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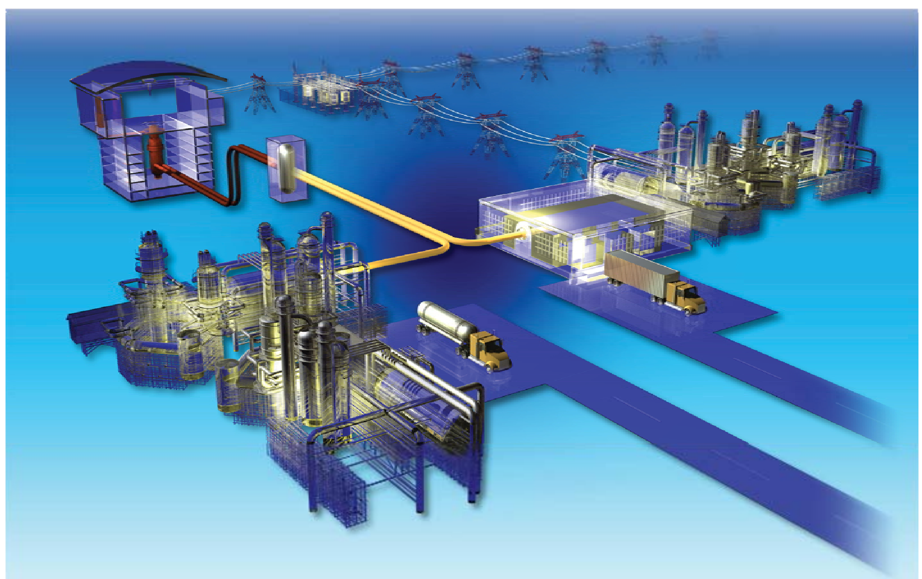
Technical Evaluation Study

Project No. 29147

NGNP Component Test Capability Test Loops Material Study



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1. INTRODUCTION

1.1 Description of the Proposed Issue or System

This technical evaluation addresses the materials technology development required for the Component Test Capability (CTC) Test Loops design and fabrication. Materials technology development requirements need to be evaluated for test loop equipment and components such as hot piping, heaters, circulators, valves, heat exchangers, recuperators, and instrumentation required for data collection and test loop control. High temperatures, high pressures, and potentially corrosive conditions in this application are the primary drivers requiring materials technology development necessary to support design and fabrication of CTC test loops.

This study is draft information only to support the August 4th & 5th Component Test Capability decision analysis meeting and will be finalized at a later date based on the alternative selected for the CTC.

1.2 Problem Statement

During various life cycle stages of the Next Generation Nuclear Plant (NGNP), a number of systems, subsystems, and components need to be developed. The CTC test loops will provide test beds to support the associated high-temperature gas thermal-fluidic technologies development needs. These test loops will generate high temperatures and pressures, simulating actual operating conditions for the various development units under test. Because of the high temperatures, high pressures, and potentially corrosive conditions that will be present at various locations in the test loops, materials technology development for the test loop design and fabrication is required.

This material study identifies the technology development required to support the CTC test loops design and fabrication. This material study is a draft. It will be finalized when the project makes a recommendation for the optimum test loop configuration.

Test modules, test sections, and the units under test (UUTs), such as Intermediate Heat Exchanger (IHX) Mockups are not considered to be part of the test loop designs; and therefore, material technology development requirements for these items is outside the scope of this study.

1.3 Definitions/Glossary

1.3.1 Component Test Capability

The capability to provide test beds for testing components in support of high temperature gas thermal-fluidic technologies development needs.

1.4 Acronyms

ASME	American Society of Mechanical Engineers
BPV	Boiler and Pressure Vessel
CBCS	Core Barrel Conditioning System
COTS	Commercial-Off-The-Shelf
CQL1	Component Qualification Loop 1
CQL2	Component Qualification Loop 2
CTC	Component Test Facility
CTF	Component Test Facility
CTL	Circulator Test Loop
DOE	Department of Energy
HGD	Hot Gas Duct
HH	Hot Header
HTF	Helium Test Facility
HTGR	High-Temperature Gas Reactor
HTS	Heat Transport System
HTTU	High Temperature Test Unit
I&C	Instruments and Controls
IEEE	Institute of Electrical and Electronics Engineers
IHX	Intermediate Heat Exchanger
MHI	Mitsubishi Heavy Industry
NEC	National Electrical Code
NGNP	Next Generation Nuclear Plant
NPS	Nominal Pipe Size
NRC	Nuclear Regulatory Commission
PBMR	Pebble Bed Modular Reactor
PCD	Pre-Conceptual Design
PE	Pressure Element
PHTS	Primary Heat Transport System
QL	Quality Level
R&D	Research and Development
SHTS	Secondary Heat Transport System
SSDT	Small Scale Development Test
TBD	To-Be-Determined
TDL	Technology Development Loop
TDRM	Technology Development Road Map
TEMA	Tubular Exchanger Manufacturers Association
TP	Test Plan
UUT	Unit Under Test

WC1 Water Cooler 1

WC2 Water Cooler 2

WEC Westinghouse Electric Company

2. BACKGROUND

2.1 Facility, Structure, System, Component Functions

2.1.1 Facility Description

The Department of Energy (DOE) has the current project Next Generation Nuclear Plant (NGNP) that will develop and demonstrate a first-of-a kind very-high-temperature gas-cooled nuclear system with the capability to generate electrical power and demonstrate nuclear hydrogen and steam production. The future CTC facilities will provide technology development platforms in support of the NGNP Project and the development of high-temperature gas thermal-fluidic technologies as applied in heat transfer and transport systems in High-Temperature Gas-cooled Reactors (HTGRs). In order for these developmental technologies to be integrated into the NGNP, it will be required that sub-assemblies, or in some cases, near full scale component tests be conducted on certain items. These tests need to be done at NGNP representative conditions, with regards to temperature, pressure, and flow.

The vendors AREVA and Westinghouse Electric Company (WEC) have generated pre-conceptual designs of test loops to provide high-temperature, pressure, and flow conditions defined in the NGNP Technology Development Road Maps (TDRMs) and associated Test Plans (TPs). These test loop pre-conceptual designs consist of a number of alternative loops and configurations.

The AREVA test loops pre-conceptual design configuration consists of two independent high-temperature helium loops that provide the required test conditions established for development and testing of the NGNP components. The AREVA test loops pre-conceptual design consists of:

- Small Loop – 1 MWth Test Loop
- Large Loop – 30 MWth Test Loop.

The pre-conceptual designs are fully documented in AREVA reference document NGNP Component Test Facility Test Loop Pre-Conceptual Design (PCD) [2]. The test loop designs are based on AREVA and Mitsubishi Heavy Industry (MHI) past experience with design and construction of high-temperature helium test loop facilities. These facilities include the French HELITE loop, the German KVK loop, and the Japanese HENDEL loop.

The WEC test loops pre-conceptual design configuration consists of five independent or partially interrelated equipment configurations for fulfillment of the overall CTC functions and requirements. The WEC test loops pre-conceptual design consists of:

- Small Scale Development Tests (SSDTs)
- Technology Development Loop (TDL)
- Component Qualification Loop 1 (CQL1)
- Component Qualification Loop 2 (CQL2)
- Circulator Test Loop (CTL).

The WEC designs are fully documented in WEC reference document NGNP Component Test Facility (CTF) Test Loop Pre-Conceptual Design Report [3].

The various test loop pre-conceptual designs presented by AREVA and WEC are comprised of various piping, heaters, circulators, valves, heat exchangers, recuperators, and instrumentation required for data collection and test loop control. This present material study is performed in the context of the test loop pre-conceptual designs presented by AREVA and WEC.

2.2 Facility, Structure, System, and Component Classification

CTC test loops and the associated data collection systems will be Quality Level (QL)-2. This present study will be used as a supporting document in a future procurement and is QL-3.

The CTC facilities are anticipated to be high hazard, non-radiological facilities.

The CTC facility designs will employ safety concepts utilizing defense-in-depth provisions to protect plant systems, structures and components, and the operating personnel health and safety. Safety concepts will rely on robust designs and high-quality equipment specifications that provide high-design margins. Test loop components will be designed to the applicable national codes and design standards provided by such organizations as the American Society of Mechanical Engineers (ASME), Institute of Electrical and Electronics Engineers (IEEE), National Electrical Code (NEC), and Tubular Exchanger Manufacturers Association (TEMA).

The CTC facilities will provide the capability to test reactor and ancillary components to demonstrate licensability of components and associated operations. These tests can be demonstrated without requiring the CTC facility to be licensed by the Nuclear Regulatory Commission (NRC).

Preliminary safety analysis, hazards analysis, and quality assessments are provided for the AREVA and WEC test loops pre-conceptual designs in their referenced reports.

3. PROPOSED SOLUTION

3.1 Elements/Functions of Proposed Solution(s)

3.1.1 General Design Concept

In general, the CTC test loops will operate by heating an insulated volume inside a pressure boundary. The high temperatures are contained inside insulated spaces so that the pressure boundary can be maintained at a much lower temperature and therefore, utilize standard technology for pressure boundary designs. The high-temperature helium inside these systems is either circulated or stagnant and will be used to create an environment for testing of HTGR materials and components.

3.1.2 Present CTC Material Study Focus

For the purpose of this present CTC materials study, the main focus is on those items with technology development issues associated with high temperature, high pressure, and potential corrosion. Items not associated with these issues do not receive detailed consideration in this present study. Major items that are outside the focus area of this study include:

- Electrical Power Systems
- Secondary Systems
- Support Systems
- Digital Control Systems
- Computer and Data Acquisition Systems.

3.1.3 Commercial-Off-The-Shelf (COTS) Technology and Standard Equipment

To avoid unnecessary technology development, a strategy to use Commercial-Off-The-Shelf (COTS) technology and standard equipment will be employed as far as practically possible in the design and fabrication of CTC facilities. No, or at most, limited materials technology development is required for COTS and standard equipment. Items identified as COTS or standard equipment do not receive detailed consideration in this present study. Major items and systems identified as COTS technology or standard equipment include:

- Standard Pressure Vessel Shells (<200°C Maximum)
- AREVA 1 MWth Test Loop – Low Temperature Piping – (<500°C) [2, p. 35].
- WEC TDL – Helium Transport System Cold Pipes – 417°C [3, Section 6, p. 25 and Section 6, p. 34].
- WEC SSDTs – Water Coolers CL1_1.1 and CL1_1.2 are COTS technology [3, Section 5, p. 34].
- WEC TDL Cooler CL 2A_1.1 and CL 2A_2.1 are likely to be COTS technology based on their fluid temperature ranges and the pre-conceptual design information presented [3, Section 6].
- WEC CQL2 Cooler C1 and C2 are likely to be COTS technology based on their fluid temperature ranges and the pre-conceptual design information presented [3, Section 8, p. 42].
- AREVA 1 MWth – Low-Temperature Heat Exchangers – The low-temperature heat exchanger is a conventional application that can be procured from various vendors [2, p. 36].
- AREVA 1 MWth – Recuperator, Medium, and High-Temperature Heat Exchangers – For applications at temperatures lower than 650°C standard stainless steels have been proven compatible with the pressure and temperature conditions involved. For applications in the range of 650–950°C, use of nickel-base alloys is required. Two potential candidate materials are Inconel 617 and Haynes 230. These heat exchangers are readily available from select vendors [2, p. 36].
- WEC SSDT3 – Recuperator operating between 80°C and 350°C is likely COTS technology [3, Section 5, p. 51].

- WEC TDL – Recuperators – Four recuperators are used in the primary loop and three for the secondary loop. The recuperators are standard units [3, Section 6, p. 43] (although there may be issues with corrosion and helium infiltration in the insulation).

- WEC CQL2 – Recuperators – Several recuperators are specified for the numerous operating configurations proposed for the CQL2 pre-conceptual design. The pre-conceptual design has not been developed to the extent of identifying materials for these recuperators. Several of the recuperators for this loop are likely to be standard COTS technology based on the temperature limits presented in the pre-conceptual design. See, for example, the recuperator for the Brayton cycle test operating between 512°C and 110°C [3, Section 7, p. 38].

- AREVA 1 MWth and 30 MWth – Circulators – There is no material issue concerning the gas circulators. Both internal AREVA experts and external vendors indicate that circulators of up to 5 MW are clearly feasible and could be readily supplied [2, p. 37].

- AREVA 1 MWth – Valves – The valves installed in the cold legs are low-temperature valves and are considered conventional valves. The valves in the hot legs are high-temperature valves, with design temperatures as high as 1100°C [2, p. C-4-C-6] and are readily available from select vendors. [2, p. 37].

- WEC SSDT1 and SSDT2 – Valves – The maximum temperature presented in the pre-conceptual designs for the valves is 100°C. These are likely considered to be standard conventional valves.

- WEC TDL – Valves – The maximum temperature presented in the pre-conceptual design for the valves is 85°C (there are no high-temperature valves in the TDL [3, Section 6, p. 51]). The valve manufacturer VELAN can supply the valve components in various types of materials, which can be combined to "build up" the valve. Operating experience with VELAN valves was obtained in the Helium Test Facility (South Africa). These are likely considered to be standard valves. [3, Section 6, pp. 36–39].

- WEC CTL – The CTL (excluding the Circulator test unit) does not require specific Research and Development to perform the required tests as all items are commercially readily available [WEC, Section 9, p. 36].

3.1.4 High-Temperature Electric Heaters

The function of electric heaters is to produce high-temperature helium gas to be supplied to the test equipment such as the IHX test module) [AREVA, PCD, p. 72].

3.1.4.1 AREVA 1 MWth Test Loop

The AREVA 1 MWth primary loop pre-conceptual design contains two heaters [AREVA, PCD, p. 35]. The First Stage heater raises the helium temperature to 850°C. The Second Stage heater raises the helium temperature to 1000°C. Each heater will have heater elements contained inside a pressure vessel that shall be made of carbon steel (SA-516 Grade 70) and internally insulated with ceramic fiber thermal insulation. The pressure vessel is of standard ASME Boiler and Pressure Vessel (BPV) Code, Section VIII, Division 1 design. For the First Stage heater the internal insulation metal liner and pipe heating elements will be made from Incoloy 800H. For the Second Stage heater the internal insulation metal liner will be made from Hastelloy X and the pipe heating elements will be made of graphite.

3.1.4.2 AREVA 30 MWth Test Loop

The AREVA 30 MWth Test Loop pre-conceptual design includes two electric heaters, namely EH1 and EH2 [AREVA, PCD, Pg. 72]. Helium gas from the primary helium circulator is heated to about 1000°C in two stages by the electric heaters. EH1 heats helium up from 427°C to 714°C and EH2 heats the helium gas up from 714°C to 1000°C. Design pressure of each of the two vessels containing the heating elements is 8.4 MPa. The two vessels outer shells are standard designs per the ASME BPV Code, Section VIII, Division 1. Internal parts, such as heater elements, insulation, etc., are designed by maker standard.

Considering availability of forging material and graphite plate for heater tube sheet, EH1 and EH2 have two units for each heater: EH1A and EH1B, and EH2A and EH2B.

The heating elements for the lower temperature heater EH1 are electrical heating pipe, with design temperatures of 745°C. The pipe heating element material is Incoloy 800H. The technology is well adapted in this high-temperature application similar to HENDEL. Heating pipes are arranged vertically to save space and to be free for axial thermal expansion. The pressure vessel has internal thermal insulation, with an Incoloy 800H insulation liner, and a water jacket. The vessel is highly reliable as a pressure boundary for the high-temperature helium side. A bolted flange joint of the pressure vessel upper head to shell is used for the convenience of assembly and maintenance of the heater elements.

The design philosophy for the higher temperature EH2 is the same as for EH1. Major differences between the two designs are in that the EH2 pipe heater elements are made of graphite, with design temperatures of 1030°C and the insulation liner is made of Hastelloy X.

3.1.4.3 WEC SSDT 1 and SDDT 2

The WEC SSDT 1 and SDDT 2 pre-conceptual designs support test requirements for a 9 MPa, 950°C, helium environment with no significant flow rate [3, Section 5, p. 20]. The requirement of 9 MPa helium pressure is addressed by installing the test setup inside a standard ASME BPV Code, Section VIII, Division 1, designed pressure vessel, with a shell maximum design temperature of 130°C. The requirement for of 950°C is addressed by installing an insulated high-temperature test vessel inside the pressure vessel, with an internal 20 kW heater used to heat the interior of the test vessel. In order to maintain the interior of the high-temperature test vessel at 950°C and to minimize heat transfer to the outer pressure vessel, several layers of insulation are used including a layer of polished stainless steel cladding for additional radiative insulation. The high-temperature vessel and insulation system requires development with regards to the insulation that is to be used. It is proposed that this be done as an initial SSDT test, where the SSDT itself is the experiment. No additional tests are performed inside the high-temperature vessel, but the vessel is heated up to normal working temperature while the pressure vessel temperature is measured. After maintaining the SSDT at working pressure and temperature for sufficient time without exceeding a threshold pressure vessel temperature, the vessel is opened and the insulation integrity evaluated [WES PCD, Section 5, p. 34].

For tests requiring a reducing atmosphere as found in the NGNP Primary Heat Transport System (PHTS) (due to the large amount of graphite in the reactor), it is proposed to heat the test space up to 950°C using graphite (uncoated) heating elements, with design maximum temperatures of 1000°C. The heating element is expected to corrode due to the unavoidable presence of trace water. Therefore, the graphite heating elements are to be treated as consumables. The inner insulation could also be graphite in keeping with the requirement for a reducing environment.

For tests requiring a mildly oxidative atmosphere as could possibly occur in the NGNP Secondary Heat Transport System (SHTS) (due to the absence of graphite), metal type heating elements, such as Kanthal, Alloy 617, Alloy 800H, or coated graphite, with design maximum temperatures of 1000°C, could be investigated. SiO2 refractory bricks could be used for the inner insulation.

From Helium Test Facility (HTF) (South Africa) experience, a power density of 1 kW per meter of 4 mm Kanthal wire is an appropriate value. To reach 20 kW, this would require 20 m of heating wire in the permitted space. The power density could possibly be increased to 2 kW per meter; however, some difficulty in fitting such a ceramic-supported metal wire element in the permitted space can be expected.

Another alternative is to use a Boron Nitride or Silicon Carbide coated graphite element. Uncoated as well as coated elements are commercially available in a flat disc-shaped geometry.

In order to test simultaneous pressure and thermal transient loads, a system using a combination of hydraulic cylinders, heaters, coolers, and control valves is proposed [WES PCD, Section 5, p. 26]. The heater concept consists of electrically heated parallel tubes of which the thermal mass is larger than that of the subject IHX test unit cell. The heaters are pre-conceptually sized at a maximum of 10 kW per heater. The heater tube itself should be capable of 950°C, at 9 MPa, and is approximately 6 mm OD × 3 mm ID.

3.1.4.4 WEC SSDT 3

The WEC SSDT 3 pre-conceptual design supports testing IHX modules at temperatures up to 950°C [3, Section 5, p. 20]. This pre-conceptual design includes a 124 kW heater, referred to as cold heater that heats a flow of helium from 280°C to 300°C, and a second 311 kW heater, referred to as hot heater that heats the helium flow from 900°C to 950°C. The level of technical detail is not as far developed for the SSDT 3 pre-conceptual design as for the SDDT 1 and SDDT 2 pre-conceptual designs. It is not clear whether the SSDT 3 pre-conceptual design requires the test vessel 20 kW internal heater as for the SSDT 1 and SSDT 2 pre-conceptual designs, but a 20 kW heater is listed for SSDT 3 in Table 5-6 in the referenced WEC pre-conceptual design document [3, Section 5, p. 54]. The 124 kW and 311 kW heaters may be considered to be a part of the IHX test module designs.

3.1.4.5 WEC TDL

The WEC TDL pre-conceptual design includes a Primary Loop Heater 1, designated HT 2A_1.1, and a Primary Loop Heater 2, designated HT 2A_1.2 [3, Section 6, pp. 27 and 28]. HT 2A_1.1 is an 8.00 MWth heater that heats a flow of helium from 625°C to 950°C. HT 2A_1.2 is a 4.4 MWth heater that heats a flow of helium from 85°C to 659°C.

The TDL Heater 1 uses Graphite heating elements and assumes the power density of the HENDEL graphite heater from which the heater core volume is calculated. It was assumed that the TDL Heater 1 has a similar "heater core geometric ratio" as the HENDEL test loop with which the core dimensions of the TDL Heater 1 were calculated. The basis for this is that the HENDEL heater operated at 40 bar, 4 kg/s, 700°C to 1000°C, while the TDL heater works at 90 bar, 4.75 kg/s, 625°C to 950°C. The higher pressure (and therefore, higher density) in the TDL should enable better heat transfer, and hence, a higher power density in the TDL heater than in the HENDEL heater.

Additionally, the HENDEL element temperature was estimated to be 1300°C, while the experience with the High Temperature Test Unit (HTTU) (South Africa) is that the maximum continuous temperature for a graphite element is 1600°C. This supports the notion that the heater size could be reduced by using a higher heater power density. The diameter of the heater is 1.22 m and the length is 5.46 m. The heater core is insulated from the pressure boundary as was done with the HTS Hot Gas Duct (HGD). This prevents the pressure boundary from overheating and losing mechanical strength. The insulation thickness (0.3 m) was calculated based on a 200°C pressure boundary outside shell temperature. The heater was oversized by 30% to compensate for the heat loss due to the environment and other unforeseen conditions and losses. The pressure boundary is of a standard ASME BPV Code, Section VIII, Division 1, design using carbon steel SA-516 GR.70 material.

The TDL Heater 2 uses Inconel heater elements and assumes the heat transfer per meter on Inconel wire to be 1 kW/m. With this as a basis, the required length of wire could be calculated. By selecting the pitch of the wire, the size of the heater could be calculated. The diameter of the heater is 0.76 m and the length is 3.39 m. If required, the heat transfer per meter of the Inconel wire can be increased to 3 kW/m. The heater core is insulated from the pressure boundary as was done with the HTS HGD. This prevents the pressure boundary from overheating and losing mechanical strength. The insulation thickness (0.1 m) was calculated based on a 200°C pressure boundary outside temperature. The pressure boundary is of a standard ASME BPV Code, Section VIII, Division 1, design using carbon steel SA-516 GR.70 material.

3.1.4.6 WEC CQL2

The WEC CQL2 pre-conceptual design includes heaters, designated Heater H1 and Heater H2, with capacities at 25 MWth plus 5 MWth margin [3, Section 8, p. 41]. These heaters are designed on the same concept as in HTF with a heat flux rate of 6 W/cm2. The heater section has a diameter of 1300 mm and height of 5000 mm (per heater unit of 5 MWth). The heaters are designed to heat the flow of helium from 660°C to 900°C.

The maximum capacity of the Heater H1 system will be 30 MWth (25 MWth minimum specified) [3, Section 8, p. 47]. There will be six heater units in parallel with each other. The heaters will be installed vertically with the inlet at the bottom and an outlet at the top of the vessel. The maximum outlet temperature is 950°C. A “hot pipe” design approach will be incorporated at the outside of the pressure vessels and at the outlet nozzles.

The pressure vessel of one heater unit is 10,000 mm high and has a diameter of 2600 mm and has a mass of approximately 185,000 kg.

Heater H2 is similar to one of 5 MWth heater units used in Heater H1 [3, Section 8, p. 47].

3.1.5 High-Temperature Vessels

3.1.5.1 WEC SSDTs

The WEC SSDTs high-temperature vessel and insulation system requires development with regards to the insulation that is to be used. It is proposed that this be done as an initial SSDT, where the SSDT itself is the experiment. No additional tests would be performed inside the high-temperature vessel in conjunction, but the vessel is heated up to normal working temperature while the pressure vessel temperature is measured. After maintaining the SSDT at working pressure and temperature for sufficient time without exceeding a threshold pressure vessel temperature, the vessel is opened and the insulation integrity evaluated [3, Section 5, p. 34].

3.1.6 Coolers

3.1.6.1 AREVA 30 MWth Test Loop

The pre-conceptual design includes water coolers WC1 and WC2, which have heat removal capacities of 5 MWth and 25 MWth, respectively. The function of the water coolers is to cool the high-temperature helium gas returning from test equipment. WC2 cools the helium gas from 950°C to 467°C, and in the next stage, WC1 cools the helium gas from 467°C to 360°C. The design pressure of the two vessels is 9.0 MPa, and the outer shells are standard of standard ASME BPV Code, Section VIII, Division 1, designs. Internal parts (heat transfer tubes, insulation, etc.) are design per maker standards [2, p. 73]. Internal thermal insulation and a water jacket are installed within the vessels for high reliability of pressure boundary of high-temperature helium, ready availability of carbon steel, and based on past experience with HENDEL loop. The pressure vessel shell material for both vessels is Carbon Steel SA-515 Gr. 70 or SA-266 Gr. 2. Tube material for WC1 is Carbon Steel SA-210 A-1. Tube material for WC2 is Stainless Steel

SA-213 TP316. Tubesheet material for both water coolers is SA-5266-2. The tubes for both water coolers are largely protected from the temperature extremes of the incoming helium gas by the cooling water. The tubesheets are largely protected from the temperature extremes by thermal shield plates. The shield plate for WC1 is of SUS 304 material and the shield plate for WC2 is of Hastelloy X or Incoloy 800H. WC1 has an impingement plate of SUS304 material. WC2 has in internal impingement plate of Hastelloy X. The internal thermal insulation for both water coolers is ceramic fiber. Internal flow liners are likely required, but are not specified [2, Figures 7–21 and 722, p. 86].

3.1.7 High-Temperature Piping, Hot Gas Ducts, Hot Gas Mixing Tanks, Hot Headers, and Hot Pipes

The layout of piping and piping supports will accommodate thermal expansion while avoiding potentially damaging strain at interfaces with major components. The high-energy components and piping will be housed in a bunker area for personnel protection.

3.1.7.1 AREVA 1 MWth Test Loop

The high-temperature piping (>500°C) located in the hot legs will have a size of DN 500 and have external and internal insulation installed. The internal insulation will be ceramic fiber and be protected by a metal liner. The smooth metal liner also reduces flow friction losses. The piping will be made from carbon steel (SA-515 Grade 70) and is of standard ASME BPV Code, Section VIII, Division 1, design. The metal liner will be made from Incoloy 800H [2, p. 34].

3.1.7.2 AREVA 30 MWth Test Loop

Hot gas ducts have internal insulation made of ceramic fiber. The pressure pipe is carbon steel (SA515-70) of standard ASME BPV Code, Section VIII, Division 1, design, and the liner material is Hastelloy X and Incoloy 800H. This design concept is based on the HENDEL experience [2, p. 75]. There are multiple design specifications for Hot Gas Ducts. Design temperatures range from 750°C to 1030°C [2, Tables 7-11 and 7-12, p. 80]. A hot gas duct section designated as from EH1~EH2 has a design temperature of 750°C, liner material of Incoloy 800H, and insulator material of ceramic fiber. A hot gas duct section designated as IHX~SG has a design temperature of 980°C, liner material of Hastelloy X, and insulator material of ceramic fiber. Hot gas duct sections designated as EH2~IHX, and DHD~WC2 have a design temperature of 1030°C, liner material of Hastelloy X, and insulator material of ceramic fiber [2, Tables 7-11, 7-12, and 7-14, pp. 80 and 81].

The primary helium loop includes a Hot Gas Mixing Tank. The Hot Gas Mixing Tank has a design temperature of 1030°C and design pressure of 8.4 MPa. The pressure boundary is of standard ASME BPV Code, Section VIII, Division 1, design and is made of SA515-70 material. Internal liner and insulation are non-code designs. The liner consists of Hastelloy X material. The insulation is of ceramic fiber. The Hot Gas Mixing Tank has an internal baffle plate of graphite material [2, Tables 7-13 and 7-15, pp. 80 and 81].

3.1.7.3 WEC TDL

The WEC TDL pre-conceptual design has Heat Transport System Hot Gas Ducts PI 2A_1.2, PI 2A_1.3, PI 2A_2.2, and PI 2A_2.3 [3, Section 6, pp. 26]. These hot gas ducts have performance specifications of 1000°C, 9.6 MPa, for the helium and 200°C for the pipe pressure boundary temperature.

The TDL's HGD concept is used to convey high-temperature high-pressure helium between the TDL components. The hot gas is passed through an internal pipe (liner) surrounded by insulation to prevent the pressure boundary from getting excessively hot. The liner material needs to be able to withstand the high temperature, possibly Monel, but the material and the thickness of this liner should be investigated further in future work. The pressure boundary itself is used to contain the pressure. The pressure boundary is not insulated in order to lose heat to the surroundings preventing it from heating up to the internal gas temperature over time.

A general maximum gas velocity assumption for hot gas test systems is 60 m/s. The internal gas flow liner diameter was calculated based on a 20 m/s average gas velocity to be conservative and to allow for future expansion and flexibility of the TDL. The insulation thickness could then be determined, based on a conservative thermal conductivity of 0.5 W/m-K to give a pressure boundary outside diameter of 200°C. The inside diameter of the pressure boundary could then be determined based on insulation thickness.

The gas temperature was assumed to be 1000°C instead of 950°C. This was done to allow for flexibility of the design for future requirements that might need higher temperatures.

Based on the thermo hydraulic inputs, the mechanical design of the pressure boundary is standard, using ASME BPV Code, Section VIII, Division 1, to do the pressure boundary calculations. The liner was assumed to be 5 mm thick and the insulation required to keep the pressure boundary below 200°C is 0.12 m thick. The pressure boundary thickness was calculated to be 48 mm when SA-516 Gr. 70 material is the proposed material.

Further development of the Heat Transport System (HTS) HGD is listed in future work and should address issues like expansion, insulation material, the effect of impurities on insulation material, temperature and pressure transients with the HGD as well as pressure boundary and liner materials and material thicknesses.

3.1.7.4 WEC CQL1

The CQL 1 pre-conceptual design consists of HGD piping sections from the TDLs merged at a Hot Header (HH), which is the interface between the TDLs and CQL 1. The HGD sections are designated PI 3_1.1, PI 3_1.2, PI 3_1.3, and PI 3_1.4. The HH is designated HH 3_1.1.

As with the TDL, the CQL 1 test loops hot-section pipes have been designed with internal flow liner diameters of 0.260 m. The internal diameter of the pressure boundary is 0.548 m leaving enough space for appropriate insulation.

The pressure boundary is a standard Nominal Pipe Size (NPS) 24, schedule 80 pipe, using SA-516 Gr. 70 as proposed material. All HGD dimensions regarding both TDLs as well as CQL 1 connections have been standardized to simplify fabrication and maintenance of all piping sections. Velocities within the pipe sections vary between 9 and 20 m/s for the Steam Generator CQL1 test.

The H2 CQL1 test has a much larger attainable helium mass flow than the SG test (due to a lower-temperature differential passing through its test station), and therefore the velocities range in the order of 28 to 35 m/s. The higher velocity for this test is still acceptable when compared to those obtained in previous test loop facilities (~60 m/s). Future work needs to be performed to verify the gas velocity threshold on the CTC HGDs.

An inner pipe diameter of 0.26 m reflecting a nominal velocity of 20 m/s for the maximum flow of ~3.65 kg/s in the TDL was chosen as the reference diameter.

A decision was made to use similar dimensions for various pipe sections, purely based on maintenance and standardization grounds. Future techno-economic tradeoff studies need to be done to determine a cost for all the proposed piping in a CTC facility, followed by an all-inclusive engineering optimization, thereby taking into account matters of standardization, thermal fluid considerations, material choice, location, cooling mode (active/passive), HVAC, and costs [3, Section 7, p. 38].

Insulation up to a diameter of 0.510 m will be sufficient to retain the surface temperature at 200°C. For the given process conditions, a standard pipe size with an internal diameter closest to this size in a NPS 24, Schedule 80 pipe, which has an internal diameter of 0.548 m. This leaves additional width of 0.019 m for insulation material [3, Section 7, p. 38].

It is proposed that the internal flow liner sections of the HGDs consist of conical sections funneling into cylindrical flow geometries. Making use of the conical flow liner arrangement allows for expansion, which is on the order of 11.6 mm/m when operating temperatures of 950°C are expected.

It is proposed that the flow liner be constructed from high-strength alloys to serve as a containment barrier for the internal insulation. The inside surface of the flow liner needs to be smooth to reduce friction. Typical materials of construction for the flow liner are:

- High-strength nickel alloy (only ~1.5 mm thick).
- Machined graphite (up to 5 mm thick). This option is only listed as an alternative to the first-choice high-strength nickel alloy.

Another option is carbon composites.

The high-strength nickel alloy flow liner will be preferred due to a proven history in high-temperature environments. Machined graphite will be much heavier, thereby requiring additional support within the HGDs. The advantage of graphite is that it has a very low thermal expansion coefficient compared to that of steels, such as nickel alloys. Although, the machinability of graphite liners could pose some serious challenges, which is not in line with the COTS philosophy anticipated in CTC facilities.

High-performance insulation is necessary to increase the thermal resistance across the HGD. The outside surface temperature is assumed to be 200°C. Typical materials of construction for the insulation are:

- Aerogel
- Microporous Silica.

The pressure boundary will be made from Standard NPS 24, Schedule 80 pipe with typical materials being:

- SA-240 (304 stainless steel)
- SA-516 (carbon steel).

The function of the HH is to ensure merging of two TDL mass flows into the bottom section of the HH pressure vessel, located near the test stations of the TDLs. Departure from the HH is from the top half of the vessel to either one of two test stations. [3, Section 7, p. 43] Pre-conceptual design of the HHs is not well developed. Presumably their designs include internal flow liners and insulation similar to that of the HGDs.

3.1.7.5 WEC CQL2

The hot pipes use coaxial flow. The hot gas is transported in the inner pipe section and a special design cold stream performs the conditioning of the pressure boundary. Special care is taken in the internal insulation system to prevent helium convection streams from transmitting heat flow. A pressure equalizing system is incorporated to prevent implosion of the inner-lined section during sudden depressurization of the system. A typical German/Japanese hot pipe design will be followed.

3.1.8 Helium Circulators and Blowers

3.1.8.1 WEC SSDT3

Pre-conceptual design of the circulator for this test loop is based on the pre-conceptual circulator design for the WEC TDL.

The greatest risk with this test loop (and the TDL) is the reliable operation of an atmospheric air-standard multistage centrifugal blower in high-density, high-pressure helium environment. Therefore, an initial proof-of-concept test will contribute greatly to minimize the risk.

From previous investigations, it was found that the pressure vessels have the longest lead times for such a circulator (up to 18 months). The timescale and cost for such a circulator proof-of-concept test will be minimized if it can be done using a pressure vessel and facilities already available at existing test facilities [3, Section 5, p. 52].

3.1.8.2 WEC TDL

The TDL has helium circulators designated CR 2A_1.1, CR 2A_1.2, CR 2A_2.1, and CR 2A_2.2 [3, Section 6, pp. 31–33]. Since custom helium circulators are not freely available commercially, WEC decided to use an “off-the-shelf” air circulator from Gardner Denver for a first estimate the density ratio between air and helium was used to scale the circulator pressure rise and power, assuming that the volume flow through a dynamic machine will be the same for helium and air. From the inputs and assumptions, an equivalent air circulator was selected. The machine has the capability to add additional stages to increase the pressure rise over the machine should this be required at a later stage.

Due to the high-pressure level of the system, a large pressure differential would normally be present over the bearings and seals of the compressor-section on the circulator. WEC decided to make use of a completely submerged motor concept, thus the complete circulator, including motor and compressor, would be placed inside a high-pressure vessel. It is proposed that the circulator be operated at a low temperature (<80°C) so that no cooling auxiliary is required for the machine. Since this circulator is built for air conditions, it is recommended that a detailed analysis and immediate test be done on the machine's mechanical strengths as well as performance when operated in helium. It is proposed that the same machine be used for both primary and the secondary circulator.

Since the pressure vessel that houses the circulator does not contain hot helium, the shell temperature is expected to be below 100°C. The shell is of standard ASME BPV Code, Section VIII, Division 1, design. The proposed material is carbon steel SA-516 Gr. 70.

3.1.8.3 WEC CQL2

One to four blower curves in parallel, similar to that for the Pebble Bed Modular Reactor (PBMR) (Republic of South Africa) Core Barrel Conditioning System (CBCS), are a close fit for the requirements of the different configurations of the CQL2 test loop [3, Section 8, p. 11]. The blowers are mounted horizontally with center inlet and side discharge. The inlet pipe provides a sufficient straight length to promote smooth flow into the inlet cone, which minimizes losses into the impeller. The impeller is directly mounted on the shaft, which is supported by oil or gas bearings. A blower with electromagnetic bearings is currently under testing and if it is proved to be industrially reliable, it can be installed. A variable speed submerged electric motor could be fitted.

The blower vessel consists of two main compartments: the system side and motor side. A barrier plate and insulator plate separate these compartments for the purpose of minimizing heat ingress into the motor compartment. The motor mounting flange is attached to the barrier plate assembly. The motor/barrier Plate Assembly is bolted to the vessel yoke section. This connection allows fitting and removal of the entire blower internal assembly from the pressure vessel.

Electrical conductors, instrumentations cabling, and cooling water services enter the pressure vessel through special pressure penetrations [3, Section 8, p. 44].

3.1.9 High-Temperature and High-Pressure Valves

3.1.9.1 AREVA 30 MWth

The AREVA 30 MWth pre-conceptual design is not well developed with respect to valve materials and availability issues. Helium service valves with design temperatures as high as 1100°C and design pressures at 10 MPa will likely be a challenge.

3.1.9.2 WEC SSDT3

The WEC SSDT3 pre-conceptual design is not well developed with respect to service conditions, valve materials, and availability issues.

3.1.9.3 WEC CQL2

The WEC SSDL3 pre-conceptual design is not well developed with respect to valve materials and availability issues.

3.1.10 Temperature Measurement

3.1.10.1 AREVA 1 MWth and 30 MWth

To measure the high temperatures in the loops Type K or N thermocouples will be used. These thermocouples have an accuracy of +/- 0.75%. If required for process monitoring, special thermocouples with higher accuracy can be supplied. Most of the thermocouples will require thermo-wells [2, p. 136].

3.1.10.2 WEC SSDTs

As the heating elements in the test vessel are electrically charged and expected to be at a temperature higher than 950°C, it is expected that temperature measurement of the element by means of metallic thermocouples could be difficult. Therefore, it is proposed to measure the heating element surface temperature with a pyrometer that is located at the bottom of the test vessel. Depending on the technical feasibility of using a quartz window for a 9 MPa pressure boundary, the pyrometer optical unit could be located outside the pressure vessel. This has to be confirmed during later design stages [3, Section 5, p. 44].

3.1.10.3 WEC TDLs and CQL2

The WEC TDL and CQL2 Instruments and Controls (I&C) designs are not well developed with respect to materials and availability issues. Temperature measuring instruments with operating ranges up to 1100°C at 11 MPa will likely be a challenge [3, Section 6, p. 59].

3.1.11 Pressure Measurement

3.1.11.1 AREVA 1 MWth and 30 MWth

Pressure measurement at high temperature and pressure is a challenge. AREVA plans to use Rosemount Transmitters and tubing runs so that the temperature drops down to an acceptable value for the transmitter. Remote Seal (diaphragm seal system) is another option, which can be used at a higher temperature and would provide isolation of the transmitter from the helium [2, p. 136].

Pressure elements PE-1 and PE-2 listed for design pressure 10 MPa and 1100°C might be a problem [2, p. C-8].

3.1.11.2 WEC TDLs and CQL2

The WEC TDL and CQL2 I&C designs are not well developed with respect to materials and availability issues. Pressure measuring instruments with operating ranges up to 11 MPa at 1100°C will likely be a challenge [3, Section 6, p. 59].

3.1.12 Flow Measurement

3.1.12.1 AREVA 1 MWth and 30 MWth

Helium mass flow in the loops is accurately measured using a Coriolis mass flow meter at the high temperatures in the test loop. Flow will be measured at the discharge of the circulator where temperature is relatively low. These flow meters can be used for a maximum process temperature of 427°C and have an accuracy of +/- 0.35%. In addition, one flow meter is installed in the high-temperature test section at 1000°C and another is installed in the medium temperature section at a temperature of 500°C. Selecting these mass flow meters at such a high temperature will be a challenge [2, p. 136 and 2, p. C-10].

3.1.12.2 WEC TDLs and CQL2

The WEC TDL CQL2 I&C designs are not well developed with respect to materials and availability issues. Flow measuring instruments with operating ranges up to 1100°C at 11 MPa will likely be a challenge [3, Section 6, p. 59].

3.1.13 Additional Instrumentation

3.1.13.1 AREVA 1 MWth and 30 MWth

The following additional instrumentation may be required for the loop control and monitoring:

- Additional instrumentations for test sections, depending on the nature of the test (strain gauges, vibrations, etc.)
- Helium impurity monitors at the inlet and outlet of the hot test sections
- Helium chemistry and impurity monitors in the loop
- Moisture content in the loops
- External air monitors to provide helium concentration around the loop for personnel safety (this is likely COTS technology and outside the scope of this study).

3.2 Detailed Evaluation

The following items warranted detailed evaluation in this material study.

3.2.1 Electric Heating Elements

The following electric heating elements are proposed in the pre-conceptual test loop designs:

Test Loop	Name	Type	Material	Design Temperature (°C)	Approximate Useful Maximum Temperature (°C)
AREVA 1 MWth	First Stage	Pipe	Incoloy 800H	TBD (~>850)	982
AREVA 1 MWth	Second Stage	Pipe	Graphite	TBD (~>1000)	1600
AREVA 30 MWth	EH1	Pipe	Incoloy 800H	745	982
AREVA 30 MWth	EH2	Pipe	Graphite	1030	1600
WEC SSDT 1 and 2	N/A	Disc (reducing)	Graphite	1000	1600
		Wire (oxidative)	Kanthal	1000	1425
			Inconel Alloy 617	1000	<<1330 (melting)
			Incoloy 800H	1000	982
		Disc (oxidative)	Boron Nitride Coated Graphite	1000	
			Silicon Carbide Coated Graphite	1000	
WEC SSDT 3	Cold Heater	Pipe	TBD	TBD (~>850)	
WEC SSDT 3	Hot Heater	TBD	TBD	TBD (~>950)	
TDL	Heater 1	TBD	Graphite	TBD (~>950)	1600
TDL	Heater 2	Wire	Inconel Alloy 617	TBD (~>659)	<<1330 (melting)
WEC CQL2	Heater H1	TBD	TBD	TBD (~>950)	
WEC CQL2	Heater H2	TBD	TBD	TBD (~>950)	

Four primary materials and some alternative materials have been proposed in the pre-conceptual designs for the various electrical heating elements. A number of the heating element materials are to-be-determined (TBD). The four primary materials identified are Incoloy 800H, Kanthal, Inconel Alloy 617, and Graphite. For the heating elements with a specified primary material, the proposed material is acceptable with respect to the design temperature as compared to the approximate useful maximum temperature of the material.

The vendors describe the technology for heater elements in this application ranging from "well adapted in this high-temperature application similar to HENDEL," in the AREVA 30 MWth pre-conceptual design to "not well proven in the industry" and "needing investigation" in the WEC CQL2 pre-conceptual design.

In the WEC SSDTs, the heating element is expected to corrode due to the unavoidable presence of trace water, as well as other potential contaminants, and is considered a consumable. There is also a potential space issue with fitting the required length of ceramic-supported Kanthal wire in the space permitted in this pre-conceptual design.

There are questions regarding the maximum achievable continuous heat fluxes and maximum design temperatures for some of the heating elements considering the high-temperature, high-pressure, and potentially corrosive helium environment.

3.2.2 Internal Liners and Baffles

The following Internal Liners and Baffles are proposed in the pre-conceptual test loop designs:

Test Loop	Equipment Name	Component	Material	Design Temperature (°C)	Approximate Useful Maximum Temperature (°C)
AREVA 1 MWth	First Stage Heater Vessel	Liner	Incoloy 800H	850	982
AREVA 1 MWth	Second Stage Heater Vessel	Liner	Hastelloy X	1000	1177
AREVA 30 MWth	EH1 Vessel	Liner	Incoloy 800H	714	982
AREVA 30 MWth	EH2 Vessel	Liner	Hastelloy X	1000	1177

Test Loop	Equipment Name	Component	Material	Design Temperature (°C)	Approximate Useful Maximum Temperature (°C)
AREVA 1 MWth	High Temp Pipe	Liner	Incoloy 800H	1000	982
AREVA 30 MWth	Hot Gas Ducts	Liner	Hastelloy X	980	1177
AREVA 30 MWth	Hot Gas Ducts	Liner	Incoloy 800H	750	982
AREVA 30 MWth	Hot Gas Mixing Tank	Liner	Hastelloy X	1030	1177
AREVA 30 MWth	Hot Gas Mixing Tank	Baffle	Graphite	1030	1600
WEC TDL	Hot Gas Duct	Liner	TBD (Monel - candidate)	1000	
WEC CQL1	Hot Gas Duct	Liner	TBD (High Strength Nickel Alloy - candidate)	1000	
			TBD (Machined Graphite -candidate)	1000	1600
WEC CQL2	Hot Pipes	Liner	TBD		

Three primary materials, as well as some candidate and alternative materials have been proposed in the pre-conceptual designs for the various internal liners and baffles. A number of the liner materials are TBD. The three primary materials are Incoloy 800H, Hastelloy X, and Graphite. For the liners and baffles with a specified primary material, the proposed material is acceptable with respect to the design temperature as compared to the approximate useful maximum temperature of the material.

Many of the proposed liners are quite thin. The liner proposed for the CQL1 HGD is only 1.5 mm thick. No corrosion or errosion allowances are specified in the designs and it is not likely that these thin materials have allowances for corrosion or errosion. These thin materials may require additional support to maintain their intended shapes and positions in the presence of thermal stresses and strains, thermal expansion, differential pressures, and flow or equipment-induced vibrations.

The liners and baffles in these applications are nonpressure parts per the ASME BPV Code. Nonpressure parts are essentially outside the scope of the code except when they are being welded to a pressure retaining surface of the vessel. Material for nonpressure parts need not conform to the code listed specifications for the materials to which they are attached or to the specifications of a code listed material. However, if a nonpressure part is welded to a pressure retaining surface of the vessel, it shall be of weldable quality material. The two proposed metallic liner and baffle primary materials, Incoloy 800H and Hastelloy X, are ASME BPV Code listed materials and are of weldable quality.

3.2.3 High-Performance Insulation

The following high-performance insulation applications are proposed in the pre-conceptual test loop designs:

Test Loop	Equipment Name	Material	Design Temperature (°C)	Approximate Useful Maximum Temperature (°C)
AREVA 1 MWth	First Stage Heater Vessel	Ceramic Fiber	TBD (>~850)	1430
AREVA 1 MWth	Second Stage Heater Vessel	Ceramic Fiber	TBD (>~1000)	1430
AREVA 30 MWth	EH1 Vessel	TBD		
AREVA 30 MWth	EH2 Vessel	TBD		
WEC SSDT 1 and 2	Test Vessel	TBD	TBD (~1000)	
		Graphite	TBD (~1000)	1600
		SiO2 Bricks	TBD (~1000)	1260
WEC SSDT 3	Test Vessel	TBD	TBD (~1000)	
WEC TDL	Heater 1	TBD	TBD (~950)	
WEC TDL	Heater 2	TBD	TBD (~950)	
WEC CQL2	Heater H1	TBD	TBD (~950)	
WEC CQL2	Heater H2	TBD	TBD (~950)	
AREVA 30 MWth	Cooler WC1	Ceramic Fiber	TBD (~467)	1430
AREVA 30	Cooler WC2	Ceramic Fiber	TBD (~950)	1430

Test Loop	Equipment Name	Material	Design Temperature (°C)	Approximate Useful Maximum Temperature (°C)
MWth				
AREVA 1 MWth	High Temp Piping	Ceramic Fiber	TBD (~>1000)	1430
AREVA 30 MWth	Hot Gas Ducts	Ceramic Fiber	TBD (~1030)	1430
WEC TDL	Hot Gas Ducts	TBD	TBD (~1000)	
WEC CQL2	Hot Gas Ducts	Aerogel	TBD (~950)	1000
		Microporous Silica	TBD (~950)	1000
WEC CQL2	Hot Pipes-Coaxial	TBD	TBD (~950)	

Five high-performance insulation materials have been proposed in the pre-conceptual designs for use in the various Ducts and Vessels. A number of the insulation application materials are TBD and all of the associated design temperatures are TBD at this pre-conceptual design stage. Design temperatures for these insulation applications are approximated for the purpose of this material study. The five proposed high-performance insulation materials are Ceramic Fiber, Graphite, SiO2 Bricks, Aerogel, and Microporous Silica. For the insulation applications with a specified material, the proposed material is acceptable with respect to the approximated design temperature as compared to the approximate useful maximum temperature of the material.

The insulation for the WEC SSDT test vessel is identified as requiring development.

The effects of helium infiltration on the thermal conductivity of insulation material, the effects of depressurization, and the effect of fluid impurities on insulation properties are not known. Thermal performance of insulation materials under hot helium, high-pressure conditions is uncertain. [3, Section 8, p. 85].

Little consideration has been given for the potential of the various insulations to affect the constituents of the high-purity helium environment such as by out-gassing, corrosion, or erosion.

Little consideration for structural and mechanical issues such as stress and strain, thermal expansion, fatigue, thermal shock, dynamic loading, and friability, regarding the insulation materials is presented.

4. RECOMMENDATIONS

4.1 Electric Heating Elements

More detailed design and further study of the various electric heating elements is recommended including determining the design maximum required temperature for each heating element. Availability and the level of technology readiness of electric heater elements should be investigated through discussion/negotiation with potential suppliers [3, Section 8, p. 85]. The effect of impurities at the heater elements have not been specified in a test specification. There will be chemical interaction (corrosion and further contamination) with the material of the heater element which will have to be taken into account [3, Section 5, p. 49]. Acceptable design maximum continuous heat fluxes and temperatures need to be validated. Heat transfer from heating elements to high-temperature, high-pressure helium gas is not well proven in the industry [3, Section 8, p. 85], and therefore should receive further consideration. In some cases, the heating elements are considered to be consumables. Acceptable design lives, in particular in the context of test run durations, need to be established.

4.2 Internal Liners

Further pre-conceptual design and study of the internal liners is recommended. Material identifications for several of the internal liner applications need to be completed. Monel was identified by WEC as a possible HGD liner material. The suitability of this material and other materials should be investigated further to find an optimum solution. Additional studies of the liners should evaluate their optimum thicknesses including consideration for corrosion, erosion, strength requirements, and design life. Design lives, in particular in the context of the number and duration of test runs, need to be established. Corrosion and erosion rates for the liners need to be determined. Pressure differentials across the liner might lead to liner failure. A stated function of the liners in the case of piping and ducts is to provide a smooth surface to reduce friction. The effects of the severe environment on liner surface roughness and flatness should be evaluated.

4.3 High-Performance Insulation

Further pre-conceptual design and study of the high-performance insulation is recommended. Material identifications for several of the insulation applications need to be completed. Further studies of the insulations should evaluate the effects of high-temperature and high-pressure helium infiltration on the thermal conductivity of insulation material, the effects of depressurization, and the effect of fluid impurities on insulation properties. The stability of the insulation structural characteristics and thermal properties with long-term exposure to the severe conditions should be assessed. The thermal performance of insulation materials under the severe conditions should be considered. The potential for the various insulations to affect the constituents of the high-purity helium environment such as by out-gassing, corrosion, or erosion should be considered. Structural and mechanical issues such as stress and strain, thermal expansion, fatigue, thermal shock, dynamic loading, and friability of the various insulation materials should be considered.

4.4 WEC SSDTs High-Temperature Vessels

The WEC SSDTs High-Temperature Vessels require development. More detailed design and further study of the high-temperature vessel design is also recommended.

4.5 Recuperators

Availability and the level of technology readiness of recuperators should be investigated through discussion/negotiation with potential suppliers [3, Section 8, p. 85].

4.6 High-Temperature Piping, Hot Gas Ducts, Hot Gas Mixing Tanks, Hot Headers, and Hot Pipes

Further study to determine the practical limit for maximum helium flow velocity is recommended. It is currently not known what the practical limit on helium pipe flow velocity is. Previous high-temperature helium test setups had velocities up to 65 m/s. Flow velocity could be limited by flow-induced vibration damage to the liner/insulation system, or there could be liner erosion at 950°C. If neither of these are actual problems, it becomes a plant design optimization task (i.e., a tradeoff study needs to be performed between pipe size and circulator pressure rise as these are linked by pressure drop) [3, Section 9, p. 37].

If 65 m/s is the limit on helium velocity, the WEC CTL pre-conceptual pipe diameter should be revised. The largest commercially available seamless pipe capable of 9 MPa and 350°C, is a NPS 24, which will cause flow velocities in excess of 80 m/s.

Optimization of the WEC CQL1 HDG layout is recommended [3, Section 7, p. 58].

Sizing of piping and ducting with more consideration of economic factors is recommended.

The future detail design of HGD should preclude unwanted pressure and temperature differentials developing in the HGD liner and insulation [3, Section 6, p. 62].

4.7 Helium Circulators and Blowers

The pre-conceptual designs are based on atmospheric air-standard machines scaled for helium application. More in-depth study and proof-of-concept tests are recommended to verify scaling of the air-standard machines for helium application. The study should include performance, as well as strength analysis of the machines in their helium application. Availability and the level of technology readiness of circulators and blowers should be investigated through discussion/negotiation with potential suppliers [3, Section 8, p. 85].

4.8 High-Temperature and High-Pressure Valves

Further design development and study including materials and availability for the high-temperature and high-pressure valves in the AREVA 30 MWth, WEC SSDL3, and WEC CQL2 pre-conceptual designs is recommended. Further study of these high-temperature and high-pressure valves should include rigorous consideration of the tendency for metallic components in contact with each other to diffuse (weld) together when subjected to high-pressure, high-temperature, and high-purity helium.

4.9 High-Temperature and High-Pressure Instrumentation

It is recommended that the pre-conceptual designs for high-temperature and high-pressure instrumentation be further developed and additional studies on these components be performed. The current designs are generally not developed with respect to instrumentation component materials and availability. The presentations identify that there will likely be challenges for applications at the temperature and pressure extremes. Little consideration is given for such instrumentation as strain gauges, vibration sensors, impurity monitors, chemical analyzers, air monitors, and helium monitors. It is anticipated that high-temperature thermocouples will be installed in thermowells and that pressure sensors in high-temperature applications will use impulse tubes. The thermowells and impulse tubes will impose errors in their respective associated measurements. To some level of accuracy, these sensing errors can be quantified and accounted for. The recommended further studies need to establish acceptable limits for sensing errors and determine the expected error of measurements involving such components as thermowells and impulse tubes. Further studies should also consider potential flow disturbances and perturbations, as well as, reaction loads on piping and ducts that can result from projections into the flow stream.

An investigation of the possibility of using ultrasound sensors to detect leaks in the IHX is recommended [3, Section 5, p. 49].

An investigation of methods to measure strain at high temperature inside a 9 MPa atmosphere is recommended [3, Section 5, p. 49].

An investigation of the feasibility of using a pyrometer either inside or outside the pressure vessel to measure high temperatures is recommended. The technical feasibility of placing the pyrometer outside the pressure vessel will depend on the possibility of using quartz glass windows at a pressure differential of 9 MPa [3, Section 5, p. 49].

4.10 Helium Purity

Provisions have to be made for introducing and controlling the contaminant concentration inside the test loops. As the type of contaminant determines the system design, a chemical composition study should be done first to determine the exact requirements [3, Section 5, p. 50].

It is recommended that the helium quality for the specific tests be determined. Purity and quality of the helium is significant from the perspective of corrosion of such components as heater elements and liners [3, Section 6, p. 61].

A study is recommended to assess cleaning helium of oil contaminants [3, Section 8, p. 85].

4.11 Analysis

It is recommended that computational fluid dynamics analysis, thermal analysis, finite element stress analysis, transient calculations, and life-cycle cost analysis be done on test loop components, systems, and designs [3, Section 7, p. 58]. Life-cycle cost analysis should consider the expected design lives of both specialty and COTS equipment and components, as well as, assess the required inventories of spare parts and materials.

5. IMPLEMENTATION, COST, AND SCHEDULE

Costs are associated with additional study, design, and evaluation time. The pre-conceptual test loop design costs and schedules from the vendors account for most of this time. Implementation of these actions will not significantly impact the schedule and should have a beneficial result since they are aimed at developing the technology to make it ready for application.

AREVA expects the risk associated with the test loops to be limited to normal construction risk. Project risk and research and development (R&D) are minimal because the final design of their small loop is available from AREVA. The large loop is a nominal scale up of a similar loop designed by MHI. Therefore, the project risk is considered nominal because of the past experience of the design teams in designing and manufacturing of similar test loops [2, pg.12]. Their test facility pre-conceptual design is a standard industrial complex and the risk of construction of such a facility is well known and acceptable. The risks associated with the design of the test loops are minimal.

The 1 MWth test loop is modeled after an AREVA test loop of similar configuration, which is designed to European standards. If this design is acquired, it will be converted to U.S.A. codes and standards. Facility construction can commence shortly thereafter.

The AREVA pre-conceptual test loop design also includes a large 30 MWth test loop that is essential in qualification of full-height scaled components, such as the IHX and the helium steam generator. The AREVA team has designed and manufactured a similar large test loop and is fully confident that it can be built again for the NGNP.

6. CONCLUSIONS

Material technology development requirements are identified for the CTC Test Loops design and fabrication.

Significant technology development requirements are identified for the following:

- Electric heater elements
- Internal flow liners
- High-performance insulation
- High-temperature piping
- Hot gas ducts
- Hot gas mixing tanks
- Hot headers
- Hot pipes.

Secondary technology development requirements are identified for the following:

- Recuperators
- Helium circulators and blowers.

Significant design development, including material selection and determining availability, is required for the following items. Material development requirements are likely to be identified as the designs develop for these items:

- High-temperature vessels
- High-temperature and high-pressure valves
- High-temperature and high-pressure instrumentation.

Recommendations are made identifying issues to be resolved and areas for future work.

The CTC pre-conceptual test loop design proposals are based on proven industrial technologies and components, but the actual capabilities to provide similar products today are uncertain [3, Section 8, p. 84].

The CTC test loops will fulfill the necessary short-term NGNP technology, component, and material development test needed to advance the R&D and the longer term testing capability needed for qualification of component. The proposed pre-conceptual designs are considered challenging, but feasible with reasonable R&D.

Testing conducted in the proposed SSDTs can yield valuable experimental information, including required material technology, and can subsequently act as a stepping stone for testing of interrelated components to be conducted in TDLs as well as CQL [3].

7. REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, 2004.

2. AREVA, NGNP Component Test Facility Test Loop Pre-Conceptual Design, Document No. 12-9097512-001, December 2008.

3. Westinghouse Electric Company, NGNP CTF Test Loop Preconceptual Design Report, NGNP-CTF MTECH-TLDR, Revision 2, February 2009.