is the total area of the heat transfer surfaces in the heat exchanger, and $\overline{\Delta T_L}$ is the log-mean temperature difference defined in Equation 22.

$$\overline{\Delta T_L} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)} \tag{22}$$

In Equation 21, ΔT_1 is defined as the temperature difference between the outlet hot temperature and the inlet cold temperature, and ΔT_2 is the temperature difference between the inlet hot temperature and the outlet cold temperature, where it is assumed that the cold fluid is being warmed, and the hot fluid is being cooled.

There are many cases for complex heat exchanger geometries, multi-pass shell-and-tube heat exchangers, and others were the log-mean temperature difference simplification cannot be made. In such cases, Equation 20 or 21 is applied locally where the assumptions are met and the heat exchanger information is piecewise integrated, or correction factors are used to adjust the log-mean temperature difference. Tables of correction factors are available in the literature for many kinds of heat exchangers (e.g., multi-pass tube-and-shell).

Information on the overall heat transfer coefficient may also be constructed from the individual contributions of the film coefficients, solid material thermal conductivities, and detailed thermal distributions throughout the heat exchanger, as obtained from detailed computer models. A comparison of measured overall heat transfer coefficients with calculated overall heat transfer coefficients constructed from such detailed calculations allows for a deeper understanding of which heat transfer modes (e.g., convection, conduction) are more influential, and provides insights into how calculations might be made more accurate.

An idealized heat exchanger test apparatus would be an extension of the flow test apparatus described in Section 2.4, and is shown in Figure 24.

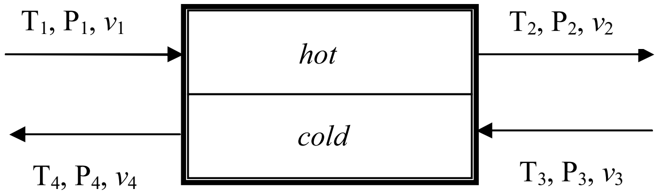
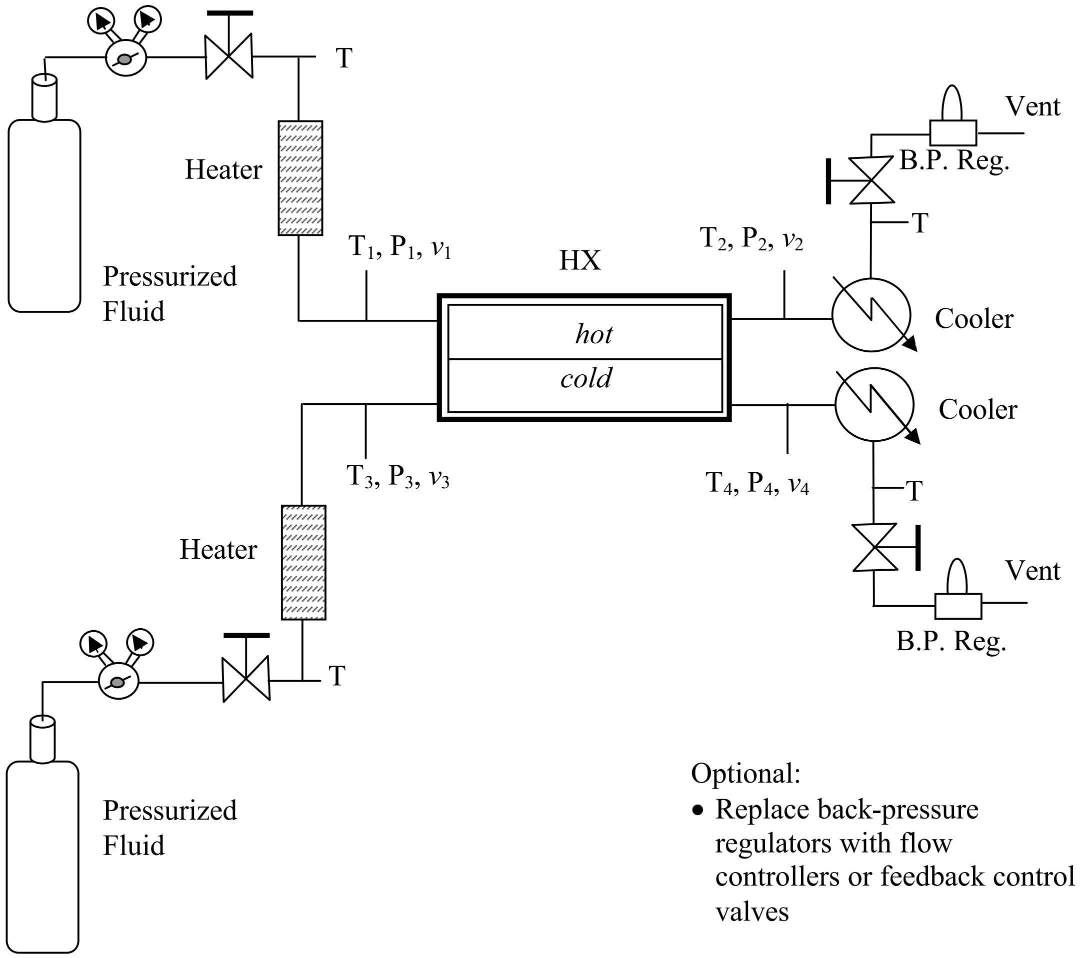


Figure 24. Idealized heat exchanger.

In Figure 23, a “hot” fluid having a temperature T_1, a pressure P_1, and fluid velocity v_1 enters the heat exchanger, deposits thermal energy into the walls of the heat exchanger, and exits with a reduced temperature T_2, and reduced pressure P_2, and a velocity v_2. The velocity v_2 may be the same as v_1 if the fluid is incompressible and the fluid inlet and outlet have the same cross-sectional area, or it may be different if the fluid is compressible. A “cold” fluid having a temperature T_3, pressure P_3, and a velocity v_3 enters the heat exchanger, receives thermal energy from the walls of the heat exchanger, and exits with an increased temperature T_4, a reduced pressure P_4, and a velocity v_4. The velocity v_4 may be the same as v_3 if the fluid is incompressible and the inlet and the outlet have the same cross-sectional area, or the velocity may be different if the fluid is compressible. Unless the heat exchanger is a direct contact heat exchanger, the hot and cold fluids never intermix, and only energy is exchanged. For a heat exchanger of known heat transfer area (A_T), temperature and flow data are used to calculate fluid enthalpies, which provides information about the total amount of heat energy exchanged (q). Once q is known, the log-mean temperature difference can be used to find the overall heat transfer coefficient U using Equation 21.



Optional:
- Replace back-pressure regulators with flow controllers or feedback control valves

Figure 25. Schematic of one possible heat exchanger testing apparatus. The HX is installed in co-current flow mode.

In order to support a heat exchanger test, the inlet temperatures, pressures, and fluid velocities (volumetric flow rates) must be known and controlled, so that a heat exchanger test can be performed under specific conditions of interest. Figure 25 shows one possible way of controlling the input fluid conditions to the heat exchanger. The average pressure on each side of the heat exchanger and the fluid velocity are controlled by using pressure regulators and back-pressure regulators. The settings of these regulators control the average pressures on the hot and cold sides of the heat exchanger, and the difference in set points between the regulators and the back-pressure regulators controls the bulk fluid velocities through the heat exchanger. The input temperatures are controlled by heating the input streams to the desired temperatures, and the down-stream valves and back-pressure regulators are protected against high temperatures by air or water-cooled heat exchangers. Due to the potentially high temperatures of the flow streams, the pressure transducers are mounted with standoff sections, and the flow measurements are performed by using venturi meters, orifice plate meters, or vortex shedding meters and differential pressure transducers. In Figure 24, the heat exchanger is presented as being in a co-current flow mode, but the piping for attaching a test heat exchanger is arbitrary, and the heat exchanger can be installed in co-current, countercurrent, and cross-flow modes.

If flow rates are small, the amount of heat transferred across the heat exchanger may approach the amount of heat lost through the external insulation of the heat exchanger, since a true adiabatic heat exchanger would be difficult to achieve. In this case, a calibration of the external heat loss is needed to more properly account for the energy balances. Also, care must be taken to account for any temperature differences between the actual fluid temperature and the measured fluid temperature due to conduction of heat from the thermal sensors. For example, if a thermocouple is used, the thermocouple wire may be cooler than the surrounding fluid due to conduction of heat through the thermocouple wire to the outside of the heat exchanger.

There is supporting equipment that is not shown in Figure 23 that would be needed to complete the test apparatus. Pressure protection devices would be needed to protect against possible over-pressurization of the apparatus. Temperature interlock circuits may be needed to shut down the heaters when the coolers shut down or become overheated. Computer controllers and data acquisition systems would be needed to control the heaters and the back-pressure regulators to maintain steady fluid conditions during a test and to collect process data. Insulation would be needed to prevent heat losses from the hot sections of the apparatus and to protect workers against hot surfaces. Ballistic shielding may also be needed to protect workers against structural failures and flying debris. Also, modifications to the fluid supply system would be needed depending upon the heat exchanger fluids. Pressurized air could be supplied from air cylinders, or a ballast tank pressurized by using an air compressor or shop air and a gas booster. Nitrogen could be supplied from a gas cylinder or by using a nitrogen generator and a gas booster. Steam could be supplied from a steam generator or from shop steam. As an option, the back-pressure regulators could be replaced with automatic flow controllers in order to control the flow rates directly.

2.6 Facility/Equipment Needs

It is expected that process heat exchanger designs (e.g., gas-heated bayonet for H_2SO_4 decomposition, gas-heated high-temperature steam generator for HTE process), valves, internal insulation, heat transfer conduit designs, and some instrumentation will require testing at the benchtop scale. Though it is anticipated that the designs recommended for the IHX and some heat exchangers the secondary helium loop may be relatively mature, such designs could be tested at the benchtop scale as well in order to verify performance expectations once benchtop testing capabilities have been established.

A benchtop component and heat exchanger testing laboratory would require at least two test stations: a component pressure/leak test station, and a heat exchanger testing station. From the previous sections on flow testing (Section 2.4) and heat exchanger testing (Section 2.5), it is apparent that flow testing can be performed using the same equipment as used for heat exchanger testing. The flow paths for the hot and cold sides of the heat exchanger test apparatus will use similar instrumentation and common equipment, and measurement of pressure drops and friction factors could be performed with either pathway. Flow measurements are made without heat transfer initially, and then can be repeated during the heat exchanger test to look for differences in the friction factors.

Though each station would be designed to operate independently, data collection and equipment controls could be managed using a single work station. A data acquisition system (e.g., Yokogawa MW100 Data Acquisition Unit or LabVIEW) with compatible viewing software to collect and process the data from the experiments is needed, and laboratory-scale process controllers (e.g., Yokogawa CX2000) manage the dynamic pressurization testing in the pressure/leak testing station and control the back-pressure regulators or flow controllers in the flow/heat exchanger testing station. Control equipment would also be needed to regulate the heater interlocks in the flow/heat exchanger testing apparatus.

If flow or temperature data are needed on specific sections of the component, additional temperature, pressure, or flow sensors may be installed in the component itself. Additional sensors may increase pressure drop in a component, and comparisons will need to be made to an uninstrumented component in order to characterize the additional pressure drop caused by adding any new flow restrictions in the instrumented component.

The power requirements of the flow apparatus are not large. If a Heat Torch like the one shown in Figure 20 is used to heat the gas stream, electrical power up to 13 kW and 480 V multiphase is needed to provide air flows up to 100 CFM and 700°C, though other heating alternatives (e.g., placing a coil of high temperature tubing in a Skutt Electric Kiln) may be used that require less voltage (240 V multiphase) or less power. Alternatively, a propane or natural gas furnace could be used to heat the input streams to the desired temperature and thus greatly reduce electrical power requirements. A propane or natural gas-fired furnace would require venting.

Aside from the prototype heat exchangers themselves, the laboratory equipment can be obtained from commercial vendors. Some customization of instrumentation may be required in order to install pressure transducers than can measure pressure at high-temperature. Water cooling or an ethylene glycol chiller may need to be installed to remove heat from the coolers if air cooling is not sufficient. Heat will need to be vented outside of the laboratory. The basic laboratory infrastructure and space required is generic, and can be found at any number of national laboratories and universities.

2.7 Benctop-Scale Testing Summary

Pressure testing is required, and leak testing may be performed to quantify the leakage rates if a leak or leaks are detected during the pressure test. Leak testing is performed at pressure and at the temperatures of interest. Dynamic pressure testing may be performed to gather information on component durability and fatigue in response to pressure fluctuations at temperature, but is not required. Flow testing is required in order to measure component pressure drops and friction factors, and is performed using air, nitrogen, carbon dioxide, water, or steam under similar fluid conditions as the actual fluid conditions of interest (similitude). Heat exchanger testing is required for heat exchangers and is performed using air, nitrogen, carbon dioxide, or steam under similar fluid conditions as the actual fluid conditions of interest. Benchtop testing may be performed at the actual conditions of interest using closed helium loops, but it is recommended that open flow paths be used in order to reduce equipment costs and equipment complexity. At least two experimental stations are needed in a laboratory – a pressure/leak testing station, and a heat exchanger testing station. The components needed to establish a laboratory are mostly off-the-shelf aside from the test articles themselves. The needs of the facility are generic and the laboratory could be physically located at nearly any national laboratory or university.

3. PILOT-SCALE TESTING REQUIREMENTS AND FACILITY NEEDS

Tests at the pilot scale are performed to evaluate component options that have emerged from previously performed laboratory-scale tests or from adaptations of fairly mature components that are used in industry for similar purposes. The data collected must be sufficient to allow for advancement of component options to **NGNP Project TRL 6** or **7**, or to eliminate component options from further consideration for the given purpose. Tests are performed under the actual conditions of interest (i.e., temperature, pressure, fluid composition), and the component must be of sufficient complexity and size to be directly and easily scaleable to the engineering scale. Data generated from tests are used to verify and adjust computational models. To match the environmental and operational conditions in an intermediate heat transfer loop, testing is performed using pressurized high-temperature flow loops (at least for the thermal supply). Fewer tests are performed, but the tests are longer in order to gather performance data over hundreds of hours. Corrosion data are collected from samples placed in flow loops or from destructive examination of test articles. In most cases, the components being tested will be larger than their benchtop counterparts, and the costs of tests will be more expensive because of higher capital and operating costs.

3.1 Pressure/Leak Testing

In order to support process safety, all test articles must be pressure tested and may require leak testing. Pressure testing is performed at room temperature first before going to higher temperatures, and can be done hydrostatically or pneumatically. The article being tested must be placed behind a barricade or positioned in such a way that a structural failure of the pressurized component will not place the experimenter in harm's way. If a component is large, performing a leak test at a controlled temperature may be difficult if there isn't an oven or kiln large enough to accommodate the component. In that case, pressure and leak testing may be performed at room temperature, and the results from prior benchtop pressure and leak tests on smaller-scale components may be compared to the pilot-scale tests in order to draw inferences about higher-temperature behavior of the pilot-scale component. The formulas displayed in Section 2.1 for calculating leak rates are also valid at the pilot-scale.

3.2 Cyclic Pressure Testing

Due to the extra expense and larger stored energy in a pilot-scale component, cyclic leak testing is not recommended at the pilot-scale. Since cyclic pressure testing creates conditions that may lead to structural failure of the component, it is better performed on smaller-scale components where the impacts of structural failures are lessened.

3.3 Flow Testing

At the pilot-scale, flow testing is performed for the purpose of determining component friction factors. The data measured during flow testing is compared to system models, and adjustments are made to the models to account for the properties of the component. There is some opportunity to change component designs to reduce friction factors, but there is generally less flexibility at the pilot scale than at the laboratory scale to adjust the actual component design, and relatively few significant design changes are expected at the pilot scale before advancing to the engineering scale.

Flow testing is performed with the actual fluids of interest under the desired operating conditions. For example, if the target fluid is helium at 5 MPa and 800°C and the flow rate is 20 m/s, then a flow test is performed at those conditions, as opposed to using similar fluid conditions (see Section 2.3, Similitude) with air or steam.

Unless the actual fluid is air, nitrogen, carbon dioxide, or steam (all relatively inexpensive fluids), the once-through flow paths as described in Section 2.4 are wasteful of fluid and will not be used for helium. Flow tests are performed using a pressurized heated flow loop instead. An example of a test flow loop is shown in Figure 26. A flow loop conserves and recycles the fluid of interest and only make-up fluid is needed to maintain the loop inventory after the loop is initially filled. The flow loop conditions (pressure, temperature, flow rate) must be controllable and instrumented so that the flow conditions into a component can be controlled and the output flow conditions can be measured. Fluid conditions are chosen to match the fluid conditions of interest for in-service use.

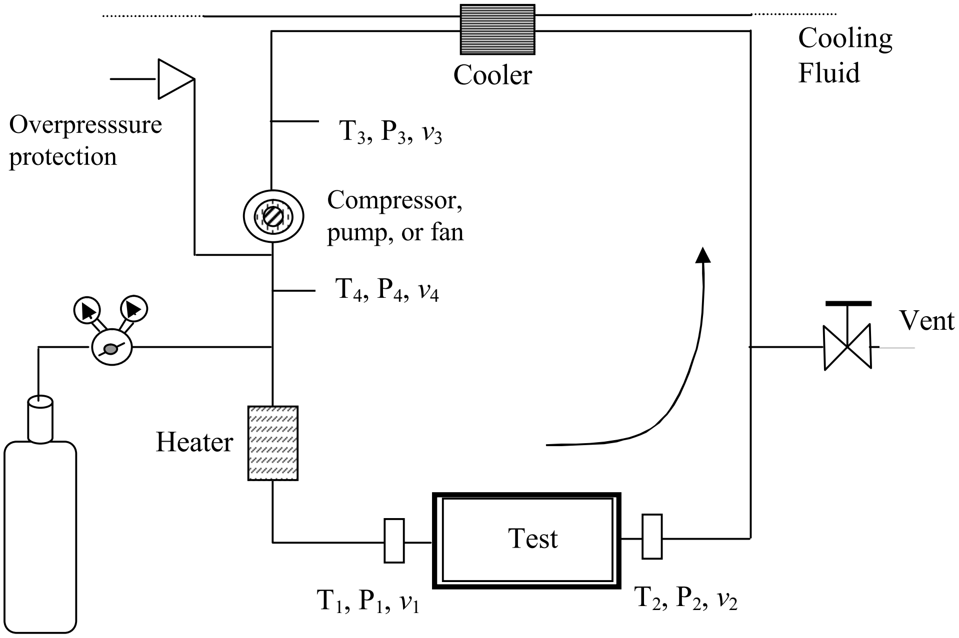


Figure 26. Schematic of basic closed flow loop.

A closed flow loop requires additional features above those used in a once-through flow path to achieve and maintain the test conditions of interest. A compressor, pump or fan is needed to move the fluid through the loop at a desired velocity or mass flow rate set point. All process piping and the test article are insulated to minimize uncontrolled heat losses. A heater is needed to heat the fluid to the desired temperature, and the temperature must be maintained by balancing the energy input from the heater and heating from fluid friction with energy output to a loop cooler. Though it may be possible to maintain loop temperature without using a cooler simply by balancing the heat input from the heater and friction heating with the general heat losses from the loop piping, greater control of fluid temperature can be realized if the friction heating contribution (which is not controlled) is much smaller than the energy interchange between the heater and the loop cooler (which is controlled). A cooler may be an uninsulated air-cooled section of pipe, or it may be actively cooled with a cooling fluid flowing through a heat exchanger. Using a heater/cooler combination also has the advantage of lowering the fluid temperature going through the pump, compressor, or fan, which may reduce its cost and/or extend its useful life. Flange connections are used to attach the test article to the loop, and a valve is used only for the vent line, which may be positioned outside of the hot pipe insulation in order to keep it at a lower temperature. Overpressure protection is provided downstream from the pump or compressor to protect the loop against excessively high pressures at the maximum point of pressure (after the pump but before the component). The loop must be fully instrumented to monitor the temperature, pressure, and flow rates at various points, and control systems are needed to maintain constant fluid conditions during a flow test.

Once the test article has been installed in the loop and the loop has been stabilized at the test conditions of interest, the mechanical energy balance described in Section 2.4 and shown in Equation 13 is used to extract information about the frictional losses of the component.

$$\Delta \frac{1}{2}\frac{v_m^3}{v_m} + \Delta\Phi + \int_{P_1}^{P_2} \frac{dP}{\rho} + W + E_v = 0 \tag{13}$$

Physical information about the component and the measured data are then used to calculate friction factors f_F. as was done in the benchtop tests.

Because the loop and the test article are pressurized and operating at possibly high temperatures during a flow test, the test loop should be placed behind barriers or positioned to protect the experimenter from potential high pressure component failures.

3.4 Heat Exchanger Testing

Heat exchanger testing is performed on pilot-scale heat exchangers in order to measure heat exchanger performance and, consequently, overall heat exchanger coefficients (*U*), as described in Section 2.6. The data measured during heat exchanger testing is compared to system models, and adjustments are made to the models to account for the heat exchanger performance of the component. There is some opportunity to change component designs to increase heat exchanger performance, but there is generally less flexibility at the pilot scale than at the laboratory scale to adjust the actual component design, and relatively few significant design changes are expected at the pilot scale before advancing to the engineering scale.

Heat exchanger testing is more complicated than flow testing because two flow paths must be used to create the test conditions in the heat exchanger, and at least one of the flow paths will consist of a closed helium loop. Figure 27 shows one possible test apparatus where a pressurized heated closed loop is used in conjunction with a pressurized heated open flow path in order to provide fluid flow to a heat exchanger. If a helium/helium heat exchanger is being tested, as would be the case with an NGNP IHX, then two closed loops must be operated at the same time with both loops connected to the heat exchanger, and this configuration is shown in Figure 26.

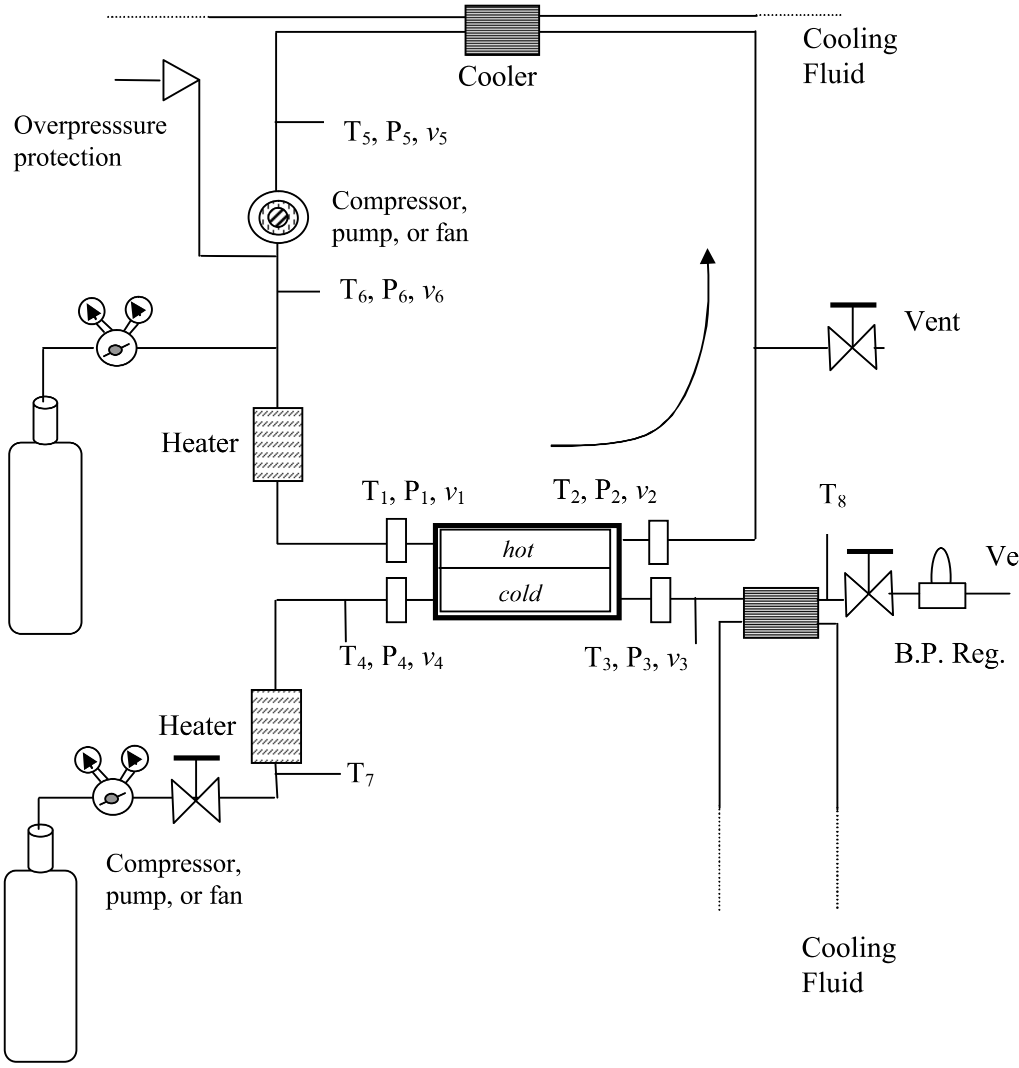


Figure 27. Heat exchanger test apparatus with one closed loop and one open flow path.

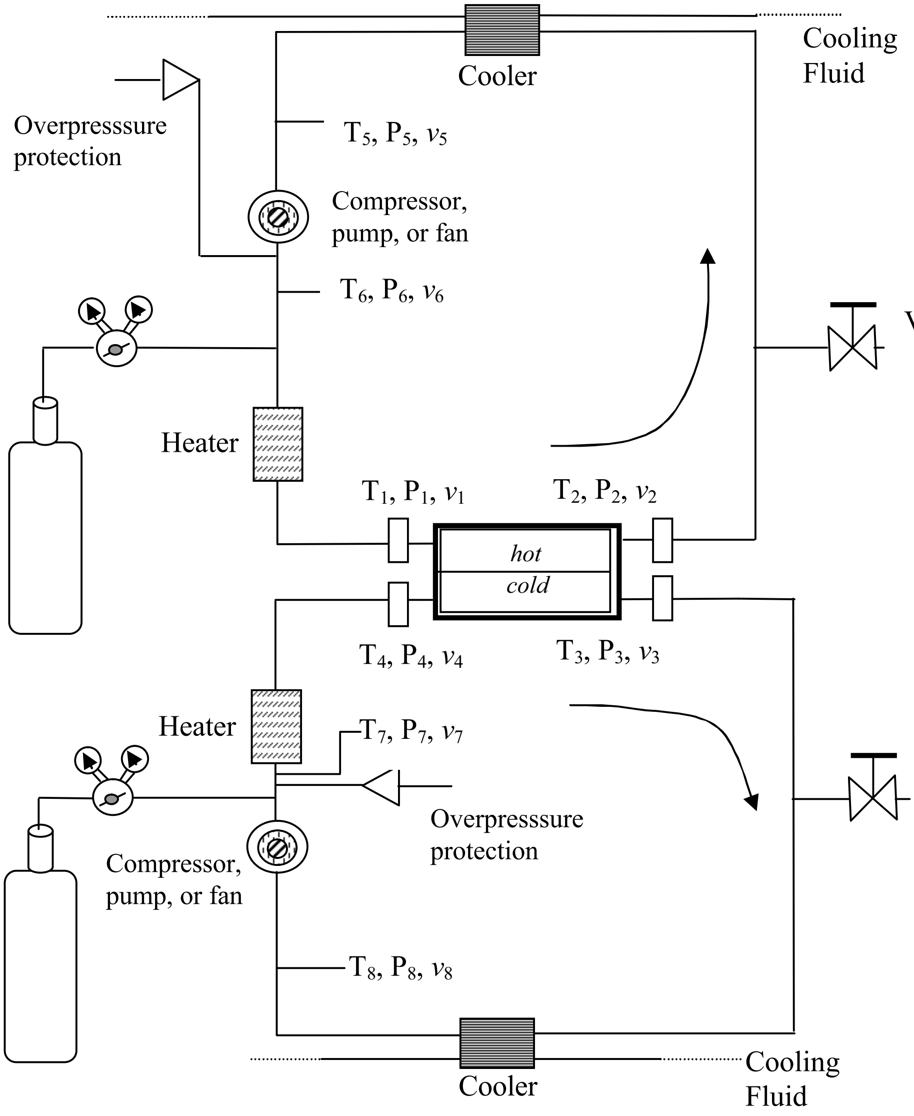


Figure 28. Heat exchanger test apparatus with two closed loops operating in parallel flow.

In Figures 27 and 28, the conditions of each flow path are managed separately in order to create and maintain the hot and cold channel fluid conditions that are going into the test heat exchanger. Energy is exchanged across the heat exchanger in either case, and a cooler is used in each flow path to restore the fluid to the desired input conditions for the pump, compressor or fan. There are many degrees of freedom in how to affect the fluid flow conditions in each channel, and some computer process controls may be needed to “dial-in” the desired fluid conditions by adjusting flow rates, the power input for each heater, and the heat removal rate for each cooler in an integrated fashion. Pressure would be adjusted independently for each flow path. Process variables such as temperature, pressure, and flow rate are measured at multiple points in each loop.

If flow rates are small, the amount of heat transferred across the heat exchanger may approach the amount of heat lost through the external insulation of the heat exchanger, since a true adiabatic heat exchanger would be difficult to achieve. In this case, a calibration of the external heat loss is needed to more properly account for the energy balances. Also, care must be taken to account for any temperature differences between the actual fluid temperature and the measured fluid temperature due to conduction of heat from the thermal sensors. For example, if a thermocouple is used, the thermocouple wire may be cooler than the surrounding fluid due to conduction of heat through the thermocouple wire to the outside of the heat exchanger.

There is supporting equipment that is not shown in Figures 25 or 26 that would be needed to complete the test beds. Temperature interlock circuits may be needed to shut down the heaters when the coolers shut down or become overheated. Computer controllers and data acquisition systems would be needed to control the heaters, the coolers, and the fluid motivators in order to maintain steady flow conditions. Insulation would be needed to prevent heat losses and to protect workers against hot surfaces. Ballistic shielding may also be needed to protect workers against structural failures and flying debris.

3.5 Ancillary Testing

Ancillary testing describes tests that do not concern direct measurements of fluid properties. Such tests are corrosion testing and endurance testing. Corrosion testing is performed by placing test coupons (stressed and unstressed) into the flow loops, and exposing the test coupons to hundreds of hours of exposure. Corrosion coupons may be used for the duration of a single experiment, or may be placed inside a test loop for a campaign involving many different loop conditions, as desired. Coupons are withdrawn from the loop at a later time and analyzed for changes in the samples which include cracking, pitting, corrosion layer build-up, and so forth. Corrosion testing is not a required part of the testing program, but it would be advantageous to install corrosion coupons during a test in order to increase the data collected from any one experiment. If corrosion coupons are installed, it is important to understand the pressure drop caused by the installed coupons, so that the pressure drop caused by the coupons is not confused with the pressure drop caused by the component.

Endurance testing is longer-term exposure of a component to the test conditions of interest. Longer-term exposure is defined as exposure of a component for up to hundreds of hours of steady operation. The goal of endurance testing is to determine whether changes occur in component function over longer time periods, and to understand those changes, so that component models can be adjusted and component designs optimized to minimize the effects of those changes at larger scales. After performing endurance testing, post-testing examination of the component should be performed (non-destructive or destructive) in order to relate any performance changes with physical changes in the component.

3.6 Facility/Equipment Needs

It is expected that process heat exchanger designs (e.g., gas-heated bayonet for H_2SO_4 decomposition, gas-heated high-temperature steam generator for HTE process), valves, internal insulation, heat transfer conduit designs, and most instrumentation will require testing at the pilot scale. Though it is anticipated that the designs recommended for the IHX and some heat exchangers the secondary helium loop may be relatively mature, such designs should be tested at the pilot scale in order to verify performance expectations of the models and the heat exchanger designs once a pilot-scale testing facility is established.

A pilot-scale component and heat exchanger testing laboratory would require at least two test stations: a component pressure/leak test station, and a heat exchanger testing station. From the previous sections on flow testing (Section 3.3) and heat exchanger testing (Section 3.4), it is apparent that flow testing can be performed using the same equipment as used for heat exchanger testing. The flow paths for the hot and cold sides of the heat exchanger test apparatus will use similar instrumentation and common equipment, and measurement of pressure drops and friction factors could be performed with either pathway. Flow measurements are made without heat transfer initially, and then can be repeated during the heat exchanger test to look for differences in the friction factors.

Though each station would be designed to operate independently, data collection and equipment controls could be managed using a single work station. A data acquisition system (e.g., Yokogawa MW100 Data Acquisition Unit) with compatible viewing software to collect and process the data from the experiments is needed, and laboratory-scale process controllers (e.g., Yokogawa CX2000) manage the dynamic pressurization testing in the pressure/leak testing station and control the back-pressure regulators or flow controllers in the flow/heat exchanger testing station. Control equipment would also be needed to regulate the heater interlocks in the flow/heat exchanger testing apparatus.

If flow or temperature data are needed on specific sections of the component, additional temperature, pressure, or flow sensors may be installed in the component itself. Additional sensors may increase pressure drop in a component, and comparisons will need to be made to an uninstrumented component in order to characterize the additional pressure drop caused by adding any new flow restrictions in the instrumented component. The standard procedures of data comparisons and measurement are also needed if the test component fails and is replaced during an experiment.

The power requirements of the pilot-scale test beds may be significantly larger than the benchtop test beds, especially if larger components must be tested in order for the test article to be easily scaleable to engineering scale. At minimum, pilot-scale testing could be performed using benchtop-scale closed and open flow paths as long as the test fluid conditions mimic the desired engineering-scale fluid conditions, and the power requirements would be no more than about 20 kW. On the other end of the scale, larger components and heat exchangers may require testing at sizes up to 1 MW, and a much larger power source must be used to supply energy to the test loops. In order to reduce electrical power needs, indirect fired heaters or furnaces may be used to heat gases to the desired temperatures, but a natural gas, propane, or diesel fuel supply would be needed, and the hot gases from the heater or furnace would need to be vented outside.

Larger coolers are needed to remove excess heat from the pilot-scale flow paths. The larger coolers may be water cooled or air cooled, but in either case, forced convection cooling will likely be needed, and accommodations for venting excess heat outside of the laboratory will need to be incorporated into the facility.

The laboratory equipment used for the pilot-scale test beds and the pilot-scale heat exchangers may be obtained from commercial vendors, though some equipment will require custom manufacturing (i.e., electrically driven helium heaters, forced-air coolers, etc.).

The laboratory space is less generic due to the larger power requirements and larger equipment sizes that may be tested. Physically, a high-bay facility may be needed to perform the component testing because of taller components. Some heat exchangers are potentially quite massive depending upon the design, and a crane may be needed to move components. Room to maneuver a forklift may also be needed if equipment is moved on palettes. Such laboratory spaces exist at most national laboratories and some universities, though availability may be a concern at any one location due to competition from other projects.

Pressurized helium and other gases must be available for filling and maintaining test loop pressure. Such gases may be supplied from standard laboratory cylinders if the closed loops are small and the leak rates of the loops are low, or they may be supplied from a larger supply tank if greater helium inventories are needed. Larger supply tanks will likely be placed outside of the facility, and a concrete pad may be needed to hold the large pressurized helium tank. Air and water, being relatively cheap, can continue to be used in a once-through fashion, and is available at little relative cost in most locations.

Aside from the prototype heat exchangers themselves, the laboratory equipment can be obtained from commercial vendors. Some customization of instrumentation may be required in order to install pressure transducers that can measure pressure at high-temperature.

3.7 Facility/Equipment Needs

Pressure testing is required, and leak testing may be performed to quantify the leakage rates if a leak or leaks are detected during the pressure test. Leak testing is performed at pressure and at room temperature if the capabilities to perform a controlled temperature pressure/leak test are not available. Dynamic pressure testing is not recommended at the pilot-scale because of the larger equipment cost and the larger stored energy in a pilot-scale component at pressure. Flow testing is required in order to measure component pressure drops and friction factors, and is performed at the actual conditions of interest using either a closed helium loop or an open flow path if the open flow path mimics the actual conditions of interest for the NGNP. Heat exchanger testing is required for heat exchangers and is performed at the actual conditions of interest using two closed helium loops or one closed loop and one open loop if the open loop conditions match the actual conditions of interest to the NGNP. Materials testing using corrosion coupons and stressed samples is desired but not required. The components needed to establish a pilot-scale laboratory are a mix of off-the-shelf and custom components. The need for a high-bay facility and larger power requirements restrict placement of a pilot-scale laboratory at a more limited set of national laboratories and universities.

4. ENGINEERING-SCALE TESTING REQUIREMENTS AND FACILITY NEEDS

Tests at the engineering scale are performed to verify component designs and to prove component performance at the largest scale of interest to the NGNP Project. The data collected must be sufficient to allow for advancement of component options to **NGNP Project TRL 8** or **9**. If possible, only components that have been verified at TRL 6 or higher will be tested at the engineering scale. Tests are performed under the actual conditions of interest (i.e., temperature, pressure, fluid composition). Data generated from tests are used to verify and adjust computational models and to prove component designs and materials. Test durations are for hundreds to thousands of hours, and equipment change-outs between different designs are infrequent. Corrosion data are collected from samples placed in flow loops or from non-destructive examination of test articles.

Engineering-scale testing is uniquely tied to the NGNP and the NGNP Component Test Facility [33, 43], and is inseparable from these facilities. The NGNP and the NGNP Component Test Facility define the engineering-scale, and all engineering-scale testing will be performed at either the NGNP or the NGNP Component Test Facility (CTF). The NGNP and the NGNP CTF are expected to be placed at the Idaho National Laboratory.

4.1 Pressure/Leak Testing

In order to support process safety, all test articles must be pressure tested and may require leak testing. Pressure testing is performed at room temperature and can be done hydrostatically or pneumatically. The article being tested must be placed behind a barricade or positioned in such a way that a structural failure of the pressurized component will not place the experimenter in harm's way. Heated pressure and leak testing can be performed, but only if the component is small enough to fit within a furnace, kiln, or other controlled temperature environment. If a component is large, performing a leak test at a controlled temperature will be difficult, and the results from prior benchtop and pilot-scale pressure and leak tests may be compared to the room temperature engineering-scale tests in order to draw inferences about higher-temperature behavior of the engineering-scale component. The formulas displayed in Section 2.1 for calculating leak rates are also valid at the engineering-scale.

4.2 Cyclic Pressure Testing

Though an engineering-scale component will undergo cyclic pressurization events, controlled cyclic pressure testing is not performed at the engineering scale. Cyclic pressurization tests performed at the benchtop scale and operational tests performed at the pilot-scale are sufficient to identify durable component designs and to define a window in which to operate relatively more mature engineering-scale components. Also, cyclic pressure testing deliberately stresses and fatigues the component, which may lead to component failure. Upon failure, an engineering-scale component may release much larger amounts of stored energy and fluid materials than would a smaller-scale component, and the probability of occurrence of such events must be minimized in order to increase process safety and to reduce material costs.

4.3 Flow Testing

Flow testing will be performed in order to measure component pressure drops and friction factors. Data collected from flow testing will be used to adjust process models and component designs. Flow testing of components is performed in-place after installation in the NGNP or the NGNP CTF, and data are collected during operational testing. The methodology for performing flow testing at the engineering-scale is similar to that used at the benchtop and pilot-scale, and it is assumed that the component will be instrumented with temperature, pressure, and flow sensors at the inlet and outlet of all flow channels in order to collect the needed information to determine pressure drops and friction factors. The duration and particular test conditions will be determined at a later time according to the needs of the NGNP Project. The design of the flow loops is still under consideration, and will advance as the designs of the overall NGNP and NGNP CTF facilities advance from the pre-conceptual to the conceptual, preliminary, and final design stages.

4.4 Heat Exchanger Testing

Heat exchanger testing will be performed in order to measure heat exchanger power and overall heat transfer coefficients. Data collected from heat exchanger testing will be used to adjust process models and component designs. Heat exchanger testing is performed in-place after installation in the NGNP or the NGNP CTF, and data are collected during operational testing. The methodology for performing heat exchanger testing at the engineering-scale is similar to that used at the benchtop and pilot-scale, and it is assumed that all heat exchangers will be well-instrumented in order to collect temperature, pressure, and flow data. The duration and particular test conditions will be determined at a later time according to the needs of the NGNP Project. The design of the heat exchanger test loops is still under consideration, and will advance as the designs of the overall NGNP and NGNP CTF facilities advance from the pre-conceptual to the conceptual, preliminary, and final design stages.

4.5 Ancillary testing

Corrosion coupons will be placed in flow loops in order to collect data on the effects of process fluids on the structural materials of interest. Corrosion coupons will be placed into the loop at the start of initial operations and will be inserted or removed at times when test equipment is being installed or removed, or when the flow and heat exchanger loops are shutdown and undergoing servicing.

Test articles will be examined using non-destructive techniques during their useful lives, and may be destructively examined at the end of useful life in order to understand how components age during operations.

This corrosion and examination data will be used to relate test indicators to actual wear conditions so that the factors leading to equipment degradation and failure may be characterized, and the reliability of components may be better understood.

4.6 Facility/Equipment Needs

The engineering-scale tests will be performed using the NGNP or the NGNP Component Test Facility. The NGNP is in the conceptual design phase, and the NGNP CTF is the pre-conceptual design phase. The necessary equipment and facilities needed to perform component and heat exchanger testing in these facilities is undergoing extensive analysis by the NGNP Project and will be undergoing many changes as the NGNP and the NGNP CTF advance to final design. Therefore, the size, configuration, and other design details for performing engineering-scale tests are not discussed here. The NGNP and the NGNP CTF are expected to be placed at the Idaho National Laboratory.

4.7 Engineering-Scale Testing Summary

Pressure testing is required, and leak testing may be performed to quantify the leakage rates if a leak or leaks are detected during the pressure test. Leak testing is performed at pressure and at room temperature if the capabilities to perform a pressure/leak test at a controlled temperature are not available. Dynamic pressure testing is not performed at the engineering-scale. Flow testing is required in order to measure component pressure drops and friction factors, and is performed at the actual conditions of interest using loops or flow paths provided by the NGNP or the NGNP CTF. Heat exchanger testing is required for heat exchangers and is performed at the actual conditions of interest using loops or flow paths provided by the NGNP or the NGNP CTF. Materials testing using corrosion coupons and stressed samples is desired but not required. The NGNP and the NGNP CTF are undergoing a rigorous design process, and are targeted for placement at the Idaho National Laboratory.

5. DATA REQUIREMENTS

5.1 Quality Basis

The heat exchanger work will comply with the applicable requirements in 10 CFR 830, Subpart A, DOE Order 414.1C for nuclear facilities and activities, and the American Society of Mechanical Engineers (ASME) NQA-1-2000. In addition, this effort will comply with the Office of Nuclear Energy Quality Assurance Program Plan dated July 2006. These requirements provide the baseline for developing and implementing a System Interface Quality Assurance (QA) Plan. At a more immediate level, work funded by the NGNP Project will comply with the specific quality requirements prescribed in the NGNP Quality Assurance Plan (QAP) [22] and the NGNP Preliminary Project Management Plan [1]. Work funded by NHI should be carried out under the applicable quality assurance requirements at the individual laboratory, university, or corporation where the work is being performed.

5.2 Experimental Work

Regardless of where work is performed, it must be carried out safely. All work funded under the NGNP Project must be carried out using the tools prescribed by the Integrated Safety Management System (ISMS). Within national laboratories, this system is formalized into work procedures, while at corporations and universities, the set of tools may be different or go by different names, but the safety principles should be the same. If a laboratory is not covered by a comprehensive safety program such as ISMS, then a stand-alone safety plan must be provided to the System Interface technical director and approved by a peer-review process prior to beginning work.

Laboratory and experiment work, unless otherwise agreed upon between the principal investigator and the responsible NGNP Project technical director, will be carried out using controlled laboratory notebooks or logbooks. Controlled laboratory notebooks or logbooks are used for research and development work where it is important to have a dated sequential record of the work. The procedures for data entry into lab notebooks or logbooks shall conform to the institution's requirements where the laboratory notebook or logbook is maintained.

In cases where the data in the controlled laboratory notebook or logbook will be used to define intellectual property or develop information for a patent application, the data must include the following information:

- What was done
- When it was done
- Who did it and had an active part in the work
- Who knew about it.

Two independent witnesses are needed for information entered into the notebook, and the date of verification by the witnesses should be the same as the date of entry of the data, if possible. If an invention is conceived prior to its entry into the laboratory notebook or logbook, then the inventor shall state the date of conception upon initial entry. If continuous experimental work is not possible, entries shall be made in the laboratory notebook or logbook to explain why significant work is not possible, why there are gaps in the work, and the dates of events shall be recorded, signed, and dated by two independent witnesses. If the work is carried out in a collaborative fashion between laboratories, the holder of the laboratory notebook or logbook shall enter information into the notebook or logbook pertaining to meetings or phone conversations, and will record at minimum the date of the meeting or conversation, the list of participants, and the outline of topics discussed.

5.3 Modeling/Software Quality Assurance

Special consideration will be made to invoke appropriate software QA requirements to ensure that the quality of data is acceptable for subsequent work. Quality requirements during the R&D (benchtop or laboratory scale) phase generally allow great flexibility. Increased levels of rigor (a graded approach) will be implemented at the pilot-scale and engineering-scale as needed to ensure that design input can be validated. Decisions regarding the quality requirements for individual modeling or software development projects must be determined prior to beginning measurements, so that the appropriate steps can be carried out during the experimental work to comply with applicable quality requirements.

5.4 Milestone/Deliverable Acceptance Criteria

Deliverables are documents that provide proof that a milestone has been achieved. Under NHI, deliverables are uploaded into PICS where they are subjected to peer review by the appropriate technical director, the NHI System Integrator, and then the NHI Program Manager. Deliverables in this process may be accepted or rejected at any stage, and final acceptance of the deliverable is indicated by the approval of the NHI Program Manager in PICS.

Under the NGNP Project, deliverables are submitted to the applicable NGNP Project Technical director and to the appropriate NGNP director (R&D or Engineering) for examination and review. Deliverables may be accepted or rejected by the NGNP director at the discretion of the director or the NGNP higher project managers or directors. Accepted deliverables will be entered into the NGNP project record.

If a deliverable is rejected, it will be rejected with explanation, and it will be between the principal investigator and the NHI Technical director to craft a response and to remediate the situation, so that an acceptable deliverable for a given milestone might ultimately be provided.

5.5 Quality Assurance Plan

The NGNP Project QA Plan will establish quality policy and requirements, and assign major functional responsibilities for NGNP-funded experimental activities. The QA requirements apply to all organizations and positions that manage and perform activities within the NGNP Project scope. Personnel supporting NGNP Project activities shall also comply with the requirements of the NGNP Project QA Plan. Performing organizations (including DOE national laboratories, universities, industrial firms, and/or commercial companies) are required to comply with the QA requirements invoked in procurement documents.

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APPENDIX: NGNP Project Technical Readiness Levels

TRL 1	**Basic principles observed and reported.**
TRL 2	**Technology concept and/or application formulated.**
TRL 3	**Analytical and experimental critical function and/or characteristic proof-of-concept.**
TRL 4	**Component/subsystem validation in laboratory environment.**
TRL 5	**System/subsystem/component validation in relevant environment.**
TRL 6	**System/subsystem model or prototyping demonstration in a relevant end-to-end environment.**
TRL 7	**System prototyping demonstration in an operational environment.**
TRL 8	**Actual system completed and "mission qualified" through test and demonstration in an operational environment.**
TRL 9	**Actual system "mission proven" through successful mission operations.**

Technical readiness levels adapted from NASA system of technology readiness levels. See J.C. Mankins, "Technology Readiness Levels," white paper, Office of Space Access and Technology, National Aeronautics and Space Administration (NASA), April 6, 1995.

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