INL/EXT-17-43269

High-Pressure, High-Temperature Thermal Hydraulic Test Facility for Nuclear-Renewable Hybrid Energy System Studies; Facility Design Description and Status Report

James E. O'Brien, Su-Jong Yoon, Piyush Sabharwall, Shannon Bragg-Sitton

September 2017

Idaho National Laboratory

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-17-43269

High-Pressure, High-Temperature Thermal Hydraulic Test Facility for Nuclear-Renewable Hybrid Energy System Studies; Facility Design Description and Status Report

James E. O'Brien, Su-Jong Yoon, Piyush Sabharwall, Shannon Bragg-Sitton

September 2017

Idaho National Laboratory
Nuclear Science and Technology
Idaho Falls, Idaho 83415

http://www.inl.gov

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

Nuclear Science and Technology

High-Pressure, High-Temperature Thermal Hydraulic Test Facility for Nuclear-Renewable Hybrid Energy System Studies; Facility Design Description and Status Report

INL/EXT-17-43269
Revision 0

September 2017

Approved by:

James E. O'Brien — 9/14/17
Author — Date

Piyush Sabharwall — 9/14/17
Reviewer — Date

Shannon Bragg-Sitton — 9/14/2017
Approver — Date

EXECUTIVE SUMMARY

A high-pressure, high-temperature water flow loop has been designed at Idaho National Laboratory (INL) for deployment in the INL Dynamic Energy Transport and Integration Laboratory (DETAIL) within the Energy Systems Laboratory (ESL) D100 northwest high bay. The high-pressure water loop will operate at Pressurized Water Reactor (PWR) conditions. This loop is the first of three thermally coupled flow loops that will comprise the Advanced Reactor Technology Integral System Test (ARTIST) facility. The ARTIST facility will ultimately include a high-temperature helium loop and a liquid salt loop, in addition to the PWR loop. It will support experimental research on nuclear-renewable hybrid energy systems as well as advanced reactor technology topics. Within DETAIL, the water flow loop will also serve as a thermal energy source, emulating a reactor system. The loop will be thermally integrated with co-located energy systems including a thermal energy transport loop, thermal energy storage system, and a 25 kW high-temperature electrolysis system for hydrogen production. DETAIL will include additional energy systems such as an integrated microgrid and renewable energy systems including solar photovoltaics. The electrically heated flow loop will be dynamically controlled to simulate nuclear fuel behavior under normal and off-normal operating conditions. DETAIL will be designed for characterization of complex system dynamics. The various components will be interfaced with Digital Real-Time Simulators for supervisory control and dynamic simulation of complete systems.

Construction of the water loop facility has been subdivided into two Phases. Phase 1 includes installation of general-purpose laboratory infrastructure/support systems necessary to perform any significant hardware testing in the High Bay. Scheduled to be completed by the end of FY17, Phase 1 covers installation of cable trays and supports, electrical conduit, a DI water system, drain lift station and the concrete pad for a chiller that will be located outside of the laboratory. Phase 2 includes the detailed design and final assembly of the flow loop, supporting structures and personnel platforms, the chiller and associated piping. As of September, 2017, the final detailed design of the flow loop is complete. Funding for Phase 2 procurement, assembly, system operability checkout, shakedown testing and initial operation of the flow loop is requested for FY18.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Nuclear Hybrid Energy Program Nuclear System Design and Analysis Division for supporting the development of the high-pressure, high-temperature thermal hydraulic test facility.

CONTENTS

FIGURES

TABLES

ACRONYMS

INL	Idaho National Laboratory
ESL	Energy Systems Laboratory
ARTIST	Advanced Reactor Technology Integral System Test
DETAIL	Dynamic Energy Transport and Integration Laboratory
P&ID	Piping and Instrumentation Diagram
ASME	American Society of Mechanical Engineers
LI	Laboratory Instruction
PPE	Personal Protective Equipment
BEA	Battelle Energy Alliance
HPW	High pressure water
CAD	Computer Aided Design

1. INTRODUCTION

A high-pressure, high-temperature water flow loop has been designed at Idaho National Laboratory (INL) for deployment in the INL Dynamic Energy Transport and Integration Laboratory (DETAIL) within the Energy Systems Laboratory (ESL) D100 northwest high bay. The water loop will operate at Pressurized Water Reactor (PWR) conditions. This loop is the first of three thermally coupled flow loops that will comprise the Advanced Reactor Technology Integral System Test (ARTIST) facility. The ARTIST facility will ultimately include a high-temperature helium loop and a liquid salt loop, in addition to the PWR loop. More detailed descriptions of ARTIST and its research objectives are provided in references [1 - 4]. It will support experimental research on nuclear-renewable hybrid energy systems as well as advanced reactor technology topics. Within DETAIL, the water flow loop will serve as a thermal energy source, emulating a reactor system. The loop will be thermally integrated with co-located energy systems including a thermal energy transport loop, thermal energy storage system, and a 25 kW high-temperature electrolysis system for hydrogen production. DETAIL will include additional energy systems such as an integrated microgrid and renewable energy systems including solar photovoltaics. The electrically heated flow loop will be dynamically controlled to simulate nuclear fuel behavior under normal and off-normal operating conditions. DETAIL will be designed for characterization of complex system dynamics. The various components will be interfaced with Digital Real-Time Simulators for supervisory control and dynamic simulation of complete systems.

2. FACILITY DESCRIPTION

2.1 Flow Circuits

The overall piping and instrumentation diagram (P&ID) of the PWR flow loop is provided in Fig. 1. There are two primary modes of operation for the flow loop: forced circulation and natural circulation. The primary flow loop for forced circulation is highlighted in green in Fig. 2. Nominal temperatures and pressures, and the flow rate are also indicated on Fig. 2 for the forced circulation base case. Valve positions for forced and natural circulation are listed in Table 2-1. The flow loop includes a high-temperature section and a low-temperature section, with heat recuperation. This design was chosen for several reasons:

1) Less intense specification requirements for circulation pump, main flow meter, valves, piping, and pipe fittings in low-temperature section.
2) The recuperator will be an advanced-technology printed circuit heat exchanger (PCHE), allowing for performance evaluation of these heat exchangers under prototypical PWR conditions.
3) This design enables support of natural circulation testing with applicability to advanced reactor operations and safety performance.
4) The recuperator and chiller enable rapid cool-down of the flow system when needed.
5) The high-power primary heater enables supply of significant high-temperature process heat to co-located hybrid systems.
6) The chiller heat rejection allows for much better loop temperature control and continuous loop operation at low temperature without a slow increase in temperature from pump heating.

Forced circulation flow is driven by the circulation pump shown in the lower right of the P&ID. Water at 50°C, 15 MPa flows up through 2-inch schedule 160 stainless steel piping past a pressure transducer (HPW-PT-01), a thermocouple (HPW-TC-01), a conductivity sensor (HPW-CN-01) and a turbine flow meter (HPW-FM-01). Base case nominal flow rate is 1130 kg/hr, which corresponds to 5 gal/min at 50°C and 15 MPa. At the first tee, for forced circulation, motor-operated valve HPW-MOV-01 is closed and the water flows through valve HPW-MOV-02 to the cold side of the recuperator where it is preheated to approximately 225°C by recuperative heat exchange with the water returning from the high-temperature section. Recuperator heat duty for the base case is approximately 285 kW. Downstream of the recuperator, water flows through a replaceable pipe section that will house conductivity and dissolved oxygen sensors, a flowmeter, and an orifice plate during natural circulation testing. The flow then enters the electrically powered auxiliary heater. For the base case, the auxiliary heater requirement will be 95 kW. However, this heater has been sized for higher flow rate cases and to supply high-temperature process heat to co-located experiments within the overall DETAIL infrastructure. Hence, it has been specified at a 175 kW rating. Water leaves the auxiliary heater at the maximum flow loop temperature of 325°C. Note that the saturation temperature for water at 15 MPa is 342°C, so the water remains in the liquid phase even at 325°C. After exiting the auxiliary heater, the flow enters the high-temperature test section. The specific design of this section will depend on the particular experimental campaign in progress such as corrosion studies, flow-induced vibration, natural circulation studies, etc. The test section will be interchangeable, with grayloc fittings for easy changeout. Downstream of the high-temperature test section, the primary water flows through valves HPW-MOV-07 and HPW-MOV-04 and enters the hot side of the recuperative heat exchanger. It exits the heat exchanger at approximately 120°C and then flows into the chiller heat exchanger where the water is cooled back down to 50°C. The air-cooled chiller that provides secondary coolant (glycol) for the chiller heat exchanger has been specified for a duty of up to 200 kW (60 ton). For the nominal baseline case, with no process heat delivery, the heat duty for the chiller will be about 95 kW. The heat duty specification of 200 kW will provide significant margin to support higher flow rate cases. The primary flow then enters the suction side of the circulation pump to complete the loop.

Table 2-1. Primary loop valve positions for forced and natural circulation modes.

Valve number	Forced circulation	Natural circulation
HPW-MOV-01	closed	open
HPW-MOV-02	open	closed
HPW-MOV-03	closed	closed
HPW-MOV-04	open	open
HPW-MOV-05	closed	closed
HPW-MOV-06	closed	open
HPW-MOV-07	open	closed
HPW-MOV-08	closed	open
HPW-MOV-09	open	closed
HPW-MOV-10	open	closed
HPW-MOV-11	open	open

For natural circulation studies, the primary forced circulation and secondary natural circulation flow loops are highlighted in Fig. 3. The primary loop is shown in green and the natural circulation secondary loop is shown in red. Nominal flow rates, temperatures and pressures are shown at various stations on the figure for the natural circulation base case. The primary and secondary loops in this case interact only thermally via the recuperator heat exchanger which in this case serves as a heat sink for the natural circulation loop.

The driving buoyancy forces for the natural circulation loop are generated by the high-temperature test section for heat addition and the recuperator for heat rejection. The high-temperature test section in this case will consist of an array of electrically heated simulated fuel rods arranged in a prototypical geometry with high heat flux capability. In the natural circulation loop, buoyancy-driven flow exits the top of the heated high-temperature test section at approximately 280°C, flows upward past valve HPW-MOV-06 and enters the top of the recuperator. The water is cooled to about 213°C in the recuperator. It then flows downward into the natural circulation instrumentation section that includes the dissolved oxygen and conductivity sensors as well as a low pressure-drop, low-flow flow meter. An orifice plate can also be inserted into this section to simulate a range of loss coefficients.

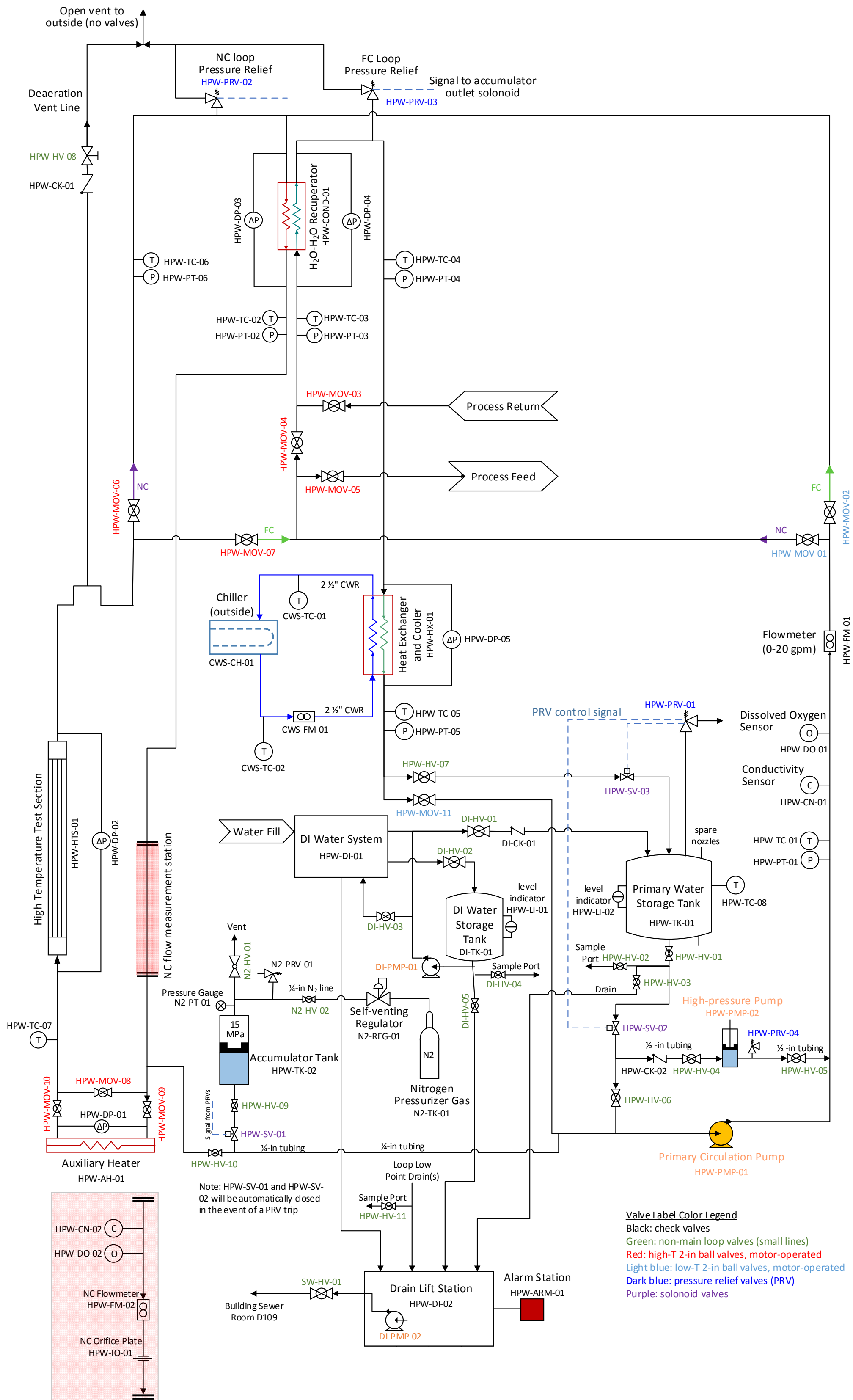

Figure 1. Piping and instrumentation diagram for the high-pressure thermal hydraulic test facility.

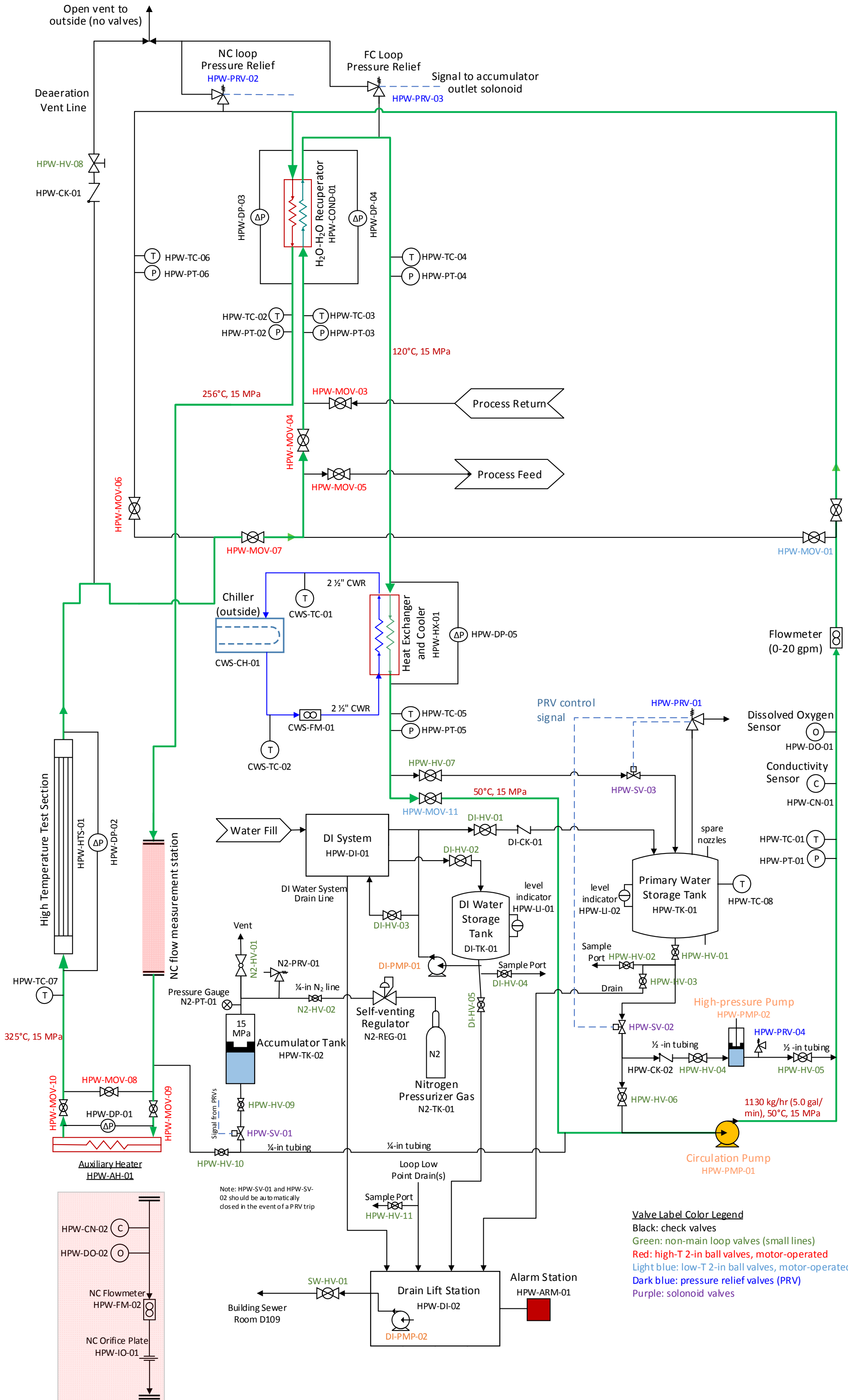

Figure 2. P&ID with the forced circulation loop highlighted.

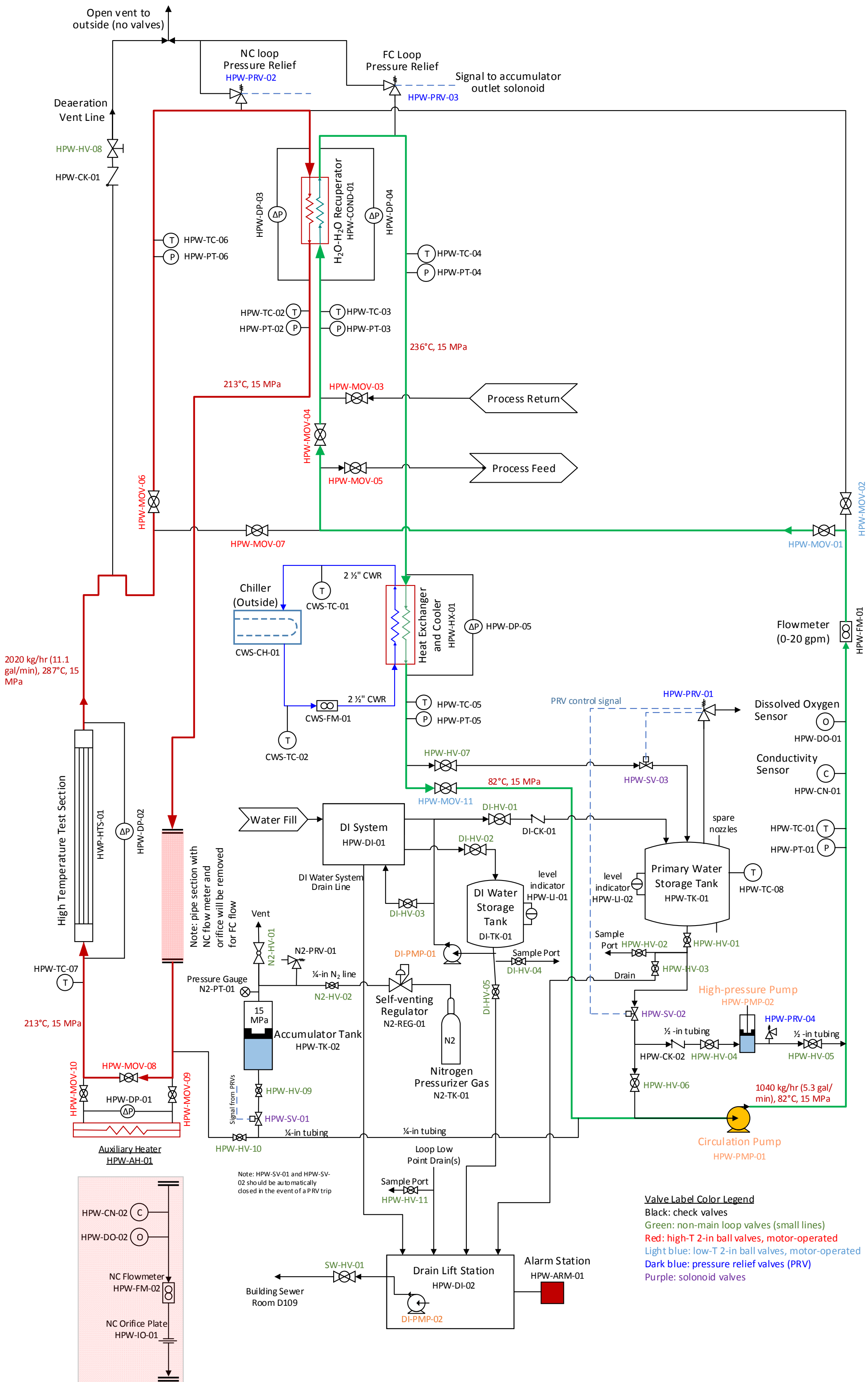

Figure 3. P&ID with the natural circulation loop highlighted.

2.2 Subsystems

Water Chemistry. The water flow loop includes a chemistry control system. The working fluid for the flow loop is deionized water with a supply conductivity value of 1 μS/cm or lower and effectively neutral pH. This water chemistry specification will be supplied and maintained using a reverse osmosis deionized water system. Instrumentation for the water loop will include in-line conductivity and dissolved oxygen sensors. Both of these sensors will be installed in the low-temperature part of the water loop.

Chiller. Primary system heat rejection is achieved using an air-cooled chiller unit to be located outside the laboratory. To prevent freezing, the working fluid on the secondary side of the chiller will be glycol. The chiller system will include coolant flow rate and temperature control.

Deaeration. For PWR systems, minimization of dissolved oxygen to <5 ppb is desired. Primary system deaeration will be achieved through heating of water flowing in the loop at ambient pressure. The solubility of air in water at atmospheric pressure drops by nearly two orders of magnitude from the freezing point to the boiling point. For deaeration, the water will be heated to a temperature just below the boiling point. Dissolved air will be released from the system at the deaeration vent which is located downstream of the heated section. Valve HPW-HV-08 will be opened during deaeration. The vented air is released to the outside vent.

Drain Lift Station. The high-bay laboratory D100 in ESL does not have floor drains in the vicinity of the experiment skid. Therefore, a drain lift station will be used to collect drain water in a sump and pump it to a floor drain located in the boiler room along the south wall of the high bay. The drain lines will be supported underneath cable trays.

Pressurization. The flow loop will be initially pressurized to operating pressures up to 15 MPa using the high-pressure pump, designated HPW-PMP-02 in the diagram. Pressure maintenance during system operation will be achieved using an accumulator tank. For loop pressurization, the accumulator tank pressure will be pre-set to an initial pressure of approximately 25% of the final loop operating pressure using nitrogen gas cylinder and self-venting regulator N2-REG-01. For full loop pressurization, the high-pressure pump HPW-PMP-02 will establish the full loop operating pressure with valve N2-HV-02 closed and valve HPW-HV-09 open such that the accumulator also achieves the full system operating pressure. At this point, the N2 regulator will also be set to the full loop operating pressure and valve N2-HV-02 will be opened. The loop can now be operated at full pressure. The use of the accumulator and the regulated nitrogen pressure will assure that the system pressure will stay constant even during heating and cooling of the water in the system. The accumulator also serves as a buffer that minimizes the effects of any pressure transients or water hammer. The regulator will be self-venting so that it will vent N_2 if the pressure in the system rises, thereby maintaining a constant system pressure. Note that during natural circulation testing, the primary flow loop and the natural circulation flow loop are independent and must both be pressurized. For these cases, valve HPW-HV-10 must be in the open position.

2.3 Components and Instrumentation

A comprehensive list and description of system components and instrumentation is provided in Table A1 of Appendix 1. Major components include: circulation pump, high-pressure pump, accumulator and nitrogen gas pressurizer, recuperative heat exchanger, chiller and chiller heat exchanger, natural circulation measurement station, high-temperature test section, auxiliary heater, DI water system, and drain lift station.

2.4 Safety Features

The primary safety concern related to this facility is high pressure. This issue is addressed in the design by assuring compliance with the ASME 31.3 Process Piping Code and through the use of AMSE-certified pressure relief valves (PRVs). There are two PRVs on the process piping (HPW-PRV-02 and HPW-PRV-03) that will be set at the system design pressure. In the natural circulation mode, there are two independent flow loops. Therefore, two PRVs are required in order to support the natural circulation mode of operation. When operating the flow loop at design conditions, release of fluid from a PRV may result in flashing of hot liquid water to steam. The PRV vent lines will be exhausted to the outside and will be sized to handle steam. The two PRVs on the process piping will be configured to generate a signal to close solenoid valve HPW-HV-01 in the event that one of these PRVs opens. This action will prevent the accumulator from maintaining system pressure in the event of a PRV release. Restoration of system pressure will require manual intervention after evaluation of the PRV release event has been completed. There is also a PRV (HPW-PRV-01) on the low-pressure primary water storage tank that will be set at a value consistent with its pressure rating . PRV (HPW-PRV-04) is located near the outlet of the high-pressure pump. It will protect the pump from over-pressurization in the event that valve HPW-HV-05 is inadvertently closed during pump operation. The high-pressure pump is only used for initial loop and accumulator pressurization.

Loop process heater controls will include an independent over-temperature shutoff feature.

Additional hazards are associated with hot surfaces. Hot surfaces will be thermally insulated to avoid possible skin contact to temperatures above 140°F.

A Laboratory Instruction (LI) document will be prepared to provide work control related to operation of this flow loop. This document will also identify all hazards associated with research activities and loop operation along with engineering and administrative controls, required personal protective equipment (PPE) and training.

3. ENGINEERING DESIGN CRITERIA

3.1 Code of Record

A. ASME B31.3 – 2014 – Process Piping, Fluid Service Category – Normal Fluid Service
B. System Fluid and Purity: Deionized water, 1.0 to 0.1 µS/cm (1.0 to 10 MegOhm/cm).
C. System Operating Pressure: 15 MPa (2176 psig)
D. System Design Pressure: 15.86 MPa (2300 psig)
E. System Design Flow Rate Range: 16.5 L/min to 56.8 L/min (4.4 gpm to 15 gpm)
F. System Operating Temperature Range: 50°C to 325°C (122°F to 617°F)
G. System Design Temperature: 371°C (700°F)
H. pH Range: 6.9 to 7.4

3.2 Quality Assurance (INL)

A. The fabrication, examination, installation, and testing inspections shall be performed by the BEA owner's inspector.
B. BEA quality assurance to perform fabrication examination in accordance with ASME B31.3-2014, chapter 6 “inspection, examination, and testing” requirements.
C. BEA shall examine all materials and components and workmanship per ASME B31.3-2014, section 341 to ensure conformance to the design.
D. Visual inspection per section 344.2 shall be used.
E. All materials, components, and workmanship of subcontractor are subject to inspection by the BEA 01 in accordance with ASME B31.3-2014, section 340.

3.3 Design Basis

A. The equipment and components within this process piping system design have been certified for use based on the ASME B31.3-2014 -- process piping code of record for listed or unlisted materials/components.

B. In the event the subcontractor selects another supplier for the equipment or components they must meet the following criteria:

1. All such equipment and components must be “listed” within ASME B31.3-2014 - process piping, fluid service category “normal fluid service.” “Unlisted" equipment or components must be proven through engineering analysis that the equipment or component meets the temperature, pressure, and fluid compatibility of the process.
2. Any fit, form, or function related design changes resulting from the selection of a supplier different from that supplier used for the bases of design shall be made by the subcontractor at their own cost and responsibility.
3. Red-lined drawings provided by the subcontractor shall include these design changes.
4. The subcontractor must ensure dimensional requirements, electrical requirements, functionality, performance and all qualifications of said supplier to meet the design requirements set forth in these specifications and drawings.
5. See component/equipment matrix on drawings for a complete list of these items.

3.4 Products

A. All piping materials used for ASME B31.3-2014 services shall adhere to the requirements listed in ASME 831.3-2014, chapter 3 “materials.”

B. All components used for ASME B31.3-2014 services shall be listed in table 326.1 "component standards" of this code. Any unlisted components shall comply with ASME b31.3-2014, section 302.2.3 “Unlisted Components.” See component/equipment matrix on drawings for adherence to these requirements.

4. INTERFACES TO CO-LOCATED SYSTEMS AND DETAIL

The high-temperature high-pressure flow loop can serve as a thermal energy source for co-located systems in a hybrid energy system configuration. The “Process Feed” and “Process Return” lines indicated in Fig. 1 provide the piping connections needed for this purpose. In the DETAIL concept, hot water from the thermal hydraulic loop will flow into a heat exchanger, delivering high-temperature process heat to an intermediate heat transfer fluid such as DowTherm. This intermediate fluid will flow through a thermal network to deliver process heat to co-located systems such as the 25 kW high-temperature electrolysis demonstration facility and a thermal energy storage unit.

In addition to the thermal energy interface, the water loop instrumentation, data acquisition, and control systems will be interfaced to one or more digital real-time simulators located in the laboratory. This virtual interface will support dynamic studies of dynamic system behavior, impacts on electrical grids, and related topics. DETAIL will include additional energy systems such as an integrated microgrid and renewable energy systems including solar photovoltaics. The electrically heated hot water flow loop will be dynamically controlled to simulate nuclear fuel behavior under normal and off-normal operating conditions. DETAIL will be designed for characterization of complex system dynamics. The various components will be interfaced with digital real-time simulators for supervisory control and dynamic simulation of complete systems.

5. ENGINEERING DRAWINGS

A complete set of engineering drawings of the hot water flow facility has been released. The drawings are based on a full 3D CAD model that was developed for the loop design. A few representative drawing cuts are provided here to provide a sense of the scale and layout of the facility within ESL D100. A plan view is presented in Fig. 4. The chiller is shown in the top of this view, located outside on the north side of the building. Coolant piping and the deaeration vent pipes are shown passing through the north wall. The flow loop is positioned on a skid, shown in three sections on the drawing. The DI water system is visible on the north (upward facing on the plan view) side of the skid. Cable trays for electrical conduit and industrial and drain lines are shown in the bottom of the drawing.

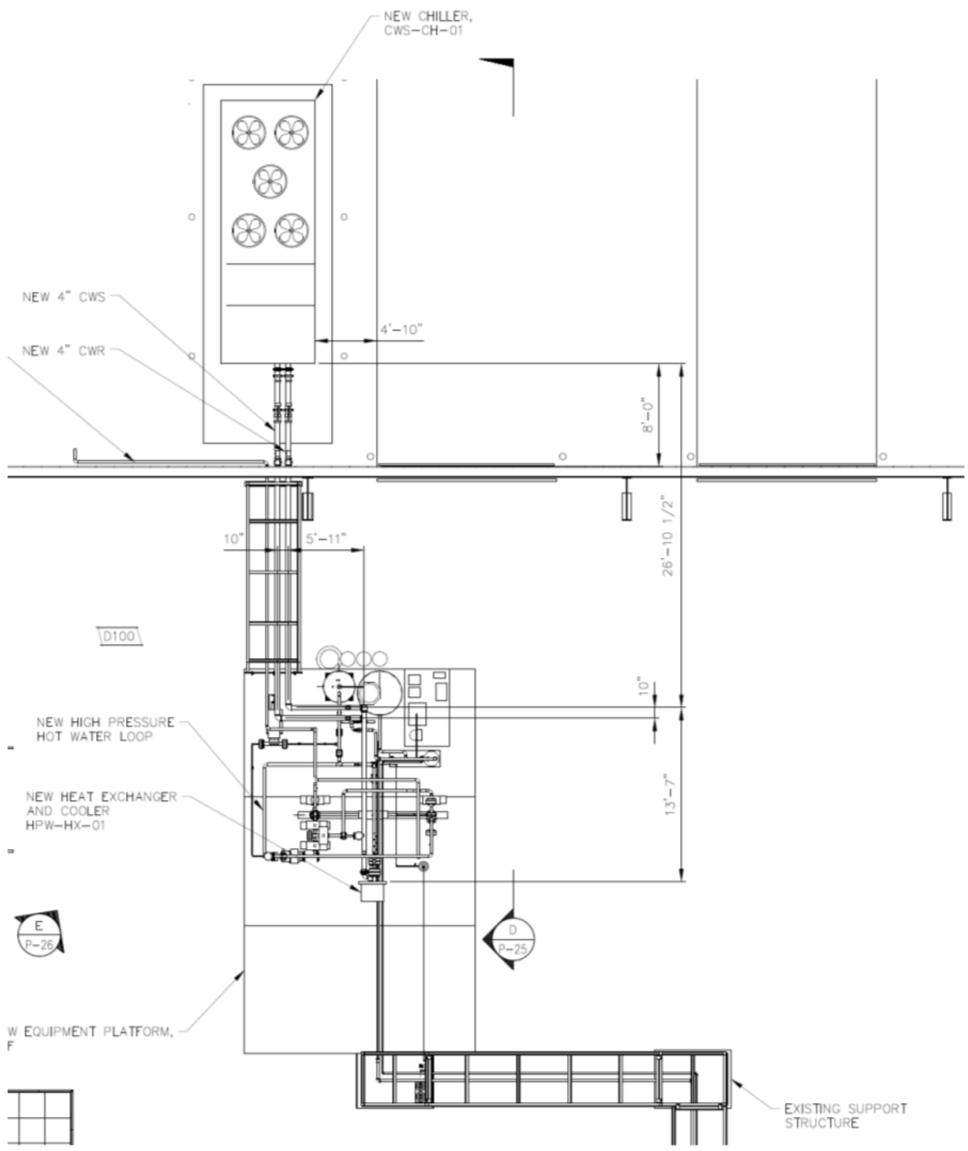

Figure 4. Plan view of flow loop and supporting systems.

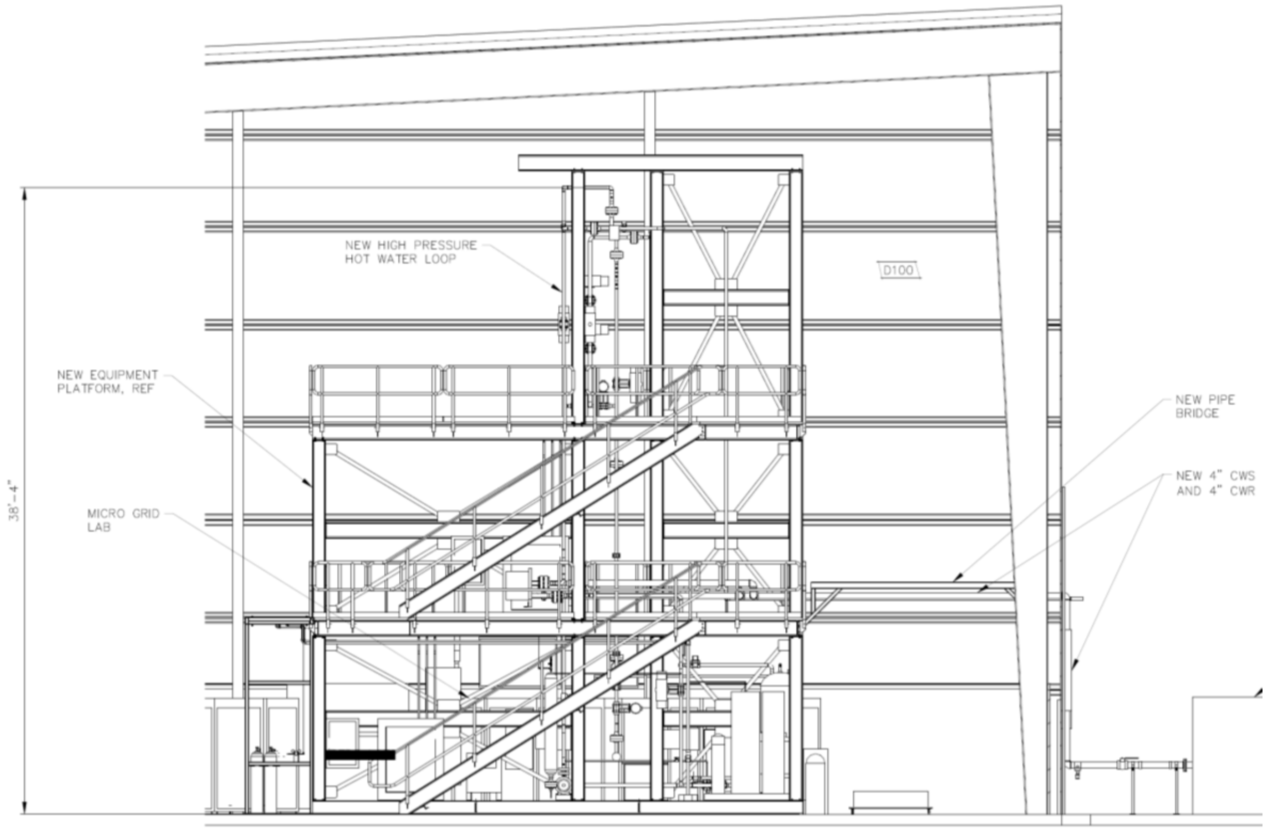

Figure 5. Elevation view of flow loop and supporting systems.

Construction of the water loop facility has been subdivided into two Phases. Phase 1 includes installation of general-purpose laboratory infrastructure/support systems necessary to perform any significant hardware testing in the High Bay. Scheduled to be completed by the end of FY17, Phase 1 covers installation of cable trays and supports, electrical conduit, a DI water system, drain lift station and the concrete pad for a chiller that will be located outside of the laboratory. The PWR loop is designed under Phase 2.

An elevation view of the flow loop and supporting systems is provided in Fig. 5. The slanted roof of the high bay ESL D100 laboratory is visible in the top of the figure. Note that the top of the flow loop is about 38 ft. above the floor. The framework surrounding the flow loop provides structural support for the piping and components plus personnel access to the valves and components. There are three levels including the skid.

An isometric view of the flow loop and supporting systems is provided in Fig. 6. In this view, the DI water system is in the lower left. Details of the support structure and personnel platforms can be seen. The mechanical integrity of the structure and platforms has been verified through appropriate stress analysis.

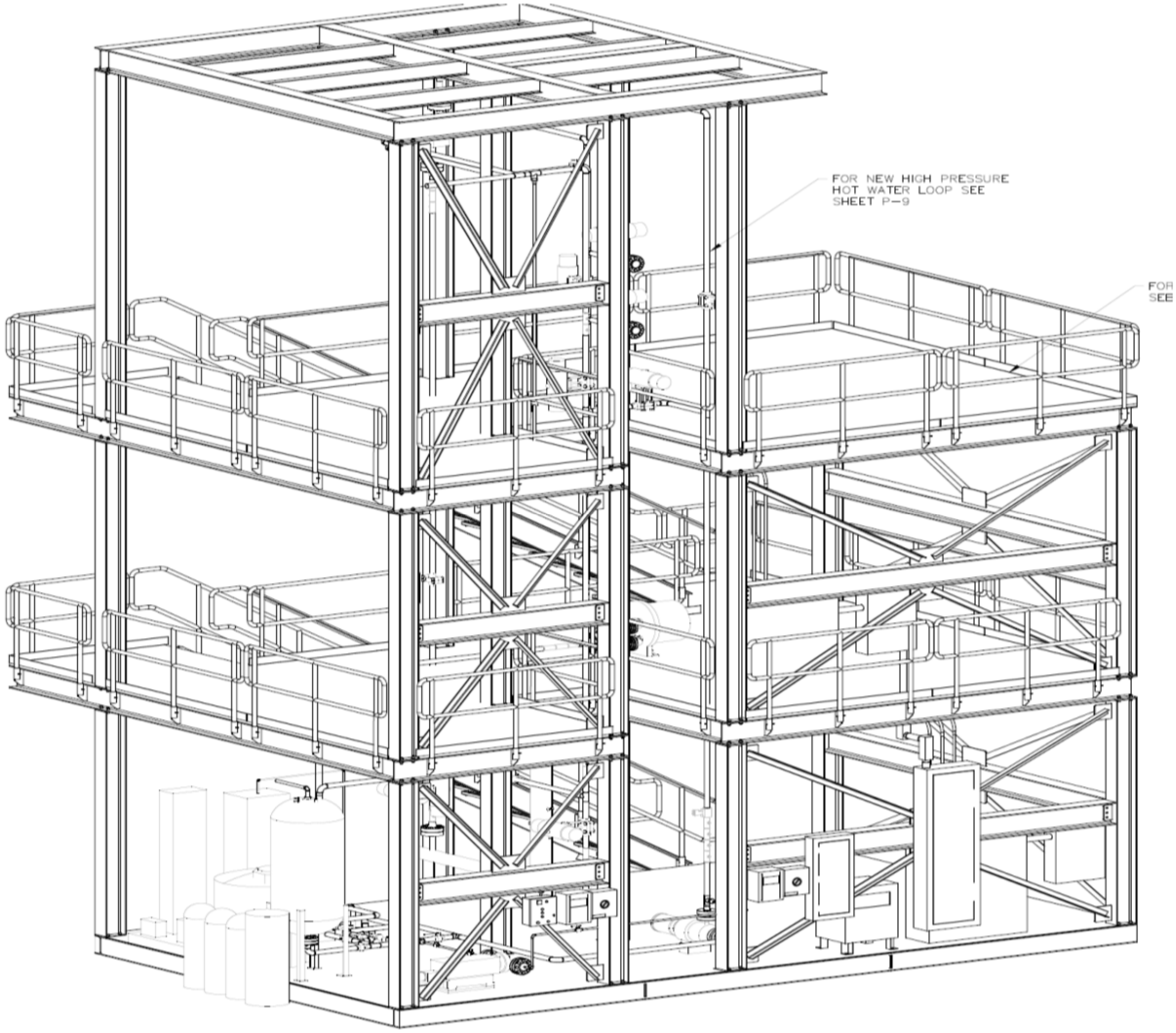

Figure 6. Isometric view of flow loop and supporting systems.

An isometric view of the flow loop and loop components without the surrounding structures and subsystems is shown in Fig. 7. The recuperator heat exchanger (HPW-HX-02) is shown near the top left of the figure. It is a compact PCHE design. In the forced circulation mode of operation, it serves as a recuperator. In the natural circulation mode, it provides heat rejection for buoyancy-driven flow. Its elevated location was required to support the natural circulation mode of operation. All eleven primary-loop motor-operated valves are visible in the drawing. The chiller heat exchanger (HPW-HX-01) located at mid-elevation is a helical coil design. Other large components visible in Fig. 7 include the auxiliary heater (HPW-AH-01), the accumulator (N2-TK-02), the high-pressure pump (HPW-PMP-02), plus the DI water system. Several pipe junctions are visible in the figure. Most of these junctions use class-2500 flanges. However, the high-temperature test section and the natural circulation measurement station use grayloc fittings for easier removal and replacement of those sections.

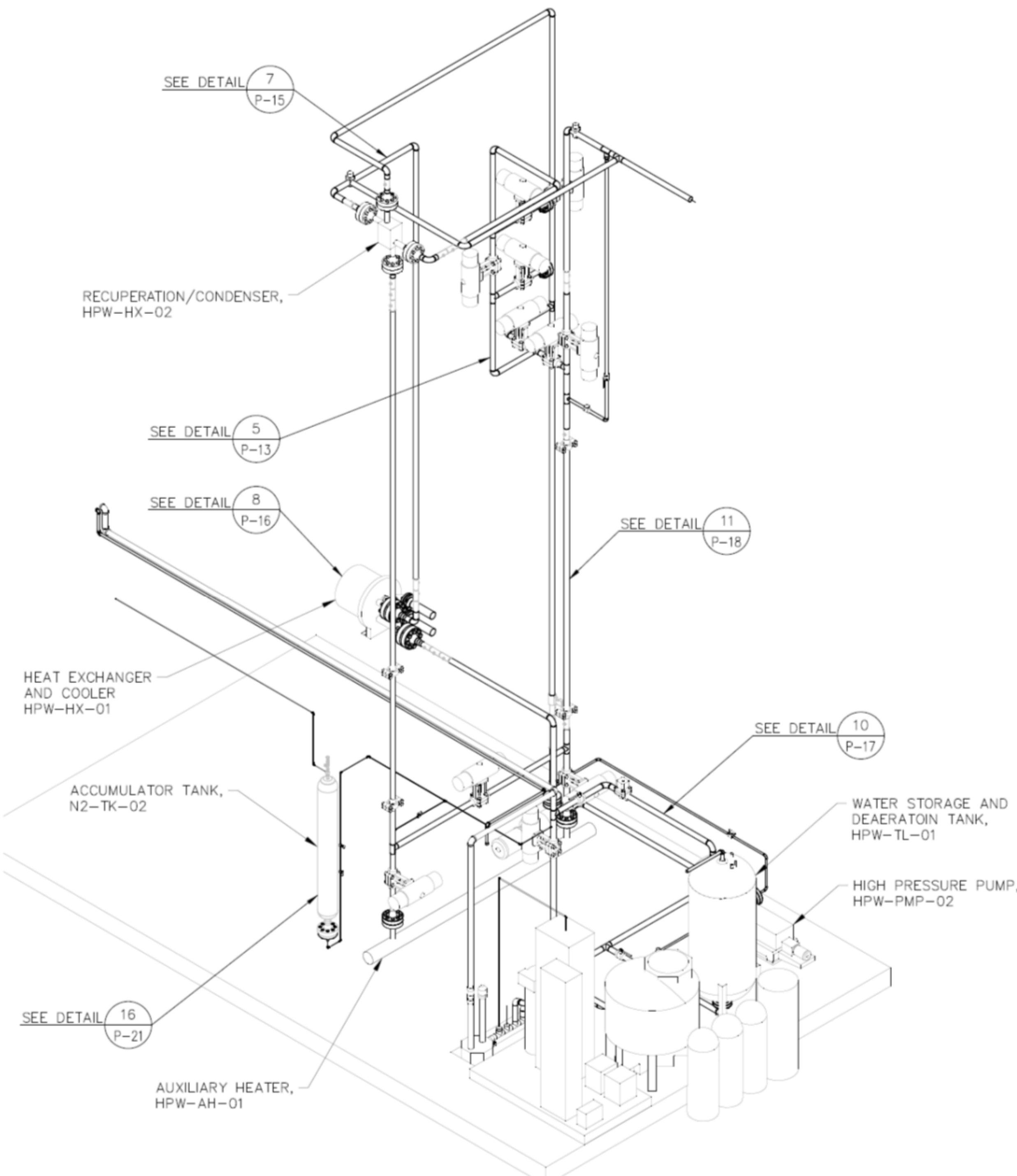

Figure 7. Isometric view of flow loop without support structure.

A second isometric view of the flow loop and loop components without the surrounding structures is presented in Fig. 8. This view is rotated 180 degrees from the view of Fig. 7. This figure provides a better view of the loop circulation pump (HPW-PMP-01) and the auxiliary heater (HPW-AH-01).

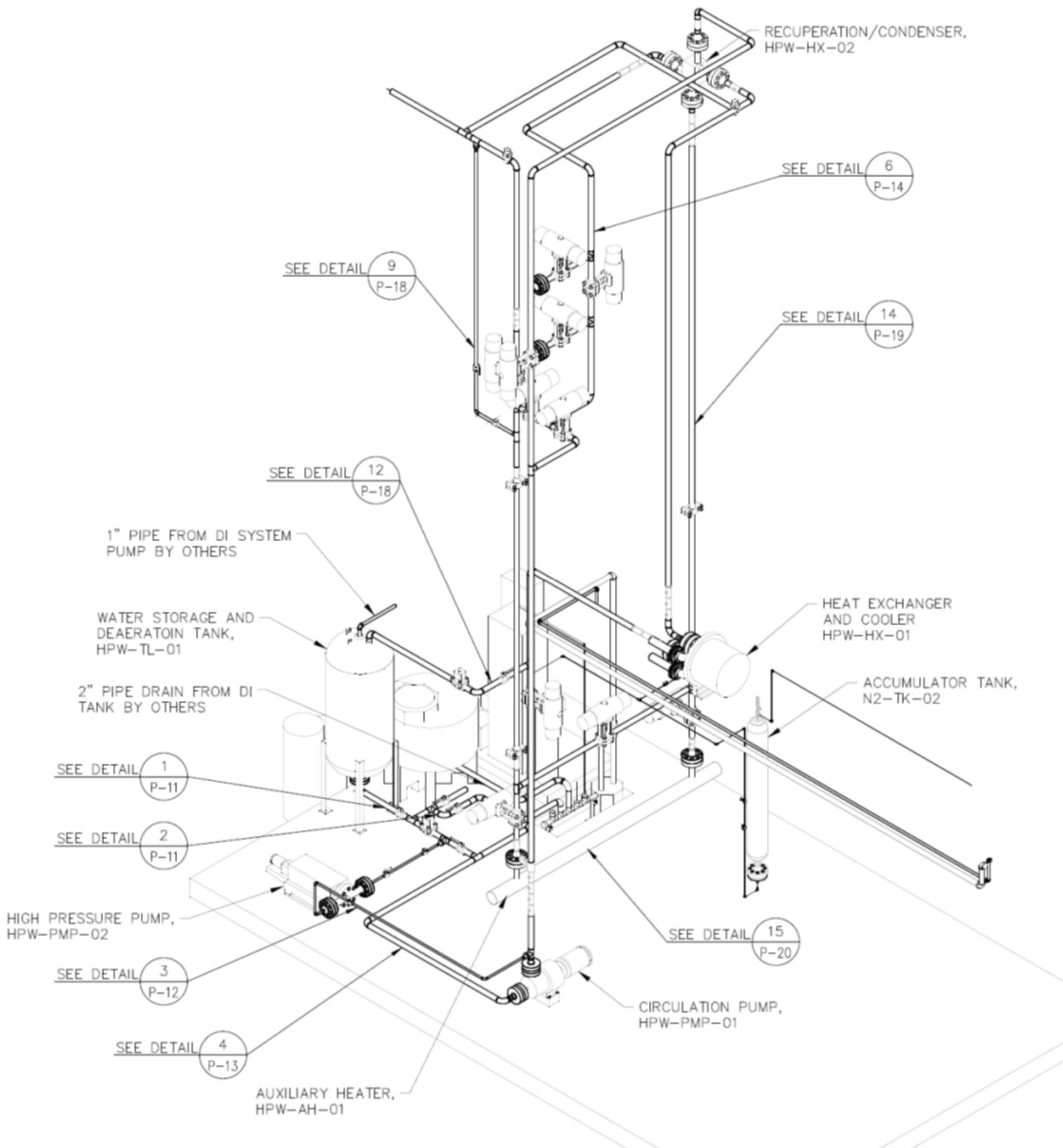

Figure 8. Rotated isometric view of flow loop without support structure.

6. SHAKEDOWN TEST PLAN

All test activities will be performed in accordance with appropriate work control, as specified in the Laboratory Instruction that will be prepared for this project. After delivery of the flow loop to the ESL D100 laboratory, shakedown testing will be performed. Activities to be completed during shakedown testing are listed below:

1. Checkout of all system instrumentation and data acquisition system.
2. Fill flow system with DI water; pressurize to 100 psig and perform leak checks.
3. Verify performance of motor-operated valves with computer controls.

4. Initiate low-pressure forced circulation flow through the loop using the primary circulation pump; verify flow measurements over a range of pump speeds (controlled by variable frequency drive).
5. Verify performance of auxiliary heater at low pressure; perform energy balances to verify power settings versus mass flow rate and temperature rise.
6. Verify performance of chiller and chiller heat exchanger; perform energy balances on both primary and chiller loops.
7. Verify performance of recuperator; perform energy balances.
8. Verify performance of drain lift station.
9. Complete a deaeration procedure and validate with visual observations and dissolved oxygen measurements.
10. Pressurize the system following the steps outlined in the description of the pressurization system. This will be done in stages at increasing pressures until the design pressure is achieved.
11. Operate the system at full pressure and design flow rates and heating values to ensure full operability.

7. PROJECT STATUS AND PATH FORWARD

Phase 1, which covers installation of general-purpose laboratory infrastructure/support systems, is currently under way and will be completed by the end of FY17. Phase 2 includes the detailed design and final assembly of the PWR flow loop, supporting structures and personnel platforms, the chiller and associated piping. A final design review was held on August 29. Review comments were formally submitted into the INL document review database. These comments have all been addressed and the final design package will be delivered by the end of September. Funding for Phase 2 procurement, assembly, system operability checkout, shakedown testing and initial operation of the flow loop is requested for FY18.

8. REFERENCES

1. O’Brien, J. E., Sabharwall, P., Yoon, S., and Housley, G. K., “Strategic Need for a Multi-Purpose Thermal Hydraulic Loop for Support of Advanced Reactor Technologies,” INL/EXT-14-33300.
2. Sabharwall, P., O’Brien, J. E., Yoon, S., and Sun, X., “Experimental Facility for Development of High-Temperature Reactor Technology: Instrumentation Needs and Challenges,” *European Physical Journal of Nuclear Science and Technology*, Vol. 1, No. 14, Dec., 2015.
3. O’Brien, J. E., Sabharwall, P., and Yoon, S., “A Multi-Purpose Thermal Hydraulic Test Facility For Support of Advanced Reactor Technologies,” ANS 2014 Winter Meeting and Nuclear Technology Expo, paper# 11705, Anaheim, CA, Nov. 9-13, 2014.
4. O’Brien, J. E., Sabharwall, P., and Yoon, S., “Development of a Multi-Loop Flow and Heat Transfer Facility for Advanced Nuclear Reactor Thermal Hydraulic and Hybrid Energy System Studies,” 2014 ASME International Mechanical Engineering Congress and Exposition, paper # IMECE2014-39057, Montreal, Nov. 14-20, 2014.

APPENDIX A. COMPONENT AND INSTRUMENTATION DETAILS

Table A-1. Component and Instrumentation Descriptions and Specifications.

Component	#Req'd	Purpose	Specification
Nitrogen Gas Cylinder	1	Pressure maintenance for water loop; connected to the gas side of the accumulator	6K cylinder (6000 psi), CGA 677 connection (this is not part of the loop, it will be ordered separately from our industrial gas supplier at the time of system qualification)
Self-venting regulator for N_2 gas cylinder	1	Maintain pressure at regulator set point, with self-venting to compensate for pressure increase in flow loop due to heating, etc.	CGA 677 connection, self-venting; inlet pressure 6000 psi, outlet pressure 0-2300 psi; example is Swagelok KHR Series
Accumulator	1	Maintain pressure in water loop; dampen pressure fluctuations	15 MPa, nominal; it should be rated for at least 3000 psi; stainless steel, nominal liquid capacity ~20 gal; gas capacity ~4700 in^3; piston accumulator Model PX2031008B10GXF-R1 from Accumulators, Inc. is an example.
High-pressure pump	1	Establish initial pressure in flow loop, while compressing the gas in the accumulator	Compression rating to 3000 psi, low flow rate; Pulsafeeder Pulsa Series 7660 with 0.56-inch piston area is an example
Water Circulation Pump	1	Provide water circulation flow through the loop	Operating conditions: 15 MPa, 50°C; nominal flow rate 4.4 gpm, maximum flow rate 15 gpm; loop pressure drop 5 – 50 psi, depending on flow rate (this needs to be estimated more accurately with all components and piping taken into account); wetted parts stainless steel; 480 V, 3-phase motor; We have a quote from Teikoku for a magnetic drive pump, Model Model GB-1.5K-22S; this model provides 37.2 m dynamic head at 17.6 gpm; cost is $45.5k; also have a quote from Klaus Union for a Mag-drive pump that provides 26 m head at 20 gpm; cost is $19.7k
Variable frequency drive	1	Pump speed control	Allow for smooth variation in pump speed; 480 V, 3-phase; will probably be purchased as a system with the water circulation pump; must be able to communicate with our DAS
H_2O-H_2O Recuperator	1	Water-to-water recuperative heat exchanger, allowing water pump and flow meter to operate at low Temp.	Operating pressure 15 MPa, heat duty: 250 kW (at nominal flow rate and heater power of 83.5 kW); maximum heat duty: 525 kW (at 9.2 gpm, 175 kW auxiliary heater power and no process heat removal); water-to-water; hot side inlet/outlet temperatures: 325/119°C, cold-side

			water inlet/outlet temperatures: 50/256°C at nominal flow rate of 994 kg/hr; flow rate range 4 – 15gpm; wetted surfaces stainless steel; we now have a quote for a PCHE from VPEI at ~$18k; with a pressure drop across the PCHE of ~6 psid.
Auxiliary Heater with control panel	1	primary heat addition for water loop	15 MPa, 175 kW rating; maximum water inlet temperature 275 C, maximum water outlet temperature 325 C, will heat water over this temperature range with a flow rate or 9.2 gpm or lower; at higher flow rates, the temperature rise across the heater will be reduced; stainless steel construction, 2500# class flanges at inlet/outlet; system includes control panel for PID heater power control; with remote setpoint and temperature sense; (we have a detailed proposal from Chromalox for a heater system that meet these specifications)
High Temp Test Section	1	flow, heat transfer, and materials studies	15 MPa, 325°C; this test section will be represented by a 2-inch NPS flanged (or grayloc) pipe section (spool piece) in the initial design and during loop qualification; length: 12 ft; all loop piping will be SS316;
Heat rejection heat exchanger/cooler	1	primary heat rejection heat exchanger	175 kW heat duty rating or higher, 15 MPa (primary side), secondary side can be at low (near-ambient) pressure, nominal conditions at a primary-side water flow rate of 994 kg/hr: hot side inlet 118°C, outlet 50 C, which corresponds to 83.5 kW heat rejection (nominal); cooling water inlet at 20 C, with a minimum flow rate rating of 15 gpm; stainless steel
Cooling Water Pump (for chiller)	1	prime mover for water loop	20°C, 0.2 MPa, 16 gpm,; (this pump may be purchased as part of the chiller system)
Chiller, air-cooled	1	Provides cooling water for the secondary side of the cooler	0.2 MPa, water flow rate up to 16 gpm minimum at 20 C, ΔT=50°C or less; must provide a minimum of 175 kW (~60 ton) heat rejection; this unit will be located outdoors adjacent to ESL; there is a possibility that it may be purchased using general-purpose funding for support of multiple projects;
Steam/Water Chemistry Control Section	1	Control chemistry of water introduced into the flow loop	0.1 MPa, 20°C; ion exchange + reverse osmosis system; resistivity specification 1.0 – 0.1 µS/cm; system will be supplied by Evoqua (Andy Tyler)
Water Storage and Deaeration Tank	1	storage of treated water for entire loop	0.15 MPa, 20°C, Approximate dimensions: D=0.76 m, H=1.78 m, V=810 L Stainless steel; (may use polyethylene)
High Temp MOVs	10	2-in NPS 160 lines	15 MPa, 350°C, 2500# class, SS 316, motor-operated, remote controllable; ball valves

Low Temp MOVs	3	2-in NPS 160 lines	15 MPa, 50°C, motor-operated, remote controllable ball valves
Other valves (HVs), not on main 2-in piping	19		Specs depend on location
Low-temperature, high-pressure Pressure Relief Valves	2	At HP pump outlet, on accumulator	15MPa, 50°C
High-temperature, high-pressure Pressure Relief Valves	2	On heater (part of heater system), primary PRV, secondary PRV (NC loop)	15 MPa, 350°C
Water storage tank pressure relief valve	1		25 psig, 20°C
Check Valves	3		15MPa, 50 C, 1500# class SS316; Additional locations for check valves may be identified
Piping			15 MPa, 350°C, NPS 2, schedule 160, SS 316
Flanges – high-temperature sections			15 MPa, 350°C, SS316, class 2500#
Flanges – low-temperature sections			15 MPa, 50°C, SS316, class 1500#
Grayloc connectors			15 MPa, up to 325°C, Grayloc 1500# class SS316 connectors should be applicable in both the low- and high-temperature sections; grayloc connections should be used wherever possible instead of flanged connections
Thermal Insulation – high temperature sections		Minimize heat loss from HT piping sections; provide safe touch temperature	Straight pipe sections should be insulated with 2-inch thickness of industrial pipe insulation such as Owens-Corning SSL II with ASJ Max no-wrap pipe insulation (suitable for process temp up to 538°C); insulation thermal conductivity at mean temperature 0.06 W/m*K or lower; custom insulation jackets may be required for some high-temperature components such as valves, heat exchangers, test section; custom jackets are available from Thermaxx

Instrumentation

Instrument	#Req'd	Purpose	Specification
Absolute Pressure transducers	6	On-line loop pressure monitoring	Range: 0-20 MPa, liquid service, 0-5 VDC output; see Honeywell Model TJE, 3000 psi range (in high-temperature zone, transducer will have to be thermally isolated from the process fluid)
Differential Pressure	6	On-line monitoring of delta-P	ΔP Range TBD, wet-wet differential pressure transducers, line pressure

transducers		across heat exchangers, heater, and test section	rating 20 MPa; see Honeywell Model HL-Z (in high-temperature zone, transducer will have to be thermally isolated from the process fluid)
thermocouples	8	On-line loop temperature monitoring	1/8-inch, Type K, SS sheath (mounting method for insertion into the flow will be via ½-inch NPT ports)
Flow meter – primary loop	1	On-line loop flow rate measurement	Line pressure 20 MPa rating, 1500# class flanges, Flow Technology turbine flow meter FT12 with extended range calibration, ball bearing/RF pickoff with frequency-to-DC converter for DC voltage output, 0.25 – 25 gpm flow rate range
Flow meter – cooling water	1	On-line monitoring of cooling water flow rate	This item may be included with the chiller; flow rate range: 0 – 10 gpm, low-pressure (~.15 MPa rating)
Dissolved O_2 sensor	2		
Conductivity sensor	2		
Nat circ flow meter	1		
Nat circ orifice plate	1		