Design of a Test Facility to Investigate Fundamental Na-CO₂ Interactions in Compact Heat Exchangers

Nuclear Engineering Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne, see <http://www.anl.gov>.

Availability of This Report

This report is available, at no cost, at <http://www.osti.gov/bridge>. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

Design of a Test Facility to Investigate Fundamental Na-CO₂ Interactions in Compact Heat Exchangers

M. T. Farmer, D. J. Kilsdonk, J. J. Sienicki, and C. Grandy
Nuclear Engineering Division
Argonne National Laboratory

September 30, 2010

SUMMARY

One of the key objectives of the SFR R&D program is to develop and demonstrate innovative cost reduction and performance enhancing technologies for SFRs. The supercritical carbon dioxide (S-CO₂) Brayton cycle power converter system has been identified as one such innovation that could contribute to meeting this objective. One appealing feature of this system is the small footprint that the hardware requires, which is in part due to the use of Printed Circuit Heat Exchangers (PCHEs) as the secondary (Na-to-CO₂) heat exchanger as well as the recuperator and cooler modules. Although PCHEs have a high degree of structural integrity, the potential for leak(s) to develop between the sodium and CO₂ coolant channels in the secondary heat exchanger cannot be ruled out, leading to discharge of high pressure CO₂ into the secondary coolant circuit. Due to the robustness of the PCHE design, catastrophic failure leading to gas jet blowdown into the secondary sodium loop is not deemed to be a likely scenario. Rather, small crack(s) (or micro-leaks) may develop in which CO₂ will bleed into the secondary system at a relatively low rate and chemically react with the sodium.

The primary focus of the current work is to develop an experiment capability to investigate reaction characteristics under micro-leak conditions. This report summarizes the progress that was made towards meeting this objective this fiscal year. In particular, the facility scaling rationale was developed, and on that basis, the detailed facility design and operating procedures were completed. Based on the design work, fabrication drawings for the three primary system components (i.e., test vessel, dump tank, and separator/vapor trap) were generated and submitted to an outside vendor (i.e., Ability Engineering Technology in South Holland, IL) for fabrication. Fabrication of these components was also completed this year. Plans are to have the facility assembled by the midpoint of FY11 and to begin shakedown testing at that time.

Table of Contents

Summary	i
List of Figures	iii
List of Tables	iii
1 Introduction	4
1.1 Background	4
1.2 Objectives and Approach	6
2 Facility Design Description	7
2.1 Facility Scaling Rationale	7
2.2 Facility Design	12
2.3 Operating Procedures	16
3 Summary	17
4 References	17

LIST OF FIGURES

Figure 1: Schematic Illustration of a S-CO₂ Brayton Cycle Power Conversion System
Coupled to a Pool-Type SFR. 4

Figure 2: Schematic Diagram Showing Key Elements of the Test Facility. 9

Figure 3: (a) Top Flange Assembly and (b) Body of Test Vessel Assembly. 13

Figure 4: Design Details for Separator/Vapor Trap..... 15

Figure 5: Design Details for Sodium Dump Tank. 15

LIST OF TABLES

Table I: Facility High Level Design Requirements and Approach..... 8

Table II: Property Data Assumed in Analyses..... 10

1 Introduction

1.1 Background

One of the key objectives of the SFR R&D program is thus to develop and demonstrate innovative cost reduction and performance enhancing technologies for SFRs. The supercritical carbon dioxide (S-CO₂) Brayton cycle power converter system has been identified as one such innovation that could contribute to meeting this objective. This system, depicted schematically in Figure 1, removes energy from the intermediate sodium circuit in a pool-type reactor plant or the primary or intermediate sodium circuit in a loop-type plant and converts it into electrical energy.

Figure 1: Schematic Illustration of a S-CO₂ Brayton Cycle Power Conversion System Coupled to a Pool-Type SFR.

A major benefit of the S-CO₂ Brayton cycle is elimination of the potential for energetic sodium-water reactions which result in the formation of combustible hydrogen gas. Desirable attributes for this system include: 1) reduction in power conversion system costs relative to the Rankine steam cycle by taking advantage of the small sizes of the turbine and compressors as well as the fewer number of components [i.e., the condenser, feedwater heaters, and deaerator of the Rankine cycle are eliminated]; and 2) higher thermal efficiency relative to the Rankine steam cycle especially at the higher reactor core outlet temperatures of some sodium-cooled fast reactor concepts. Operating pressures are 20 MPa or higher at the compressor outlets and remain above the CO₂ critical pressure of 7.377 MPa at the compressor inlets during normal operation at nominal load. The CO₂ temperature remains above the CO₂

critical temperature of 30.98 °C during normal operation. The components including the turbine and compressors must be manufactured from alloys that are resistant to corrosive oxidation attack by CO₂ while also meeting other structural requirements.

One feature contributing to footprint reduction for this system is the use of compact diffusion-bonded heat exchangers such as Printed Circuit Heat Exchangers (PCHEs) or Hybrid Heat Exchangers (H²Xs) [1,2] as the secondary (Na-to-CO₂) heat exchanger as well as the recuperator and cooler modules. PCHEs are high integrity plate type heat exchangers that are fabricated from flat metal plates (sheets) that have fluid flow channels that are chemically etched using the same process developed for electronic printed circuit board production. The etched plates are stacked and diffusion bonded together to make the core of the heat exchanger. These units can be four to six times smaller than conventional shell and tube heat exchangers of the equivalent duty cycle, and they have pressure and temperature capabilities in excess of 600 bar and 900°C, respectively.

Although PCHEs and H²Xs have a high degree of structural integrity, the potential for leak(s) to develop between the sodium and CO₂ coolant channels in the secondary heat exchanger cannot be ruled out, leading to discharge of high pressure CO₂ into the secondary coolant circuit. Due to the robustness of the PCHE design, catastrophic failure leading to gas jet blowdown into the secondary sodium loop is not deemed to be a likely scenario. Rather, small crack(s) (or micro-leaks) may develop in which CO₂ will bleed into the secondary system at a relatively low rate and chemically react with the sodium. This is the failure mode that has been observed for PCHEs used in the offshore oil and gas industry. The former (gas jet) scenario is more relevant for shell and tube heat exchanger designs that do not have the monolithic construction features of PCHEs. Modeling and experiments addressing this case have been carried out by Gicquel et al. [3]. The primary focus of the current work is to develop an experiment capability to investigate reaction characteristics under micro-leak conditions.

In terms of the theory underlying the chemical reaction process, Gicquel et al. [3] note that two Na-CO₂ chemical reaction scenarios are possible. In particular, for a temperature below ~ 500 °C, the CO₂ reacts with sodium, principally forming sodium oxalate (Na₂C₂O₄) and carbon monoxide (CO). The oxalate then further reacts with the sodium to form oxide (Na₂O). The reactions are of the form [3],

The carbonate is effectively inert in the sodium, remaining as a solid solution that can precipitate out within the system with potentially undesirable consequences. Oxygen is normally present in the coolant at ppm levels; the oxide may decompose or remain in solution depending upon the oxygen potential in the coolant. The CO can react with sodium also, but the kinetics of this reaction are much slower than the sodium-oxalate reaction [3] and so the potential exists for the monoxide to loiter in the solution for some (undetermined) length of

time, possibly passing out of the system as a gas that could accumulate at high points in the secondary sodium loop.

As noted earlier, above ~ 500 °C the Na-CO₂ reaction takes a different form. In particular, the sodium rapidly reacts with the gas to form elemental carbon as well as carbonate; i.e. [3],

As is evident from this equation, in this temperature regime there is no gaseous byproduct from the reaction. Moreover, the carbonate remains as an inert solid in solution with the sodium.

The above discussion indicates that if a small leak in a compact heat exchanger were to develop, then solid byproducts (principally sodium carbonate) will be formed below ~ 500 °C. One question that arises is whether or not the carbonate that forms could possibly plug the leak over time, yielding the beneficial outcome that the small leaks are self-healing. This is one of the principal questions to be addressed as part of this work, along with evaluating the chemical reaction characteristics under low flow conditions.

1.2 Objectives and Approach

The purpose of this work is to develop the capability to conduct well-controlled experiments that can achieve the following two technical objectives:

1. Determine the nature and extent of the chemical reactions that occur between high pressure CO₂ issuing into liquid sodium from a micro leak across a stainless steel pressure boundary as a function of the sodium pool temperature and inlet CO₂ flowrate, and
2. Examine the potential for the micro-leak to seal itself up as a result of blockage formation from the chemical reaction byproducts of the Na-CO₂ reaction.

The experiment approach for achieving these objectives is to construct a well-instrumented test facility that consists of a vessel containing molten sodium with a test specimen that mocks up a micro-crack in a PCHE located at the bottom of the pool. High-pressure CO₂ is bled through the crack under controlled (i.e., constant pressure and temperature) conditions; flowrate through the crack is monitored over time to determine if the crack plugs and, if so, the rate at which plugging occurs. The gas composition over the interaction is monitored with a gas mass spectrometer to determine the gaseous byproducts that evolve from the chemical reactions described above; local sodium temperatures around the crack are also monitored. Aside from examining the potential for a micro-crack to plug, these data provide additional information to validate the proposed chemical reaction sequences given by Gicquel et al. [3] that were outlined above.

The balance of this report describes progress made towards meeting these objectives this fiscal year. To that end, the scaling rationale, facility design, and planned operating procedures are described in the next section. This information is followed by a summary of the project status.

2 Facility Design Description

The purpose of this section is to summarize the design for a facility focused on investigating Na-CO₂ reactions under conditions that mock up a small leak within a PCHE. In order to guide the design effort, a scaling rationale (or design basis) was first established. This basis is described immediately below, and with that foundation in place, the facility layout and operating procedures are provided in the balance of this section.

2.1 Facility Scaling Rationale

The high-level facility design requirements and corresponding experiment approach are summarized in Table I, while a schematic diagram showing key elements of the facility is provided in Figure 2. The basic test concept is to bleed high pressure (20 MPa) CO₂ through a small hole that mocks up a postulated leak site in a PCHE into a high temperature (500°C+) sodium pool and investigate the ensuing interaction. Due to the temperatures, pressures, and nature of the materials involved, a robust facility design is required that is coupled with a sound operational approach that will ensure that safe operating conditions are maintained even under postulated accident conditions. Thus, the first requirement is to provide robust facility that can tolerate elevated pressures at high temperatures. To this end, the key facility components (i.e., test vessel, flow separator, and dump tank) are designed and fabricated according to ASME Section VIII Division 1 standards for operation at 510° C at up to 30 bar pressure. All components are also rated for operation at full vacuum, which is relevant during initial facility setup wherein the apparatus is evacuated and backfilled with an inert gas (i.e., argon) prior to filling with sodium.

The next criteria involve sizing the facility so that prototypic interaction data can be obtained. The exact design for a H²X or PCHE that would be employed in a Brayton cycle power conversion system for a SFR is currently not known, nor have detailed assessments been made of the nature or extent of crack(s)/leak(s) that may develop in these units over time. Thus, it is not currently possible to propose an experiment that would address design-specific issues (if any). Thus, the approach taken herein is to develop a test capability to examine leak site behavior under conditions that mock up an open pool configuration (i.e., geometry effects are deliberately neglected), but to also provide enough space in the facility so that geometry-specific mockups could be addressed at a later time once the design details are known. With the intent of mocking up open pool conditions established, the basic requirement then becomes that facility geometry will not effect thermalhydraulic conditions at the leak site. Small leaks are addressed as part of this study and so it is envisioned that discrete bubbles would periodically be discharged from the site, as opposed to gas-jetting behavior. Under bubbly flow conditions, the maximum bubble size is limited to the length scale of the Rayleigh-Taylor instability that is given through the equation [4]:

$$d_{\max} \sim \lambda_{R-T} = \sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} \quad (3)$$

Thermophysical property data assumed in this study are provided in Table II. Given this data, the maximum bubble size in the sodium pool under bubbly flow conditions is estimated as 4.9 mm from Eq. 3. As described later in this section, a 10 cm (4 inch Schedule 40) pipe is

used as the test vessel. Thus, the ratio of vessel diameter to stable bubble diameter is ~ 20 at atmospheric pressure (assumed sodium pool condition), which for thermalhydraulics testing is more than adequate to minimize wall effects. Another requirement is that the test vessel axial dimension should be large enough to mock up deep pool behavior. This issue relates to the kinetics of the Na-CO₂ chemical reactions described earlier in relation to the bubble residence time in the pool. The residence time will be determined by the bubble terminal rise velocity in the pool which can be approximated from the equation [4]:

$$U_{\infty} = 1.53 \left(\frac{g\sigma(\rho_l - \rho_g)}{\rho_l^2} \right)^{1/4} \quad (4)$$

Table I: Facility High Level Design Requirements and Approach.

No.	Design Requirement	Approach
1	Provide robust facility capable of safe operation at 500°C+ and at elevated pressure.	Fabricate test column, dump tank, and demister per ASME Section VIII Division 1 standards for operation at 510° C at up to 30 bar pressure.
2	Test vessel diameter shall be large enough to mock up open pool behavior	Provide 10 cm ID test column; ratio of vessel diameter to stable gas bubble diameter is 20
3	Test vessel axial dimension shall be sufficient to mock up deep pool behavior	Initial working sodium pool level height is 1.2 m. Design is modular so that additional columns can be added to increase testable pool depth.
4	The facility shall be designed and instrumented to (initially) test leak sizes of up to 75 µm equivalent diameter at 20 MPa back pressure.	Maximum leak rate through 75 µm hole size estimated using a choked flow calculation; control and instruments sized and laid out accordingly.
5	Facility shall be capable of long-term unattended operation.	Test section instrumented to detect plugging or failure at the leak site location; facility shuts down automatically if either condition is detected.
6	Facility design should be flexible so that design-specific issues related to plugging, as well as other thermal-hydraulic issues, can be addressed without major rework.	As noted under Req. No. 3, design is modular so that additional columns can be added to increase testable pool depth. In addition, many extra fittings are provided for additional access to the test section for multiple/diverse testing capabilities.

Figure 2: Schematic Diagram Showing Key Elements of the Test Facility.

Table II: Property Data Assumed in Analyses.

Property	Value
Sodium density (~ 500 °C)	832 kg/m ³
Sodium viscosity (~ 500 °C)	2.3·10 ⁻⁴ Pa·s
Sodium surface tension	0.2 N/m
CO ₂ ideal gas constant (PCHE inlet)	1.26
CO ₂ density (PCHE inlet)	179 kg/m ³
CO ₂ ideal gas constant (PCHE outlet)	1.35
CO ₂ density (PCHE outlet)	138 kg/m ³
Inlet CO ₂ pressure	20 MPa
Sodium pool normal operating pressure	0.1 MPa

The terminal velocity is calculated as 33.7 cm/sec from this expression give the property data in Table II. As shown later in this section, the test vessel is of modular construction with a working pool sodium depth of up to 1.2 m in each section. Thus, with the base design, the bubble residence time can range up to (1.2 m divided by 0.337 m/sec equals) 3.6 seconds. If test results indicate no off-gas from the interaction (see Eq. 2), or the off-gas is essentially all CO (see Eq. 1), this would imply that the chemical reactions had reached completion as the bubbles ascend through the pool. However, if significant CO₂ is detected in the offgas stream then pool depth could be increased as required to determine if the reaction is kinetics- or species-limited at the given sodium pool temperature. This knowledge is important to support the development of leak detection methods for this particular power converter system.

The next criterion relates to sizing the facility equipment to provide a regulated CO₂ flow through a specified leak size. As part of this work, materials specialists were consulted in order to ascertain the size of leaks that may form in a PCHE under prototypic operating conditions. This turned out to be a difficult task and no definitive size range could be established. On this basis, ANL Central Shops was consulted in order to identify the smallest hole diameter or slit width that could be machined into stainless steel to form a test specimen that mocks up a leak site. This enquiry indicated that well-defined holes/slits of 25 – 75 µm width (viz. 1-3 thousandths of an inch) could be produced in stainless steel using an Electron Discharge Machine (EDM). In order to move forward with the apparatus design, this size range was thus adopted as the initial hole sizes to be addressed in the experiment.

Under design operating conditions, the CO₂ pressure upstream of the leak will be nominally 20 MPa, while the sodium pool temperature will be atmospheric. Hence, the flow across the leak will certainly be choked. The critical pressure and critical gas mass flux through the leak site can thus be approximated through the equations [5]:

$$\frac{P_c}{P_o} = \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} \quad (5)$$

$$\frac{G_c}{\sqrt{k P_o \rho_o}} = \left(\frac{2}{k+1} \right)^{\frac{k+1}{2(k-1)}} \quad (6)$$

Given the data in Table II, the gas mass flux through a postulated leak near the PCHE CO₂ inlet and exit sections are evaluated as 39,475 and 35,513 kg/m²·sec, respectively. The choked-flow leak rate out of a 25 μm diameter hole near the CO₂ inlet to the heat exchanger would thus be ~ 0.019 g/sec, which corresponds to a volumetric flowrate of $\dot{Q} \sim 0.65$ standard liters per minute (slpm). Conversely, the leak rate out of a 75 μm hole near the inlet would be ~ 0.17 g/sec, which corresponds to a volumetric flowrate of $\dot{Q} \sim 5.8$ slpm. It is of interest to estimate the sodium pool void fraction given this flow range, since this will determine the extent of pool swell during the experiments. Under bubbly flow conditions in a pool configuration the void fraction can be evaluated from the following drift flux model [4]:

$$\alpha = \frac{j_g}{C_o j_g + U_\infty} \quad (7)$$

where $C_o = 1.2$ according to Zuber and Findlay [6] and the pool superficial gas velocity is given through the expression:

$$j_g = \frac{\dot{Q}(T_p)}{A} \quad (8)$$

In the above, T_p denotes sodium pool temperature and A is the test vessel cross-sectional flow area (78.5 cm²). Bubbly flow conditions are maintained in the pool as long as j remains below the threshold value for onset of the churn-turbulent flow regime, which is given by [7]:

$$j_{b-ct} = 0.5 \left(\frac{g \sigma (\rho_l - \rho_g)}{\rho_l^2} \right)^{1/4} \quad (9)$$

The pool superficial gas velocities evaluated from Eq. 8 at a sodium temperature of 500°C range from 0.4 to 3.6 cm/sec for the 25 and 75 μm hole diameters, respectively. Threshold gas velocity for onset of churn-turbulent flow is found from Eq. 9 as 11 cm/sec, and so bubbly flow pool conditions will exist for the range of hole diameters considered as part of this planning study. The pool void fraction evaluated from Eq. 7 ranges from 0.12 to 9.7 % over this hole size range, which is modest. Thus, sodium pool depths of up to 1.08 m could be tested without exceeding the single test section maximum pool depth of 1.2 m.

The fifth requirement in Table I focuses more on the details of the experiment design and operating procedures as opposed to overall approach. If plugging occurs, the timescale may be quite long (e.g., days to weeks), and so autonomous operational capability is required. Also, if some sort of failure were to occur in the test specimen, this could lead to an accelerated rate of CO₂ flow into the test section that exceeds design conditions. The section should be instrumented to detect either plugging or failure at the leak site location, and to shut down automatically if either condition is detected.

Finally, the sixth requirement calls for the facility to be flexible so that other types of testing can be conducted. As noted earlier, the vessel design is modular so that deeper pool configurations can be evaluated if the need arises. In addition, many extra fittings are provided for additional access to the test section for multiple/diverse testing capabilities. Other possible testing missions that were discussed during the test planning phase for this test facility include:

1. fission product scrubbing tests focused on providing basic data to validate aerosol scrubbing models that evaluate the extent of aerosol retention in the sodium coolant following fuel cladding breach, and¹
2. CO₂ blowdown tests at higher flowrates to provide data to support validation of codes (e.g. see Giguel et al. [3] for a summary of French work, and Shin et al. [8] for a description of the original SWAAM code, which has recently been updated to examine Na-CO₂ interactions) that examine the thermalhydraulic aspects of CO₂ gas jets interacting with sodium.²

Other potential uses for the facility may be identified as R&D on the SFR moves forward.

2.2 Facility Design

As shown in Figure 2, key elements of the test facility consist of: i) the test vessel, ii) argon covergas supply system, iii) CO₂ supply system to the test specimen that mocks up the leak site in the PCHE, iv) sodium dump system, and v) offgas system.

The test vessel, shown in greater detail in Figure 3, is constructed from 10 cm (4 inch) diameter Schedule 40, 304 stainless steel pipe. Grayloc fittings are used for all primary vessel penetrations as these have been shown over years of experience to function very effectively for liquid metal systems. The vessel contains many extraneous 2.5 cm (1 inch) diameter penetrations through the sidewalls that provide access for instrumentation and/or ancillary equipment that may be needed for experiment purposes. A total of 5 instrument penetrations are mounted on the test vessel lid, and these are sealed with VCR fittings as these also have been shown to function quite well in liquid metal systems. The test vessel as well as other key system components (i.e. separator/vapor trap and sodium dump tank) are fabricated per ASME Section VIII Division 1 standards and stamped for operation at 510° C at up to 30 bar pressure. All vessel penetrations are stood off by 10 cm from the vessel main body to provide room for insulation, and so that the penetrations can be freeze-sealed if so desired. The vessel lid is mounted to the main vessel body with a 10 cm Grayloc flange, so that additional spool pieces can be added if needed to increase overall vessel height. The lower assembly is 1.2 m (48 inch) high which effectively defines the maximum pool depth that can be tested with the single lower section configuration. The vessel body and lid are trace heated using mineral-insulated coaxial heater cable (temperature operating limit: 630°C) in order to maintain the

¹To examine the potential for fission product scrubbing, a metered dose of fission product surrogates would be injected into the sodium pool at a pre-defined depth; the resultant concentration of fission products in the gas plenum of the apparatus would then be measured with an aerosol detection system. The extent of scrubbing would then be determined by the difference of the injected vs. detected quantities.

²To provide data to evaluate the consequences of CO₂ gas jet blowdown, a fixed volume of compressed gas would be injected at a higher flowrate near the base of the apparatus. The extent of pool swelling and jet breakup during the blowdown event would be evaluated with a flash X-ray video camera system, thereby providing data to support code validation efforts.

Figure 3: (a) Top Flange Assembly and (b) Body of Test Vessel Assembly.

assembly at a designated temperature during the experiments. In terms of instrumentation, spot-welded Type K thermocouples are placed on the exterior of the vessel to monitor vessel temperature. These instruments are also used as input for the heater controllers. Thermocouple rakes are mounted through the VCR fittings on the lid of the assembly to provide axial as well as radial temperature measurements in the sodium pool. Conductivity

probes, also mounted through the lid, are used to determine sodium depth during fill operations. Finally, a rupture disk provides overpressure protection for the test section. This line is vented to a sand-filled drum to filter out any sodium droplets that may be entrained through the vent line if the rupture disk were to fail during an experiment.

As currently envisioned, the test specimen with mockup leak site would consist of a 6.4 mm diameter (1/4 inch) stainless steel tube with the end welded shut. The simulant hole is machined laterally through the side of the tube near the tip using an EDM. The tube is then welded into a Grayloc blind flange to produce a sound mechanical penetration; the penetration is located near the bottom of the test vessel. The current design does not include any dedicated device for preheating of the CO₂ before it enters the test vessel. Rather, the approach is to supply sufficient tubing length within the vessel itself so that the CO₂ will be heated by the surrounding sodium to the pool temperature as it flows to the leak site. The final design configuration will thus consist of a coil of sufficient length to ensure that the desired temperature rise can be achieved.

The CO₂ source consists of a traditional bottle manifold that feeds a booster pump. The pump pressurizes a reservoir cylinder that is used to supply a regulated pressure to the leak site at up to 20 MPa pressure; the reservoir is used to dampen pressure fluctuations that are inherent when the pump is operational. Flowrate to the tube is measured with an orifice that has two additional transducers for measuring, separately, pressures upstream and downstream of the orifice. The occurrence of plugging will be evidenced by the pressure across the orifice tending towards zero. A flow-limiting orifice is positioned upstream of the flow measurement orifice. This is a safety device that limits the peak CO₂ flowrate to the test section to an acceptable level should the tube feeding the leak site fail, but does not result in a significant pressure drop under normal operating conditions. The output from the orifice differential pressure transducer provides a feedback signal that automatically closes an isolation valve on the feed line to the leak site if the flowrate exceeds a user-defined threshold value.

The offgas system consists of a separator/vapor trap (Figure 4) that removes any sodium aerosol before exhausting the gas mixture to the atmosphere. The mixture will consist of the argon covergas plus any CO₂/CO that escapes from the sodium pool. Offgas composition is measured using an on-line gas mass spectrometer. The argon covergas is fed into the system at a constant flowrate using a mass flow controller. Given the offgas composition measured by the spectrometer, then the flowrates of CO and CO₂ issuing from the pool can be determined given the (known) flowrate of argon. The CO flowrates determined by this analysis can then be used through a mass balance to determine the extent of the gas retention in the pool as a function of time.

Aside from these basic elements, the facility also includes a 41 liter capacity (11 gallon) sodium dump tank (Figure 5) with a dedicated trace heating system that serves as the storage location for the sodium when tests are not being conducted. The tank is equipped with the usual valving architecture that is required to drain and fill (using argon pressure as the driving force) the test section with sodium. The tank is also configured with a remotely actuated dump valve so that sodium can rapidly be drained from the system under off-normal operating conditions (e.g. sodium leakage from the test section, or failure of the CO₂ leak site leading to high purge of CO₂ into the test vessel). The sodium volume to fill the test vessel to the 1.2 m elevation is ~ 9.4 liters. Thus, the dump tank holds sufficient sodium to fill the test column to a depth of ~ 5 m if additional vessel spool pieces were added for future tests.

Figure 4: Design Details for Separator/Vapor Trap.

Figure 5: Design Details for Sodium Dump Tank.

2.3 Operating Procedures

The above sections have outlined the scaling rationale and overall mechanical approach for carrying out tests to investigate the potential for plugging of a small leak in a PCHE. This section provides a summary of the planned operating procedure once facility fabrication is completed.

After the facility is completely assembled, the first step is to helium leak check the apparatus at room temperature by pressurizing the system. After the system is rendered leak tight, the facility components (i.e. test vessel, dump tank, and separator/vapor trap) along with interconnected piping that will contact sodium will be trace heated to 450°C while pulling a vacuum to remove volatile impurities (e.g. cutting oil). This process will continue (usually over the course of several days) until the vacuum level (i.e., pressure) stabilizes, indicating that no additional impurities are being liberated. Once this step is completed, the test apparatus will be helium leak checked again at temperature (450°C) and any fittings that may have come loose during thermal cycling will be retightened. After this step is completed, the apparatus will be allowed to cool to room temperature while maintaining a continuous argon purge through the system. Once at room temperature, the apparatus will be evacuated and back-filled with argon at least three times in order to achieve an inert argon atmosphere.

With these steps completed, the facility will be ready for initial filling with sodium. The sodium dump tank, test vessel, and all interconnected piping will be trace heated to a nominal sodium transfer temperature of 110°C. A slow purge of argon³ will then be initiated through the microleak in the test section so that the hole does plug upon initial sodium transfer into the test section. Once this step is completed, the plenum of the sodium dump tank will be pressurized with argon to a level that is sufficient to overcome the pressure head required to raise the sodium into the test section. The isolation valve on the dump tank will be opened to start pushing sodium up into the test section; the test section plenum isolation valve will then be opened to atmosphere to vent argon from the system while the transfer occurs. Once the sodium level reaches a predefined level (as evidenced by a contact reading with the conductivity probe in the test section that has been positioned at the target sodium fill level), the transfer valve on the dump tank will be closed as well as the test section vent valve to atmosphere. Purge of the test section plenum with argon covergas will then be started, and the sodium dump tank will be vented to atmospheric pressure.

With these steps carried out, the controllers on the trace heaters will be adjusted to the target sodium pool temperature for the experiment. Once the pool temperature stabilizes at the target value, the argon purge through the test specimen will be terminated and then the booster pump on the CO₂ supply line will be activated to bring the line up to target pressure for the test and start the CO₂ flow through the system. Long term test operation will then be initiated while monitoring differential pressure across the flow orifice to determine if/when plugging occurs. Gas sampling of the offgas system with the online gas mass spectrometer will also be carried out to determine gas speciation as a result of the Na-CO₂ interactions. During operations, the sodium dump tank and transfer line are maintained at transfer temperature (110°C) so that the sodium can immediately be returned to the dump tank (by

³Argon is used rather than CO₂ during this stage to prevent any reactions/interactions/early oxidation/tube plugging from occurring during initial test startup.

opening the isolation valve on the transfer line as well as the pressure balancing line between the dump tank and test section plenums) under any type of off-normal operating condition.

Once the test is declared to be completed, either by plugging of the microleak or by satisfying some other test termination criterion, the sodium will be returned to the dump tank for interim storage between experiments. The test specimen will then be removed from the test section and the sodium removed by soaking in an alcohol bath so that the characteristics of the leak site can be examined.

3 Summary

One of the key objectives of the SFR R&D program is thus to develop and demonstrate innovative cost reduction and performance enhancing technologies for SFRs. The supercritical carbon dioxide (S-CO₂) Brayton cycle power converter system has been identified as one such innovation that could contribute to meeting this objective. One appealing feature of this system is the small footprint that the hardware requires, which is in part due to the use of Printed Circuit Heat Exchangers (PCHEs) as the secondary (Na-to-CO₂) heat exchanger as well as the recuperator and cooler modules. Although PCHEs have a high degree of structural integrity, the potential for leak(s) to develop between the sodium and CO₂ coolant channels in the secondary heat exchanger cannot be ruled out, leading to discharge of high pressure CO₂ into the secondary coolant circuit. Due to the robustness of the PCHE design, catastrophic failure leading to gas jet blowdown into the secondary sodium loop is not deemed to be a likely scenario. Rather, small crack(s) (or micro-leaks) may develop in which CO₂ will bleed into the secondary system at a relatively low rate and chemically react with the sodium.

The primary focus of the current work is to develop an experiment capability to investigate reaction characteristics under micro-leak conditions. This report summarizes the progress that was made towards meeting this objective this fiscal year. In particular, the facility scaling rationale was developed, and on that basis, the detailed facility design and operating procedures were completed. Based on the design work, fabrication drawings for the three primary system components (i.e., test vessel, dump tank, and separator/vapor trap) were generated and submitted to an outside vendor (i.e., Ability Engineering Technology in South Holland, IL) for fabrication. Fabrication of these components was also completed this year. Plans are to have the facility assembled by the midpoint of FY11 and to begin shakedown testing at that time.

4 References

1. D. Southall and S. J. Dewson, "Innovative Compact Heat Exchangers," Paper 10300, Proceedings of ICAPP '10, San Diego, CA, June 13-17, 2010.
2. See www.heatric.com.
3. L. Gicquel, C. Latgé, and N. Simon, "Supercritical CO₂ Brayton Cycle Coupled with a Sodium Fast Reactor: Na/CO₂ Interaction Experiments and Modeling," Paper 10215, 2010 International Congress on Advances in Nuclear Power Plants (ICAPP '10), San Diego, CA, USA, June 13-17, 2010.
4. G. B. Wallis, One-Dimensional Two-Phase Flow, McGraw-Hill, New York, NY, 1969.

5. F. J. Moody, Introduction to Unsteady Thermofluid Mechanics, J. Wiley & Sons, New York, NY, 1990.
6. N. Zuber and J. A. Findlay, "Average Volumetric Concentration in Two-Phase Flow Systems," J. Heat Transfer, Vol. 87, pp. 453–468, 1965.
7. I. Kataoka and M. Ishii, "Mechanistic Modeling and Correlations for Pool Entrainment Phenomenon," Int. J. Heat Mass Transfer, Vol. 27, pp. 199-2014, 1984.
8. Y. W. Shin, H. H. Chung, A. H. Wiedermann, and H. Tanabe, "SWAAM-LT: The Long-Term Sodium/Water Reaction Analysis Method Computer Code," SMiRT-12, Elsevier Science Publishers, 1993.

Nuclear Engineering Division

Argonne National Laboratory

9700 South Cass Avenue, Bldg. 208

Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC