Fundamental Na-CO₂ Interactions in Compact Heat Exchangers Experiments (SNAKE): FY 2011 Status Report

Nuclear Engineering Division

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ABSTRACT

The U.S. Department of Energy (U.S. DOE) Advanced Reactor Concepts (ARC) Program is developing the Sodium-Cooled Fast Reactor (SFR) as a reactor that could dramatically improve performance in sustainability, safety, economics, security, and proliferation resistance. The near-term Program goal is to reduce technical barriers (e.g., by resolving key feasibility and performance challenges) to improve the prospects of advanced technology reactor systems. In the long-term, integrated advanced reactor system designs will be developed that implement the chosen missions and complete the testing and demonstration necessary for licensing. The supercritical carbon dioxide (S-CO₂) Brayton cycle, coupled with an SFR, has been identified as a new and innovative energy conversion technology that could contribute to meeting these objectives.

One appealing feature of this energy conversion system is the smaller footprint that the hardware requires relative to the traditional superheated steam cycle, which is in part due to the use of Printed Circuit Heat ExchangerTM (PCHETM) compact diffusion-bonded heat exchangers as the heat source heat exchanger (sodium-to-CO₂) 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 intermediate sodium loop is not deemed likely. 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.

In recognition of the anticipated failure mode for a PCHE sodium-to-CO₂ heat exchanger, an experiment program at Argonne was initiated in FY 2010 to investigate the reaction characteristics between sodium and CO₂ under micro-leak conditions. This report describes the facility scaling rationale and design. Significant progress toward completion of the assembly of the SNAKE (S-CO₂, Na Kinetics Experiment) has been made in FY 2011. All major components and instruments have been specified and purchased. The gas delivery system has been designed and is nearly assembled. A simple water mockup system has been built and will be coupled with the gas delivery system in FY 2012 to visualize the micro-nozzle physics prior to use in sodium. A temperature control system has been assembled to control the trace heating of all sodium-carrying vessels and pipes. A large (3.7m) enclosure has been constructed and is currently being used as the support system for experiment assembly. This assembly includes adding sodium-management equipment such as stainless-steel catch trays and sodium-smoke removal fans and duct work. A number of analyses have been completed to support the safety case for the operation of this experiment facility. The facility itself has been designed to be flexible to accommodate other types of testing in the future. Many of the facility components are modular and include a number of extra fittings for diversity.

The goal of the sodium-CO₂ interaction tests is a fundamental understanding of sodium-CO₂ interactions under prototypical conditions of compact diffusion-bonded heat exchanger failure, a fundamental understanding of self-plugging if it occurs, and the development of one-dimensional phenomenological models for the interactions between high-pressure CO₂

issuing into liquid sodium from a micro leak across a stainless steel pressure boundary. These models will be validated using the experiment data obtained.

Most major components have been purchased, and portions of the facility have been assembled in 2011. Completion of procurement is expected in December 2011. Complete assembly of the facility and initial sodium loading is anticipated in June 2012. A report documenting these activities will be produced the following month. Facility shakedown and initial data will be complete in September 2012, along with a summary report. Fiscal Year 2013 will consist of obtaining the complete experiment data matrix, with a detailed report delivered in September 2013. Model development and validation will take place the following Fiscal Year, with a detailed model report anticipated to be delivered in June 2014.

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1 Introduction

1.1 Background

The U.S. Department of Energy (U.S. DOE) Advanced Reactor Concepts (ARC) Program is developing the Sodium-Cooled Fast Reactor (SFR) as a reactor that could dramatically improve performance in sustainability, safety, economics, security, and proliferation resistance. The near-term Program goal is to reduce technical barriers (e.g., by resolving key feasibility and performance challenges) to improve the prospects of advanced technology reactor systems. In the long-term, integrated advanced reactor system designs will be developed that implement the chosen missions and complete the testing and demonstration necessary for licensing. The supercritical carbon dioxide (S-CO₂) Brayton cycle, coupled with an SFR, has been identified as a new and innovative energy conversion technology that could contribute to meeting these objectives. 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 at greatly improved thermal efficiencies over comparable Rankine cycle conversion schemes depending upon the reactor core outlet sodium temperature). The S-CO₂ Brayton cycle was identified as the primary energy conversion system of interest under the ARC Program and evaluation of the chemical reactions between the reactor coolant and balance of plant fluid was specifically mentioned as a program goal (ARC, 2011).

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 Printed Circuit Heat Exchangers (PCHEs) (Li et al., 2006) as the heat source heat exchanger (Na-to-CO₂) as well as the recuperator and cooler modules. PCHEs are high integrity plate type heat exchangers that are fabricated from flat metal plates that have fluid flow channels formed via chemical etching using a process similar to that 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 heat duty, and they can have pressure and temperature capabilities in excess of 600 bar and 900°C, respectively.

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. Heatric claims that the pressure-boundary failure mechanism consists only of slow leakage due to the formation of small cracks between the streams (Chang et al., 2006). It is expected that small crack(s) (or micro-leaks) may develop in which CO₂ will bleed into the sodium at a relatively low rate and chemically react with the sodium (see Figure 2 for a schematic of this interaction). The former (gas jet) scenario is more relevant for shell-and-tube heat exchanger designs that do not have the monolithic construction features characteristic of PCHEs. Modeling and experiments addressing this case have been carried out by Gicquel et al. (2010) and Gerardi et al. (2011). The primary focus of the current work is to develop an experiment capability to investigate reaction characteristics under micro-leak conditions. Some research (Eoh et al., 2010) on microcrack leaks of CO₂ into sodium has been carried out by the Korea Atomic Energy Research Institute (KAERI) subsequent to the initiation of the current project. Some important distinctions between the KAERI work and the current project include the CO₂ injection pressure (the KAERI work had a maximum CO₂ pressure of 55 bar, vs. 200 bar for the current project), sodium pool height (~0.4 m for the KAERI work,

vs. ~1.0 m for the current project), and the crack size investigated (the KAERI work evaluated sizes greater than 300 microns, while the present work will examine sizes as low as 50 microns).

Figure 2: Schematic of potential microcrack formation mechanism in a PCHE and subsequent sodium-CO₂ reaction.

As discussed by Gicquel et al. (2010), 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 ($Na_2C_2O_4$) and carbon monoxide (CO). The oxalate then further reacts with the sodium to form oxide (Na_2O). The reactions are of the form (Gicquel et al., 2010),

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 (Gicquel et al., 2010) 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. (Gicquel et al., 2010),

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. Potential also exists for oxide buildup on such a small crack due to the high temperature CO₂ passing stainless steel, and for enlargement of small cracks due to high thermal stresses near the nozzle due the Na-CO₂ reaction. These are some of the principal questions to be addressed as part of this work, along with evaluating the chemical reaction characteristics under low flow conditions.

International work on Na-CO₂ interactions

As alluded to above, several other research organizations are in the process of developing experiment and modeling capabilities to understand the sodium-CO₂ reaction. The primary organizations studying this reaction are the Korea Atomic Energy Research Institute (KAERI) and the Commissariat à l'énergie atomique (CEA).

The CEA work (Gicquel et al., 2010; Gicquel et al., 2011) primarily is focused on larger breaks typical of a shell-and-tube type rupture (jetting), and has been carried out at subcritical pressures. No plans to study the effect of CO₂ pressure on the reaction are planned. They are currently developing an analytical model for CO₂ jetting into a pool of sodium, which includes a reaction model. At this time, their model does not do a good job of predicting the experiment results. They do report a threshold temperature of approximately 500 °C, above which the reaction becomes extremely energetic. Their jetting experiments include a mass spectrometer to evaluate carbon monoxide production, and some calorimetric work was completed to evaluate the reaction enthalpies. Their modeling work consists of modifying and improving existing steam jetting into sodium models. This work includes extensive evaluation of the velocities and temperatures throughout the jet, which is the validation objective of their experiments. The model is complicated by the three-phase nature of the reaction and the complicated kinetics of the primary reactions.

The KAERI work (Eoh et al., 2010) is examining two issues: 1) wastage of stainless steel in a sodium pool due to impact by a CO₂ jet, and 2) understanding the reaction between sodium and CO₂. The first issue is important for both shell-and-tube heat exchangers and PCHEs in that a single failure could cascade into multiple tube (or channel) ruptures should the wastage effect be strong. However, this issue is beyond the scope of the present work. The second issue that KAERI is studying is very much related to the present work. They have done simple surface reaction tests of blowing CO₂ across the surface of a large sodium pool over a large range of temperatures (200 °C – 600 °C). They used a mass spectrometer to analyze the reaction gases and several diagnostic approaches to examine the solid reaction products after each test. While these tests are not prototypic of PCHEs, they add much to the knowledge base regarding the reaction itself, including kinetic parameters. They also have an experiment program investigating more PCHE prototypic geometries and conditions. They have injected gas bottle pressure (5.5 MPa) CO₂ at several temperatures (400 °C & 550 °C) through small holes (down to 0.3 mm) into a small diameter (2 mm) sodium channel. These channels did not plug after several minutes of CO₂ injection. Lastly, they have injected low pressure (0.5 MPa) CO₂ through larger cracks (0.5-1.5 mm) into sodium pools at a range of temperatures (300 °C – 600 °C). Some plugging of the smaller nozzles (<1.5 mm) were seen for low initial leak rates at high temperatures (> 500 °C).

There is a clear niche for obtaining data for truly prototypic heat source heat exchanger conditions namely at high pressure (20.0 MPa) and for small crack sizes (< 100 µm), which the present project will attempt to provide.

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,
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, or as a result of oxide layer buildup on the crack faces,
3. Develop one-dimensional phenomenological models for the interactions between high-pressure CO₂ issuing into liquid sodium from a micro leak across a stainless steel pressure boundary. These models will be validated using the experiment data obtained during the completion of the previous two objectives.

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 are expected to evolve from the chemical reactions described above; local sodium temperatures around the crack are also monitored. Post-test examination of solid reaction products will also be possible. 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. (2010) that were outlined above.

The balance of this report describes progress made towards meeting these objectives this fiscal year. An experiment facility called SNAKE (S-CO₂, Na Kinetics Experiment) has been designed and is currently undergoing assembly in the Building 206 High-Bay at Argonne National Laboratory. A summary of the underlying scaling rationale, and facility design, is provided in the next section. This information is followed by a summary of key achievements this fiscal year. Planning for the modeling approach to complete Objective 3 will be prepared in FY 2012, while actual modeling and validation work will begin in FY 2014. No further discussion of modeling plans will be made in the present report.

2 Facility Design Description

An initial design description was provided in 2010 (Farmer et al., 2010) for a facility focused on investigating sodium-CO₂ reactions under conditions that mock up a small leak within a PCHE. That document provided the starting point for further design improvements, detailed specifications, and purchases in FY 11. The changes and improvements in the facility design made in FY 11 are detailed below. Portions of the FY 10 design section, namely the scaling rationale, are repeated here in order to provide the complete design picture in a single document.

Facility Scaling Rationale

The high-level facility design requirements and corresponding experiment approach are summarized in

Table 1, while a schematic diagram showing key elements of the facility is provided in Figure 3. 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 a 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 (450 psig) 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 facility was sized so that prototypic interaction data can be obtained. The exact design for a 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 was 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 affect thermal hydraulic 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 as (Wallis, 1969):

Figure 3: Schematic diagram showing key elements of the sodium-CO₂ reaction test facility.

Table 1: 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.

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

Thermophysical property data assumed in this study are provided in Table 2. Given this data, the maximum bubble size in the sodium pool under bubbly flow conditions is estimated as 5.0 mm. 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 thermal hydraulic 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 as (Wallis, 1969):

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

The terminal velocity is calculated as 33.7 cm/sec from this expression given the property data in Table 2. 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, or the off-gas is essentially all CO, 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. Thus, it was decided to use a range of hole sizes near the small end of what could economically and reliably be machined. The minimum wall thickness in which the holes will be machined was set to 0.762 mm (0.030 inches), which is approximately the wall thickness of 3.2 mm (1/8 inch) OD stainless steel tubing that can withstand 20.0 MPa (2900 psi) at 500 °C. After consultation with ANL Central Shops, it was determined that only rather large diameter (>100 μm) holes could be produced using an Electron Discharge Machine (EDM) through this wall thickness. Since sub-100 μm were desired to simulate the leak sizes expected in a PCHE under prototypic operating conditions, an alternate approach of laser machining was chosen. This technique also has aspect ratio limitations, approximately 15:1. This meant that a 63 μm was the minimum achievable hole diameter that had acceptable quality and repeatability (50 μm holes were possible, but the roundness and smoothness of the resulting hole was poor). Thus, both 63 μm and 75 μm holes were chosen for the initial round of tests. Larger micro-holes (or smaller using a different technique) may be tested in the future.

Table 2: 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, 364 °C)	1.26
CO ₂ density (PCHE inlet, 364 °C)	179 kg/m ³
CO ₂ ideal gas constant (PCHE outlet, 515 °C)	1.35

CO ₂ density (PCHE outlet, 515 °C)	138 kg/m ³
CO ₂ density@ 1 atm, 500 °C)	0.68 kg/m ³
Inlet CO ₂ pressure	20 MPa
Sodium pool normal operating pressure	0.1 MPa

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 (Moody, 1990):

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

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

Given the data in Table 2, the gas mass fluxes through a postulated leak near the PCHE CO₂ inlet and exit sections are evaluated as 38,740 and 33,625 kg/m²·sec, respectively. The choked-flow leak rate out of a 63 μm diameter hole near the CO₂ inlet to the heat exchanger would thus be ~ 0.12 g/sec, which corresponds to a volumetric flowrate of $\dot{Q} \sim 4.0$ 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 (Wallis, 1969):

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

where $C_o = 1.2$ according to Zuber and Findlay (1965) 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 (Kataoka and Ishii, 1984):

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

The pool superficial gas velocities evaluated from Eq. 8 at a sodium temperature of 500 °C range from 2.2 to 3.1 cm/sec for the 63 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 4.7 to 6.6 % over this range of hole sizes, which is modest.

The fifth requirement in

Table 1 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. Backup physical engineered controls will also be used whenever possible (such as a safety orifice on the CO₂ line), which are discussed later in this report.

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) Geometry specific testing of sodium-CO₂ reaction by including a representative PCHE channel section at the nozzle.
- 2) Sodium-water reaction testing. This facility can be benchmarked against a number of previous sodium-water reaction experiments in the literature through flame temperature data. This information can be used to broaden the applicability of the newly obtained sodium-CO₂ reaction data in validating reaction models. Basically, it can be used to compare the severity and properties of the reaction between sodium and water to that of sodium and CO₂.
- 3) Fission product scrubbing tests¹ 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.
- 4) CO₂ blowdown tests at higher flowrates to provide data to support validation of codes [e.g. see Giguel et al. (2010) for a summary of French work and Gerardi et al. (2010; 2011) for a description of recent U.S. work on the adaptation of the SWAAM code for evaluating Na-CO₂ interaction]) 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.

Facility Design

As shown in Figure 4 (schematic in Figure 3), the key elements of the test facility consist of 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.

- i. test vessel,
- ii. argon cover gas supply,
- iii. CO₂ supply system to the test nozzle that simulates a leak site in a PCHE,
- iv. argon supply system to the test nozzle to prevent sodium plugging prior to CO₂ flow initiation,
- v. sodium dump system including a filter/cold trap to clean sodium and capture solid reaction products,
- vi. off gas system,
- vii. confinement system to direct smoke from any accidental sodium spill to the building scrubbing unit,
- viii. instrumentation (flow meters, pressure transmitters, level measurement, thermocouples, mass spectrometer, etc.)

The test vessel (Figure 5 & Figure 6) 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. These penetrations will be used for sodium temperature, pressure and level measurements. 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 magnesia-insulated coaxial heater cable (temperature operating limit: 982 °C) in order to maintain the assembly at a designated temperature during the experiments.

The argon cover gas flows through the same penetration as the level measurement viewport in order to prevent sodium vapor or contaminants from accumulating on the viewport window (see Figure 6a). This supply system consists of a standard bottle manifold that feeds a 6.4 mm (¼ inch) line. A flow controller is used to manage and measure the flow rate of argon fed into the system. This flow rate measurement is important when analyzing the exhaust gas composition since the mass spectrometer will only provide a gas mixture ratio. The argon flow rates and the gas mixture ratios will then be used to calculate the CO and CO₂ quantities.

Figure 4: Drawing of sodium components of the sodium-CO₂ reaction test facility.

Figure 5: Test vessel assembly drawings of the (a) top flange and (b) body.

Figure 6: Test vessel assembly as delivered to Argonne.

The CO₂ micro-nozzle (see Figure 7) consists of a 3.2 mm (1/8 inch) seamless 316 stainless steel tube with a machined stainless steel injector coil tip connected with a brazed coupling. The end of each injector coil tip has a laser machined 63-75 μm diameter hole to form the actual nozzle which will simulate the PCHE microcrack. The tube is welded onto a 5.1 cm (2 inch) Grayloc blind hub (attached to the bottom horizontal test vessel penetrations)

as the nozzle sodium barrier. This tube is coiled in the sodium pool in order to preheat the CO₂ so that the temperature is approximately the same as the sodium pool temperature once it exits the micro-nozzle (see Figure 8).

Figure 7: Drawing of CO₂ micro-nozzle.

Figure 8: Drawing of CO₂ micro-nozzle connected to coiled tube installed in a cutaway of the test vessel.

An argon supply line is also connected to the micro-nozzle system. This will force a small amount of argon through the micro-nozzle when an experiment is not being conducted but liquid sodium is present in the test vessel. This constant argon supply ensures that no liquid sodium enters the nozzle and gas supply line, where it would bypass all of the sodium leak prevention systems designed into the sodium portion of the experiment. This line has its own dedicated flow meter to keep track of the argon injected, and can be used to calibrate the coriolis flowmeter on the main gas supply line.

The CO₂ source consists of a traditional bottle manifold that feeds a booster pump (see Figure 9 for a magnified schematic view of gas supply system). The pump pressurizes a reservoir cylinder that is used to supply a regulated pressure to the leak site at up to 20 MPa (2900 psig) pressure; the reservoir is used to dampen pressure fluctuations that are inherent when the pump is operational. Flowrate to the tube is measured with a Coriolis flowmeter. The occurrence of plugging will be evidenced by the flow rate tending towards zero. The output from the Coriolis flowmeter 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. A flow-limiting orifice is positioned upstream of the flowmeter. This is a backup safety device that limits the peak CO₂ flowrate to the test section to an acceptable in the unlikely event that the tube feeding the leak and the isolation valve failed simultaneously. This orifice does not result in a significant pressure drop under normal operating conditions.

Figure 9: Schematic of gas supply system.

A dump system with a 41 liter capacity (11 gallon) sodium dunk tank (see Figure 10 and Figure 11) serves as the storage location for sodium when tests are not being conducted. This system has dedicated trace heating circuitry. Both manual and pneumatic valves are required to open in order to drain or fill the test section. Argon pressure is used as the driving force to move the sodium between the dump tank and test section. The pneumatic valve can be remotely actuated (manually and via PC) to rapidly drain sodium from the system under off-normal operating conditions which may include sodium leakage or failure of the CO₂ leak site leading to high pressure purge of CO₂ into the test vessel. A filter (Figure 12) and a cold trap (Figure 13) are also included for normal draining operations. These are constructed from 7.62

cm (3 inch) diameter Schedule 40, 304 stainless steel pipe, and built and tested to ASME B31.3 pressure piping standards for operation at 538° C at up to 31 bar pressure. The filter assembly includes a 316L stainless steel mesh filter element to capture any solid reaction products that are carried by the sodium. The filter itself can be removed if it clogs or to analyze the solid particles it traps. The cold trap assembly includes wire packing to provide ample surface area for the oxides to collect upon, and a five-junction thermocouple rake to monitor the liquid sodium temperature for best control of dissolved oxygen.

Figure 10: Sodium dump tank assembly drawings.

Figure 11: Sodium dump tank as delivered to Argonne.

Figure 12: Drawing of filter assembly (cutaway view of internal filter).

Figure 13: Drawing of cold trap assembly (cutaway view of internal thermocouples and wire packing).

The off gas system consists of a separator/vapor trap (Figure 14 & Figure 15) that removes any sodium aerosol before exhausting the gas mixture to the atmosphere. The separator will be heated to allow the liquid sodium to drip down a 1.3 cm ($\frac{1}{2}$ inch) line back to the sodium dump tank. The gas mixture flowing through the separator will consist of the argon cover gas plus any CO₂/CO that escapes from the sodium pool. An additional inline filter is also installed on the low temperature portion of the off gas line for final removal of any solid particulate that makes it past the separator. Off gas composition is measured using an on-line gas mass spectrometer. A rupture disk provides overpressure protection for the test section. This vent line extends to a sand-filled drum to filter out any sodium droplets that may pass through the separator if the rupture disk were to fail during an experiment. The exhaust line is directed through an exterior high bay penetration to vent to the environment during normal operations.

Figure 14: Drawings of the separator/vapor trap.

Figure 15: Separator/vapor trap as delivered to Argonne.

A confinement, or enclosure, system (see Figure 16) is being constructed to direct smoke from any accidental sodium spill to the Building 206 Scrubber unit. The Scrubber (or the Alkali Metal Passivation Booth) is specifically designed and permitted for safe alkali metal (sodium) waste treatment and to collect and dispose of smoke from experiments that have an accidental fire or release of aerosols. A stainless-steel-paneled enclosure supported by steel-angle iron surrounds all of the sodium bearing components of the apparatus. A 25.4 cm (10 inch) diameter duct booster fan with an 18,000 slpm (650 cfm) flow rating is placed on the outside of the enclosure and vented to pull any smoke through duct work that runs from the fan to the Scrubber. A smoke alarm inside the confinement will automatically activate the Scrubber should smoke be detected. The system can also be manually activated should the smoke alarm fail or if it is desired to have the booster fan and Scrubber operating for other reasons (e.g. system testing or during operations that have higher potential for sodium leakage such as sodium loading). Stainless steel catch trays line the entire floor of the enclosure. These trays have 4 inch high walls and welded seams, which should adequately contain any liquid sodium that could potentially drip from the experiment.

Figure 16: Enclosure/confinement system structure surrounding sodium components. Total height of enclosure is 4 m (12 feet). Stainless steel panels and doors will be placed over all openings to contain potential smoke release. A booster fan and duct work (upper right) direct smoke to the Building 206 Scrubber.

Instrumentation

A variety of instruments will be used to operate and control the experiment (thermocouples, flow controllers, pressure transmitters, level measurements, etc.), and to investigate the interaction between sodium and CO₂ (thermocouples, gas composition, etc.). A complete summary list of instruments is included in Table 3.

Table 3: Summary of instruments used in experiment.

Measurement	Location	Instrument	#	Description
Heater cable temperature	Wound around all sodium carrying vessels and piping	Thermocouple (K-type)	100	Placed near heater cable on all sodium components; attached by spot weld
Cold trap sodium temperature	Cold trap	Thermocouple (K-type)	1	5-junction thermocouple sheathed, ungrounded assembly extending along cold trap length
Dump tank sodium temperature	Dump tank	Thermocouple (K-type)	1	3-junction thermocouple sheathed, ungrounded assembly extending to bottom of dump tank
Gas exhaust temperature	Exhaust line, just upstream of filter	Thermocouple (K-type)	1	Placed near end of exhaust line to ensure gas temperature reduced to <100 °C to protect low temperature components (filter, mass spec, etc.)
Vessel pressure	Vessel head	Absolute pressure transmitter	1	Wireless pressure transmitter; monitor vessel pressure to prevent overpressure
Vessel sodium level	Vessel head	Laser level indicator	1	Monitor vessel level during filling/draining; monitor during experiment to prevent overflow
Nozzle temperature	At tip of CO ₂ nozzle	Thermocouple (K-type)	1	Inserted in 1/8" CO ₂ tubing all the way to tip; 0.02" diam sheath
Test vessel sodium temperature	Top of vessel head into sodium pool	Thermocouple (K-type)	1	10-junction thermocouple sheathed, ungrounded assembly extending down near nozzle, 1/8" OD
CO ₂ line pressure	Near reservoir	Absolute pressure transmitter	1	Wireless pressure transmitter; measure CO ₂ injection pressure; monitor booster to prevent overpressure
Argon cover gas flow control	Cover gas line	Gas mass flow controller	1	Control argon flow to ensure adequate cover gas; measurement important to determine ratio of reaction gas products
Argon supply line flow meter	Argon supply line	Gas mass flow meter	1	Monitor argon flow to micro-nozzle
CO ₂ /Argon flow meter	CO ₂ /Argon supply line	Coriolis gas mass flow meter	1	Monitor CO ₂ or argon flow to micro-nozzle; Used to determine ratio of reaction gas products; Control emergency gas valve in case of accidental nozzle break
Gas composition	Exhaust line	Mass spectrometer	1	Measure exhaust gas composition for analysis of sodium-CO ₂ reaction

Temperature measurement:

A number of temperature instruments will be included to analyze the sodium/CO₂ reaction, monitor the experiment status, and control the sodium temperature.

A 0.5 mm (0.02 inch) diameter sheathed Type K thermocouple is inserted into the 3.2 mm (1/8 inch) diameter CO₂ nozzle line to the nozzle tip in order to monitor the temperature as close as possible to the sodium/CO₂ reaction interface. This data will be used in analyzing the reaction and flame front temperature.

A sheathed 10-junction Type K thermocouple assembly extends along the length of the test vessel, passing through a vessel-head penetration. The majority of these junctions will be used exclusively to characterize the test sodium temperature. The bottom-most junction will be placed close to the CO₂ nozzle tip in order to supplement the reaction and flame front temperature measurements.

Sheathed 5-junction and 3-junction Type K thermocouple assemblies are placed in the cold trap and dump tank, respectively. The cold trap thermocouples will allow accurate control of the cold trap sodium temperature in order to manage oxygen content precisely. The dump tank thermocouples will be used to ensure that the dump tank temperature remains above the melting point of sodium during experiment operations in order to ensure reliable emergency sodium dumping.

An inline Type K thermocouple is placed in the gas exhaust line. This allows for monitoring the exhaust temperature to ensure that it has been sufficiently reduced ($< 100\text{ }^{\circ}\text{C}$) to protect low temperature components such as the gas filter and mass spectrometer.

Spot-welded Type K thermocouples are placed on the exterior of the vessels to monitor vessel and piping temperature. These instruments are also used as input for the heater controllers.

Pressure measurement:

Absolute pressure will be measured in the CO₂ line (after the reservoir) and in the test vessel (at a vessel head penetration) using Rosemount 3051S wireless pressure transmitters (see Figure 17). These transmitters have a measurement accuracy of $\pm 0.007\text{ MPa}$ from 0-27.5 MPa ($\pm 1\text{ psi}$ in the range of 0 to 4000 psia). They use the WirelessHart protocol to transmit their data to a Smart Wireless Gateway (see Figure 17) which then passes the pressure readings to the DAQ via Modbus TCP/IP. A single gateway can communicate with multiple pressure transmitters.

Figure 17: Rosemount wireless pressure transmitter (left) and wireless gateway (right).

Flow measurement and control:

Several flow meters and flow controllers will be used on the gas lines in order to accurately measure the mass flow rates of Argon and CO₂ into the test section. These are important measurements since the data from these devices will be compared with the exhaust gas composition (as measured by the mass spectrometer) in order to evaluate the reaction between the CO₂ and sodium.

A Coriolis flow meter will be placed on the main gas supply line to measure the CO₂/Argon gas injection rate. This is a Brooks QUANTIM QMBM 3 Mass Flow Meter (see Figure 18). It is rated for operation up to 31 MPa (4500 psig) at up to 65 °C. The device is designed to measure a flow rate up to 0.63 kg/hr of CO₂, specifically at 20 MPa (2900 psig) at 25 °C. The measurement error is less than 2.4% at 10% of the maximum design flow rate measurement, but closer to 0.5% at higher flow rates, as shown in Table 4. The selection of this flowmeter is discussed in greater detail in Section 0.

Table 4: Error as a function of mass flow rate for the Brooks QUANTIM Mass Flow Meter.

Mass flow (kg/hr)	% Error	Sensor Tube flow velocity (m/s)
0.063	2.38	0.14
0.0945	1.59	0.21
0.126	1.19	0.28
0.1575	0.95	0.35
0.189	0.79	0.42
0.2205	0.68	0.49
0.252	0.6	0.56
0.2835	0.53	0.63
0.315	0.5	0.7
0.3465	0.5	0.78
0.378	0.5	0.85
0.4095	0.5	0.92
0.441	0.5	0.99
0.4725	0.5	1.06
0.504	0.5	1.13
0.5292	0.5	1.18
0.5544	0.5	1.24
0.5796	0.5	1.3
0.6048	0.5	1.35
0.63	0.5	1.41

Figure 18: Brooks QUANTIM QMBM 3 Mass Flow Meter.

A Teledyne Hastings HFM-D-300 gas mass flow meter (see Figure 19) will be placed on the argon supply line feeding the micro-nozzle. It will be used to monitor the mass flow rate of argon during the pre-experiment activities, and can be used to confirm the operation of the Brooks mass flow meter since the Argon will pass through both meters. This flow meter is rated for 3.45 MPa (500 psia) at 25 °C. A check valve will be placed on the argon line to protect it from the higher CO₂ pressures in case the pneumatic valves do not operate as designed. It is rated to 0-10 slpm of argon with an uncertainty of < 0.65%.

Figure 19: Gas mass flow meter (Teledyne HFM-D-300) to measure the argon mass flow to the micro-nozzle.

A Teledyne Hastings HFM-D-302 gas mass flow controller (see Figure 20) will be placed on the argon cover gas line. It will be used to monitor and control the mass flow rate to ensure that there is adequate cover gas flow to preclude air ingress into the system. This cover gas will also preclude sodium vapor condensation on the glass window in the viewport used for the sodium laser level measurement. Accurate measurement of the argon injection gas flowrate is also important for determining the ratio of reaction gas products as measured by the gas mass spectrometer. This flow controller is rated for 3.45 MPa (500 psia) at 25 °C. The device has a flow control range of 0-25 slpm of argon with an uncertainty of <0.5%. For CO₂, the device is rated for 0-15 slpm with an uncertainty of <0.5%. The additional CO₂ calibration was obtained to have the flexibility of calibrating the Brooks Quantum flowmeter in-house using a controlled CO₂ flow.

Figure 20: Gas mass flow controller (Teledyne HFC-D-302) to measure & control the argon mass flow to the cover gas line.

Sodium level measurement:

A MODULOC LT2000-ST Laser Distance Meter (see Figure 21) will be used to measure the level of the sodium during loading and experiments. This device uses a visible Class II Laser (1 mW max output) in order to make the distance measurement with an accuracy of ± 5 mm at up to 30 m from the sensor. It has an air-cooling chamber to allow for operational temperatures up to 60 °C. The laser will be directed through a specially designed sapphire viewport assembly (see Figure 22) straight down to the sodium surface. The measurement technique is specifically designed to measure distance from metal surfaces at temperatures up to 600 °C.

Figure 21: MODULOC Laser Distance Meter to measure sodium level in test vessel.

Figure 22: Vessel head with viewport and MODULOC Laser Distance Meter.

Gas composition:

A Stanford Research Systems UGA 200 gas mass spectrometer (see Figure 23) will be used to measure the off-gas composition. The sample will be drawn from the system exhaust line. Since the argon cover gas is fed into the system at a constant flowrate using a mass flow

controller, and the CO₂ flow rate through the micro-nozzle will be measured, it is possible to compute the flowrates of CO and CO₂ that are released from the sodium pool. The CO flowrate determined by this analysis can then be used through a mass balance to determine the extent of the gas retention/reaction in the pool as a function of time.

Figure 23: Mass spectrometer (Stanford Research Systems UGA 200 Universal Gas Analyzer) as delivered to Argonne.

3 FY 2011 Status

Significant progress toward completion of the experiment apparatus has been made in FY 2011. The major accomplishments made in FY 2011 are detailed in the following section. An anticipated timeline (Gantt chart) for the project is included in Table 5. The facility design was completed in September, 2010 which included a detailed design report (Farmer et al., 2010). Most major components have been purchased, and portions of the facility have been assembled in 2011, which the present report documents. Completion of procurement is expected in December 2011. Complete assembly of the facility and initial sodium loading is anticipated in June 2012. A report documenting these activities will be produced the following month. Facility shakedown and initial data will be complete in September 2012, along with a summary report. Fiscal Year 2013 will consist of obtaining the complete experiment data matrix, with a detailed report delivered in September 2013. Model development and validation will take place the following Fiscal Year, with a detailed model report anticipated to be delivered in June 2014.

Table 5: Anticipated timeline for Na-CO₂ experiment program. Completed portions of tasks are colored in black, while uncompleted tasks are gray. Deliverable reports timeframes are marked with a yellow dot.

	3/10	6/10	9/10	12/11	3/11	6/11	9/11	12/11	3/12	6/12	9/12	12/12	3/13	6/13	9/13	12/13	3/14	6/14
Facility Design																		
Component Purchases																		
Facility Assembly																		
Shakedown and Initial Data																		
Experiment Data Collection																		
Model Development																		

Gas delivery system assembly

Significant effort was devoted to the design and assembly of the gas delivery system for the micro-nozzle that is shown in Figure 9. This system consists of both CO₂ and argon lines, several flow meters, control valves, instrumentation, and control hardware. The main components of this system have been assembled in a vertical leveled platform fashion as shown in Figure 24. All of the components such as the flow meters, pneumatic valves, solenoid valves, pressure transmitter, and booster pump have been integrated into this assembly. Final gas line connections and shakedown testing of individual components as well as the integrated assembly remains as an FY 2012 task.

Figure 24: Gas delivery system assembly depicting the levels for each gas line sub-assembly.

A control scheme was developed (schematic shown in Figure 25) to allow for both manual and computer control for all four pneumatic valves on the gas supply system. A centralized control box (shown in Figure 26) was built to house the electronics and switches for this system. Individual control of the low-pressure CO₂ supply and nozzle valves is possible. A single switching scheme is used to control the argon supply and pressurized CO₂ supply since the ability to instantaneously switch from argon to CO₂ supply to the nozzle will be needed.

Figure 25: Control scheme schematic for the Na-CO₂ nozzle system enabling pneumatic valve control from a control box or computer.

Figure 26: Control box for the Na-CO₂ nozzle system for pneumatic valve control.

The gas manifold system has been installed on a wall near the experiment enclosure (see Figure 27). Each manifold is capable of being fed by four gas bottles. Two argon manifolds (one for the cover gas, one for the argon nozzle supply) and one CO₂ manifold are in place.

Figure 27: Gas manifold system (CO₂ and argon) installed on wall near enclosure.

Water mockup assembly & planning

A water mockup of the nozzle injection is being assembled in order to first test the gas delivery system and visualize the nozzle physics prior to use in sodium (where visualization will be impossible). This mockup will utilize all of the gas delivery system components as discussed above while having the end of the nozzle immersed in a glass water tank (shown in Figure 28). Each component of the gas delivery system will be fully shaken down during these mockup tests. Flow rate data and video will be recorded in order to help predict the response of the nozzle and gas flow rates during sodium testing. These tests will be a significant portion of the pre-experiment assessments, and be used in the safety case for the facility.

Temperature control system

Three chassis (shown in Figure 29) that will be used for temperature control of sodium components have been assembled and tested. A total of 29 zones can be controlled (up to 10 Amps each) with these systems. Trace heating of every sodium-carrying component to at least 110 °C is required in order to maintain the sodium in a liquid state. Some components, like the test vessel and cold trap, will be maintained at specific temperatures depending on the experiment status. For example, the test vessel can be heated up to 510 °C to evaluate the sodium-CO₂ reaction over a range of sodium temperatures. During sodium dumping, the cold trap will be maintained at a fairly low temperature to precipitate dissolved oxides.

Figure 28: Glass model and nozzle tip of water mockup assembly. The full glass chamber is shown on the left, while a close-up of the nozzle penetrating the bottom of the chamber is shown on the right.

Figure 29: Temperature control chassis for trace heating sodium vessel and piping.

Miscellaneous activities

Additional activities carried out in FY 2011 that were not listed above but are worthy of mention are outlined below. This list provides a nearly complete picture of the facility construction status as of the writing of this report.

- Connection of the experiment enclosure to the Building 206 Alkali Metal Passivation Booth (Scrubber) has begun. This work consists of installing a booster fan on the outside of the enclosure and a duct system extending from the enclosure, through a wall, to the scrubber. Final assembly is awaiting approval by Argonne Health Physics since scrubber and the pipes associated with the scrubber are radioactively contaminated.
- The facility enclosure framework has been painted, assembled, and installed at the experiment location (see Figure 30). It has been anchored to the floor. Stainless steel catch trays have been placed in the bottom of the enclosure, as shown in Figure 31.
- Heater wire has been installed on major vessels, including the test vessel, test vessel head, separator vessel, dump tank, cold trap, and filter. Special connectors have been placed on each wire end to enable electrical connection to the power supply and to mechanically support and prevent electrical arcing between the heater wire and its sheath. Initial heatup testing of all these heaters has been completed showing that the heater controllers can adequately power the heater cables and accurately maintain temperature.
- Several components have been installed in the enclosure including the test vessel and dump tank. The framework supporting those components and several other components has also been installed.
- Gas nozzle injectors have been manufactured. Ten nozzles each have been laser machined with 63 and 75 micron holes drilled into nozzle stock. The stock was originally manufactured by ANL central shops. Two of these nozzles have been brazed to connectors and attached to 1/8" tubing. These completed nozzles will be used for the water surrogate testing. If these tests are successful, then the remaining nozzles will be attached to tubing. A test braze of one of these models was sectioned, cleaned, mounted and visually inspected to confirm that the brazing technique was successful with this geometry.
- Wire cable trays that will carry the power cables and thermocouples for the heater cables, and other cabling for instruments have been installed (see Figure 32) in the enclosure and on its exterior.

The assembled state of the facility as of the writing of this report is shown in Figure 32 and Figure 33.

Figure 30: Steel facility enclosure painted and installed at experiment location.

Figure 31: Stainless steel catch trays installed at the base of the facility enclosure.

Figure 32: Assembled state of the experiment facility as of this writing. The test vessel can be seen supported within the enclosure frame. Cable trays are installed in the interior and exterior. Duct work extends from the wall toward the enclosure which will act as the emergency enclosure exhaust to the scrubber (behind far wall, not shown). The mass spectrometer, dump tank, temperature control chassis, and vessel head are also shown.

Figure 33: Assembled state of the experiment facility as of this writing. The test vessel can be seen supported within the enclosure frame. Cable trays are installed in the interior and exterior. The gas manifolds can be seen in the background on the white wall. The dump tank, temperature control chassis, and vessel head are also shown.

Data Acquisition System

A centralized data acquisition system will be used to monitor, record, and control nearly all components and instrumentation. This data acquisition system consists of a PC, a National Instruments PXI-module-based data acquisition hardware system, and measurement and control software (Labview 2011). The following list of instruments have been through initial testing and successfully communicated with the software through the appropriate NI PXI modules. Basic data acquisition and control programs have also been developed for these components. These control programs will be consolidated in FY 2012 into one centralized program for ultimate control and recording.

- Wireless pressure transmitters
- Main gas supply line (CO₂/Argon) Coriolis mass flow meter
- Argon gas supply line mass flow meter
- Argon cover gas supply line mass flow controller
- Laser level indicator

Control of the pneumatic valves, booster pump, and integration of the mass spectrometer data will be completed in FY 2012.

4 Safety & Miscellaneous Analyses

This section documents several analyses that have been carried out in support of the safety case for the experiment. Additional analyses will be needed in FY 2012 to fully make the safety case for the planned experiment series.

Flow limiting orifice

A gas flow limiting safety orifice, or flow restrictor, will be placed on the CO₂ line in order to prevent vessel overpressure in case of the unlikely event that the test nozzle or tube feeding the CO₂ into the test section fails. A flow restrictor is a passive device which is sized to limit the flow to an acceptable rate. The only failure mode of this passive device is plugging, which would preclude gas flow, but that is preferred over an unrestricted leak. The limiting flow rate of CO₂ is just below that which causes the liquid sodium to swell (or holdup) to the level of the 1" line leading to the separator. The sodium could potentially solidify in this region or in the unheated 1.3 cm exhaust line, which would cause the pressure vessel to pressurize to the point at which the rupture disk would fail. It is noted that an excess flow switch will also be placed in the CO₂ inlet line. The flow meter will automatically close a pneumatic valve just prior to the test section inlet should the mass flowrate exceed a preset value. The flow restrictor is designed to act as a backup should this mechanism fail.

As mentioned in the above section, the collapsed sodium pool depth is limited by the corresponding voided pool height that would result at the peak gas flowrate through the orifice under choked flow conditions. It is desirable to have a pool height of at least 0.9 m which requires that the void fraction, α , remain below 25 %. This void fraction value happens to correspond to what is typically considered to be the transition from bubbly to slug or churn flow where bubble coalescence occurs (Todreas and Kazimi, 1990). Thus, the flow rate that corresponds to this void fraction is calculated below using standard bubbly flow models, and this result determines the maximum permissible CO₂ flowrate.

The threshold value for the onset of the churn-turbulent flow regime is given as (Kataoka and Ishii, 1984):

$$j_{b-ct} = 0.5 \left(\frac{g \sigma (\rho_l - \rho_g)}{\rho_l^2} \right)^{1/4} \quad (10)$$

While the bubble terminal rise velocity, U_{∞} , can be approximated from (Todreas and Kazimi, 1990):

$$U_{\infty} = 1.53 \left(\frac{g \sigma (\rho_l - \rho_g)}{\rho_l^2} \right)^{1/4} \quad (11)$$

Using the properties of sodium and CO₂ (calculated from a state equation MATLAB script based on Span and Wagner, 1996), the threshold value for the onset of slug or churn flow is found to be approximately 11 cm/sec. The corresponding gas flow rate is found by:

$$\dot{Q}(T_p) = \frac{j_g}{A_{vessel}} \quad (12)$$

where $\dot{Q}(T_p)$, and A_{vessel} are the volumetric flowrate of CO₂ at the sodium pool temperature, and cross-sectional area flow area of the vessel, respectively. Thus, the target maximum desired CO₂ flowrate calculated using Eq. (12) and sodium and CO₂ properties from Table 6 is approximately 20.2 slpm.

Table 6: Sodium Properties.

Property	Value
Density (500 °C)	832 kg/m ³
Viscosity (500 °C)	2.3 x 10 ⁻⁴ Pa-s
Surface tension	0.2 N/m

The corresponding orifice diameter is found by:

$$D_{safety\ orifice} = \left(\frac{4}{\pi} \frac{\dot{m}}{G_{c,safety\ orifice}} \right)^{1/2} \quad (13)$$

where the mass flow rate of CO₂ is easily found as:

$$\dot{m} = \dot{Q} \rho_g \quad (14)$$

At first glance, one would assume that the mass flux, G_c , through the safety orifice would be choked and could be found using the standard critical gas mass flux equation (Moody, 1990):

$$G_{c,safety\ orifice} = \sqrt{k P_0 \rho_0} \left(\frac{2}{k+1} \right)^{\frac{k+1}{2(k-1)}} \quad (15)$$

This relation holds as long as the back pressure, P_0 , is higher than the critical pressure:

$$P_c = P_0 \left(\frac{2}{k+1} \right)^{\frac{k}{(k-1)}} \quad (16)$$

The back pressure as supplied by the booster pump is 20 MPa, and the gas constant for CO₂ at 25 °C and 20 MPa is approximately 2.3. The critical pressure and mass flux for these conditions using Eq. (15) are 8.24 MPa and 108,620 kg/m²-s, respectively.

Note that Eq. (15) assumes a constant value for the gas specific heat ratio, k . This is a fairly good assumption for the expansion of CO₂ at 500 °C from 20 MPa to atmospheric pressure, as the gas specific heat ratio only decreases from 1.26 to 1.20. However, this is not a good assumption for the expansion of CO₂ at 25 °C from 20 MPa to atmospheric pressure. First, the upstream CO₂ is in a liquid state, so the gas specific heat ratio technically has no value there. However, the specific heat ratio decreases from 2.3 to 1.3, which is too large of a change to satisfactorily use the standard choked flow equations. In this situation, the CO₂ is operating too far from the ideal gas properties to use the above equations. In reality, the CO₂ will behave like an ordinary fluid blowing down from a small orifice. The proper equation describing the critical pressure for an ordinary fluid is as follows (Moody, 1990):

$$P_c = P_0 \left(1 - \frac{E_m}{2P_0} \right) \quad (17)$$

where the modulus of elasticity for CO₂ can be calculated as:

$$E_m = \frac{P_0 - P}{(\rho_0 - \rho) / \rho_0} \quad (18)$$

This equation yields approximately 19.94 MPa for these conditions. Thus, the critical pressure from Eq. 17 is approximately 10.0 MPa. This means that the flow is critical through the safety orifice. The proper equation to use for the critical mass flux for an ordinary fluid (which is uncommon) is (Moody, 1990):

$$G_c = \sqrt{2P_0\rho_0} \sqrt{\frac{E_m}{2P_0}} \quad (19)$$

Note that if the flow was not choked, then the proper equation to use for an ordinary fluid would be:

$$G_c = \sqrt{2P_0\rho_0} \sqrt{1 - \frac{P}{P_0}} \quad (20)$$

Thus, the mass flux from the safety orifice, using Eq. (19) will be approximately 17,250 kg/m²-s. Using the same analysis as described above, this would require a safety orifice of 214 μ m. The pressure drop across this orifice (using the pressure drop equations for standard form and flow inside a channel) for a 6.3 mm thick orifice plate would be 5.2 kPa, which is sufficiently small relative to the 20 MPa driving pressure across the nozzle exit.

The gas holdup model discussed by Brockman et al. (1989) was also used to estimate the void fraction. This study focused on modeling the sparging of high temperature (1823 K) molten steel with nitrogen, which is more akin to the current work than the previous models

that were developed predominately on the basis of water voiding experiments. Brockman et al. reviewed several models, and on this basis developed their own correlation to match the data they obtained with molten steel and oleic acid. Their correlation is based on the Morton Number:

$$M = \frac{g\mu_l^4(\rho_l - \rho_v)}{\rho_l^2 \sigma_l^3} \quad (21)$$

and is given as:

$$\alpha = cM^a j_g^{*b} \quad (22)$$

where the values of the coefficients a, b, and c come from data fit by Brockman et al. (1989) and Renjun et al. (1988) in Table 7. The dimensionless gas face velocity is given as

$$j_g^* = \frac{v_f}{\left[\frac{\sigma_l g}{\rho_l} \right]^{1/4}} \quad (23)$$

Table 7: Values of a, b, and c for Equation Eq. (22).

Source	a	b	c
Brockman et al. (1989)	0.0207	0.584	0.128
Renjun et al. (1988)	-0.0070	0.5897	0.1966

The void fraction calculated using these equations, assuming that the gas phase velocity, v_f , is the bubble terminal rise velocity, U_∞ , is 0.33 and 0.32 for the Brockman et al., and Renjun et al. correlations, respectively. These values are significantly higher than the 0.25 assumed in the previous drift flux analysis. Thus, the safety orifice diameter will still be sized to that analysis, 214 μm , but some extra margin in the initial sodium height will be taken to ensure there is no sodium overflow. In this case, a **maximum height of 0.80 m** will be allowed during initial experiment operations. Once the level increase due to voiding during several experiments is measured directly, this limit can be reevaluated. It should be noted that the Morton Number of sodium at 500 °C, 10^{-4} , is outside the valid range of the Brockman et al. correlation (10^{-12} to 10^{-4}), thus there would still be some uncertainty regarding the relevance of this model to the Na-CO₂ system. The Renjun model is valid for an even narrower Morton Number range.

Flow meter selection

Measuring the flow rate of CO₂ from the nozzle into the sodium is challenging. The line pressure is high, 20.0 MPa (2900 psi), which means the CO₂ will be a liquid in the room temperature feeder lines, with density close to that of water. The flow rates will be extremely low, with a maximum of 5.8 slpm (0.18 g/sec) expected, which is difficult to measure for a liquid. A large flow rate measurement range is desired in order to measure a variety of nozzle

sizes and accurately measure the anticipated clogging of the nozzle. A turndown ratio of at least 1:100 is desirable. A graph showing the conversion from standard liters per minute (slpm) to the volumetric flow rate in L/min at 20 MPa is included in Figure 34, and a table of the major flow conditions that are anticipated with a conversion from volumetric to mass flow rate is included in Table 8.

Table 8: Anticipated flow conditions with volumetric and mass flow rate conversions.

Flow condition	Volumetric flow rate (slpm)	Volumetric flow rate (at 20 MPa) (mL/min)	Mass flow rate (g/sec) [kg/hr]
Maximum flowrate for 75 μ m nozzle	5.8	11.6	0.1772 [0.63]
Maximum flowrate for 25 μ m nozzle	0.65	1.30	0.0200 [0.07]
Desired minimum flowrate measurement	0.06	0.120	0.0018 [0.006]

Figure 34: Conversion from standard liters per minute (slpm) to the volumetric flow rate in L/min at 20 MPa.

Expected flow rates

Detailed information on the flow rates expected for various inlet temperatures is described here. For a 75 μ m nozzle, the maximum mass flow rates expected in the temperature range of 100 to 500 $^{\circ}$ C varies between 1.3 to 0.55 kg/hr (shown in Figure 35). For a 63 μ m nozzle, the maximum mass flow rates expected in the same temperature range vary between 0.9 to 0.38 kg/hr (shown in Figure 36). For a 75 μ m nozzle, the maximum mass flow rates vary between 0.14 to 0.06 kg/hr (shown in Figure 37).

Figure 35: The critical flow rate of the CO₂ as a function of a 75 μm nozzle outlet temperature. The volumetric flowrate at STP conditions (left) and mass flow rate (right) are shown.

Figure 36: The critical flow rate of the CO₂ as a function of a 63 μm nozzle outlet temperature. The volumetric flowrate at STP conditions (left) and mass flow rate (right) are shown.

Figure 37: The critical flow rate of the CO₂ as a function of a 25 μm nozzle outlet temperature. The volumetric flowrate at STP conditions (left) and mass flow rate (right) are shown.

Measurement techniques that have some potential for success (e.g. a vortex flow meter was not considered since the flow rate is too low for vortices to be formed) include:

- 1) Coriolis flow meter
- 2) Ultrasonic flow meter

- 3) Tracer element in CO₂ feed gas to be detected at mass spectrometer
- 4) Level detection
- 5) Orifice flow meter

Each method is summarized below, along with some analysis and/or examples discussing the advantages and disadvantages of each technique.

Level detection, Orifice and Tracer element methods

The level detection and orifice flow meter can be ruled out because neither can easily meet the turndown ratio requirement of 1:100. The tracer element method is a possibility, but could alter the chemical reaction between the sodium and CO₂, which is the experiment's primary objective. Sodium is considered a good scrubbing agent, so it would be difficult to show that none of the tracer is captured as it bubbles through the pool of sodium.

Ultrasonic sensor

Ultrasonic sensors (transit time flowmeters) are capable of measuring low flow rates as long as the flow velocities are within their measurable range. The sensors typically clamp on to the outside of the pipe and non-invasively measure the flow velocity. In theory, it is possible to reduce the size of the pipe/tube to increase the velocity. Of course, this is only possible to a point, as these types of sensors have a minimum pipe size requirement, usually 6.3 mm (¼ inch). For this size pipe, the velocities corresponding to the desired measurement flow rate range are shown in Table 9. The velocity ranges that these types of flow meters are typically good for are in the range of 0.03-20 m/s (such as the TFXL Series Transit Time Flowmeter from Dynasonics). The flow rates for the 6.3 mm tube are well below the minimum measurable flow rate, as are the majority of the flow rates of the 1.6 mm (1/16 inch) tube which is far too small for all known sensors. Thus, ultrasonic flowmeters are ruled out for this application.

Table 9: Anticipated flow conditions with corresponding velocities through various diameter tubes for evaluation of the ultrasonic flow meter.

Flow condition	Volumetric flow rate (slpm)	Flow velocity through ¼" tube (mm/s)	Flow velocity through 1/16" tube (mm/s)
Maximum flowrate for 75 µm nozzle	5.8	6.12	97.9
Maximum flowrate for 25 µm nozzle	0.65	0.686	11.0
Desired minimum flowrate measurement	0.06	0.0633	1.01

Coriolis flowmeter

Coriolis flow meters are considered to be a very accurate and reliable method to directly measure the mass flow rate. These meters operate utilizing the Coriolis effect that causes a laterally vibrating tube to distort depending on the mass flow rate. They are capable of working over a wide range of flowrates without recalibration.

Micromotion can provide an ELITE sensor (1/10") which has the accuracies listed in Table 10. The cost of this sensor is approximately \$11 K. The accuracies are acceptable for high flow rates, but the poor accuracy at 0.1 mL/min is discouraging. This value is approximately 1/10 of the maximum flow rate from the small (25 µm) nozzle that will be tested. While this is a very low flow rate, it would still be desirable to have reasonable confidence (at most 5 % error) of this value in order to accurately model the nozzle clogging behavior.

Table 10: Flowrate accuracy for Micromotion ELITE 1/10" sensor.

Volumetric flowrate (at 20 MPa), (L/min)	Error %
1	0.62
1 x 10 ⁻³	5.7
1 x 10 ⁻⁴	86.0

Another popular Coriolis flow meter manufacturer, Endress & Hauser, was also considered for this application. However, their low flow meter (Proline Promass 80A) is accurate in the range of 0.02-20 kg/hr, which corresponds to a flow rate of approximately 0.17 slpm at the low end of the range. Thus, their sensor is not capable of measuring the lowest flow rates any better than the Micromotion sensor.

Brooks is able to supply a QUANTIM QMBM 3 mass flow meter that nicely fits the desired flow range of this experiment. This flow meter has an accuracy of 3 % down to 0.01 kg/hr, and has a maximum flow rate measurement of 1.0 kg/hr with an accuracy of 0.06 %. Thus, this flow meter was chosen for our application.

Stored energy calculation

The hazard level associated with the CO₂ or argon inventory can be gauged through an estimation of the stored energy within the fluid. The stored energy can be approximated from the energy associated with the isentropic expansion of the gas from high pressure, P_1 , to atmospheric pressure, P_2 (1 atm), which is historically calculated as follows (Lindeburg, 2001):

$$E = \frac{P_1 V_1}{k-1} \left[1 - \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \right] \quad (24)$$

The two situations examined here are: A) the pressurization of CO₂ into a 1.3 cm (½ inch) line which is vented through a small micro-nozzle to ambient or into a pool of room temperature/pressure water; and B) the pressurization of the entire main system including the test vessel and dump tank with argon for inerting purposes, testing of instrumentation and equipment, and preparation for sodium filling. Both cases were found to have a stored energy within the range of a medium hazard level designation (i.e., less than 75,000 ft-lbf).

A) Stored energy in CO₂ Line

The stored energy in the CO₂ gas line is calculated first. A schematic of this system is included in Figure 38. The high pressure CO₂ line is labeled “High P CO₂ line” and outlined in red dotted lines in this figure. This line consists of the booster pump that increases the line pressure from that of the CO₂ compressed cylinders to 20 MPa, the 6.3 mm CO₂ line, a small 150 cc reservoir, flow meter and additional instrumentation. The line ends with a small nozzle at the tip.

As part of the pre-experiment preparations, this high pressure CO₂ line will be tested on the benchtop by either by blowing CO₂ directly into air, or by bubbling the gas through a small pool of room temperature/pressure water at a maximum flowrate of ~15 slpm. The key properties of the CO₂ in this line are shown in **Error! Reference source not found.**

Table 11: Key parameters for CO₂ line.

Line Description	Volume (L)	Temperature (°C)	P ₁ (MPa)	Ideal gas constant, k	Stored energy (ft-lbf)
¼” High Pressure CO ₂ line	0.27	30	20	1.25	2,883

The total stored energy in the CO₂ line calculated for these properties using Eq. (24) is approximately 2,883 ft-lbf. This is considered a “medium” hazard level since the stored energy would be below 75,000 ft-lbf, and a ductile pressure relief valve is placed in the line.

Figure 38: Schematic of sodium CO₂ reaction system showing the gas system for the stored energy calculation.

B) Stored energy of Argon in “sodium” vessel and “sodium” system

As part of the pre-experiment preparations, the “sodium” system will be pressurized with argon. This system is marked “sodium system” and outlined in red dotted lines in Figure 39. Sodium will not be present in these vessels during the pre-experiment preparations. The vessel and piping will be heated up to 450 °C and an argon purge will be maintained through the system to ensure an inert atmosphere prior to sodium filling. This will allow shakedown of all of the system’s gas lines, flow meters and controllers, and gas sample port/mass spectrometer prior to placing any sodium into the system. It is expected for these operations that the pressure will be very low (i.e., 2-3 atmospheres maximum), but it is desirable to have the pressure relief valve set closer to the maximum system pressure of 3.1 MPa (450 psi) for greatest flexibility.

A list of the major components in this system and their respective volumes is included in Table 12. A maximum pressure of 1.37 MPa (200 psi) was chosen as an appropriate upper bound for the pressure relief valve setting that would still maintain a total stored energy below the medium hazard level designation. The stored energy calculated for each component is also listed in this table, with the total stored energy calculated as 60,550 ft-lbf. This is considered a “medium” hazard level since the stored energy would be below 75,000 ft-lbf, and a ductile pressure relief valve will be placed in the line.

Figure 39: Schematic of experiment showing sodium portion of system for stored energy calculation.

Table 12: Key parameters for vessel/main system.

Line Description	Volume (L)	Temperature (°C)	P ₁ (MPa)	Ideal gas constant, k	Stored energy (ft-lbf)
Test vessel (4" line)	14.8	450	1.37	1.67	14,547
Cold trap and Filter (3" lines)	2.5				2,462
Dump Tank	41				40,227
Interconnecting lines (3/4" & 1/2" lines)	3.3				3,275
Argon line	<0.01				37
TOTAL	62				60,550

Sodium Fire

The chemical reaction of sodium with air will add energy to the enclosure environment, heating up the air. This will result in an expansion of the air, which gives an estimate of the required capabilities of the scrubber.

According to Newman and Payne (1978), the measured flame temperature of sodium burning in air is approximately 1000 °C. As a conservative estimate, it is assumed that once the sodium starts burning, the entire enclosure is heated to this value. Obviously, this would not be the case, as the air near the enclosure walls would be significantly lower due to heat loss through the walls. However, this provides an upper bound on the volume expansion.

The densities of air for room and flame temperatures are listed in Table 13 (Munson et al., 1998).

Table 13: Density of air as a function of temperature.

Temperature (°C)	Density (kg/m ³)
25	1.184
1000	0.2772

Assuming an isobaric process, the ratio of the volume of expanded air due to heatup, V_2 , from the initial volume, V_i , can be written in terms of the densities at each state:

$$\frac{V_2}{V_i} = \frac{\rho_i}{\rho_2} \quad (25)$$

This ratio is approximately 4.27 for the conditions discussed above. The initial volume of the enclosure is approximately 13.56 m³. Thus, the expanded volume is approximately 57.9 m³. Assuming that the full volumetric flow rate capacity of the scrubber of 80 m³/min is used (which would not be the case due to the pressure drop in the duct), then the expanded enclosure air could be recycled in under a minute.

Pressure drop in duct

The pressure drop in the duct run should be taken into account in order to estimate the maximum volumetric flowrate that the scrubber can pull. A schematic of this scenario is shown in Figure 40.

The diameters of the scrubber and SNAKE duct are 38 cm (15 inch) and 15 cm (6 inch), respectively. The total volumetric flowrate of the scrubber is 80 m³/min. The duct length is estimated to be 13.7 m (45 feet). The viscosity of air at 25 °C is 1.85·10⁻⁵ Pa·s, while the density of air at 25 °C is 1.184 kg/m³.

The air velocity in the 38 cm scrubber pipe above the duct, v_{scrub} , will be 12.4 m/s if the volumetric flow rate of the scrubber is at the design design value..

The sum of the volumetric flow rates of the section of 38 cm duct from the snake enclosure and from the burn stall, Q_1 , will equal the total scrubber flow rate, i.e.:

$$Q_{\text{tot}} = Q_1 + Q_2 = A_1 v_1 + A_2 v_2 \quad (26)$$

Assuming that the pressure at the burn stall entrance and in the SNAKE enclosure are equal to atmospheric pressure, P , then the pressure drop's can be approximated by:

$$\Delta p_{\text{fric},1} = \Delta p_{\text{fric},2} + \Delta p_{\text{form}} \quad (27)$$

Figure 40: Schematic of scrubber and duct work.

This is, of course, a gross approximation for several reasons. The form loss from the scrubber pipe to the burn stall is neglected. The pressure in the enclosure should be slightly below atmospheric pressure. The effect of the duct booster fan is neglected.

The pressure loss due to friction can be written as:

$$\Delta p_{\text{fric}} = f \frac{L}{D} \left(\frac{\rho v^2}{2} \right) \quad (28)$$

where the friction coefficient, f is taken as

$$f = 0.184 \text{Re}^{-0.2} \quad (29)$$

and the Reynold's number is

$$\text{Re} = \frac{\rho v D}{\mu} \quad (30)$$

The form loss can be calculated as:

$$\Delta p_{\text{form}} = K \left(\frac{\rho v^2}{2} \right) \quad (31)$$

Where K is the form loss parameter and is equal to 0.5 for a sharp ended entrance, and approximately 0.9 for the elbow that will turn from the enclosure to the scrubber.

The velocities in each section of duct, v_1 and v_2 , can be determined via a simple iterative scheme. Table 14 shows the velocities, pressure drop and volumetric flow rate in the enclosure duct for various duct diameters.

Table 14: Enclosure duct conditions for various diameter pipes.

Enclosure duct diameter (inches)	Velocity in enclosure duct, v_2 , m/s	Pressure drop in enclosure duct, Pa	Volumetric flow rate in enclosure duct, Q_2 , L/s (cfm)
6	0.43	0.17	7.9 (17)
8	0.44	0.17	14 (30)
12	0.44	0.17	31 (67)
15	0.43	0.16	50 (104)

The total pressure loss in the ductwork is quite small, and should easily be managed by the blower.

The typically acceptable velocity limit for ducts which keep the generation of noise to acceptable limits is on the order of 12-18 m/s (2360-3540 ft/min) (ASHRAE, 1980).

A booster fan rated to 650 cfm (18.4 m³/min) will be added to the duct work, attached to the outside of the enclosure to assist in the removal of smoke from the enclosure. This booster would be able to recycle the air in the enclosure assuming the conservative volume expansion of the air discussed above approximately every 3.2 minutes. Even with the booster fan operational, some smoke may leak out of the enclosure. If this occurs, the smoke would trigger the high bay smoke alarm and alert the fire department.

5 Summary

One appealing feature of the supercritical carbon dioxide Brayton cycle energy conversion 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 heat source heat exchanger (Na-to-CO₂) 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, and this would lead 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 likely. 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.

Therefore, an experiment program at Argonne was initiated in FY 2010 to investigate the reaction characteristics between sodium and CO₂ under micro-leak conditions. This report described the facility scaling rationale and design. Significant progress toward completion of the assembly of the SNAKE (S-CO₂, Na Kinetics Experiment) has been made in FY 2011. All major components and instruments have been specified and purchased. The gas delivery system has been designed and is nearly assembled. A simple water mockup system has been built and will be coupled with the gas delivery system in FY 2012 to visualize the micro-nozzle physics prior to use in sodium. A temperature control system has been assembled to control the trace heating of all sodium-carrying vessels and pipes. A large enclosure has been constructed and the frame is currently being used as the support system for experiment assembly. This assembly includes adding sodium-management equipment such as stainless-steel catch trays and sodium-smoke removal fans and duct work. A number of analyses have been completed to support the safety case for the operation of this experiment.

The facility itself has been designed to be flexible to accommodate other types of testing in the future. Many of the facility components are modular and include a number of extra fittings for diversity. Additional potential testing missions could include geometry specific testing of the sodium-CO₂ reaction, sodium-water reaction testing, fission product scrubbing tests, and high flowrate (jetting) CO₂ blowdown tests into sodium.

The goal of the sodium-CO₂ interaction tests is a fundamental understanding of sodium-CO₂ interactions under prototypical conditions of compact diffusion-bonded heat exchanger failure, a fundamental understanding of self-plugging if it occurs, and the development of one-dimensional phenomenological models for the interactions between high-pressure CO₂ issuing into liquid sodium from a micro leak across a stainless steel pressure boundary. These models will be validated using the experiment data obtained.

Table 15: Anticipated timeline for Na-CO₂ experiment program. Completed portions of tasks are colored in black, while uncompleted tasks are gray. Deliverable reports timeframes are marked with a yellow dot.

	3/10	6/10	9/10	12/11	3/11	6/11	9/11	12/11	3/12	6/12	9/12	12/12	3/13	6/13	9/13	12/13	3/14	6/14
Facility Design																		
Component Purchases																		
Facility Assembly																		
Shakedown and Initial Data																		
Experiment Data Collection																		
Model Development																		

Most major components have been purchased, and portions of the facility have been assembled in 2011. Completion of procurement is expected in December 2011. Complete assembly of the facility and initial sodium loading is anticipated in June 2012. A report documenting these activities will be produced the following month. Facility shakedown and initial data will be complete in September 2012, along with a summary report. Fiscal Year 2013 will consist of obtaining the complete experiment data matrix, with a detailed report delivered in September 2013. Model development and validation will take place the following Fiscal Year, with a detailed model report anticipated to be delivered in June 2014. See Table 15 for the schedule outline.

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