DOE-IIPS PROPOSAL
Award Number: ID14832
Project Number: 07-037
Program Area: AFC R&D
Nuclear Energy Research Initiative

FINAL TECHNICAL REPORT on

Experimental Development and Demonstration of Ultrasonic Measurement Diagnostics for Sodium Fast Reactor Thermal-hydraulics

By

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Submitted to:
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Project Summary

This research project will address some of the principal technology issues related to sodium-cooled fast reactors (SFR), primarily the development and demonstration of ultrasonic measurement diagnostics linked to effective thermal convective sensing under normal and off-normal conditions. Sodium is well-suited as a heat transfer medium for the SFR. However, because it is chemically reactive and optically opaque, it presents engineering accessibility constraints relative to operations and maintenance (O&M) and in-service inspection (ISI) technologies that are currently used for light water reactors. Thus, there are limited sensing options for conducting thermohydraulic measurements under normal conditions and off-normal events (maintenance, unanticipated events). Acoustic methods, primarily ultrasonics, are a key measurement technology with applications in non-destructive testing, component imaging, thermometry, and velocimetry. This project would have yielded a better quantitative and qualitative understanding of the thermohydraulic condition of sodium under varied flow conditions. The scope of work will evaluate and demonstrate ultrasonic technologies and define instrumentation options for the SFR. Under the workscope, the researchers accomplished and/or report the following:

- A sodium loop, just under 10 liters, was designed, constructed, and operated but only tested in water. One of the two test sections was a natural convection heat transfer experiment wherein ultrasonic velocimetry was tested. The loop received design and safety review approval from the Center for Advanced Energy Studies (CAES) and is thus ready to be operated with sodium, given CAES' preparedness to receive sodium.
- Development and demonstration of ultrasonic thermometry was not fulfilled. However, we learned that this can essentially be done by signal processing with the well-known variation of the acoustic velocity in sodium. Therefore the dual-purpose velocimetry and thermometry is still possible.
- Testing of a compact sodium-to-supercritical CO_2 heat exchanger was not realized. However a prototype compact heat exchanger manufactured by Tranter was procured. It will be tested and thus leverage in an ongoing NEUP project.
- Limited natural convective transient heat transfer and velocimetry data was obtained using the Met-Flow Dual ultrasonic Doppler velocimetry profiler (UVP). A number of transducers rated up to 150°C are being leverage in another ongoing sodium project.
- Access to the ANL sodium plugging experiment was not provided as indicated by a letter from ANL in 2007.
- The project experienced a number of transfers, delays and departure of co-PIs, from Kansas State University to University of Idaho. A final ill-informed 'work stoppage' order at CAES made completing the SOW all but impossible. Unexpended funds were returned to DOE-ID.
- There has been interest expressed by a FFRDC to assume possession of the project related hardware.

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Background

The international sodium fast reactor R&D effort, most recently summarized in the R&D Program Plan for the Sodium Fast Reactor (SFR), rests on relatively well-established technologies and reactor engineering knowledge and experience base. Thus, within the context of renewed interest in the SFR and closed fuel cycle, the majority of the R&D issues that remain are technology performance and demonstration related issues rather than feasibility of concepts. Both under Generation IV and GNEP objectives, there is a need to re-address SFR realizability in terms of design concept economics, in-service inspection and repair, verification of inherent safety and updated analyses (i.e. advanced simulations).

Sodium, although well-suited as the heat transfer medium for the SFR, is chemically reactive and (optically) opaque. As such, sodium presents engineering accessibility constraints relative to LWR operations and maintenance (O&M) and in-service inspection (ISI) technologies. Thus in terms of thermohydraulic measurements under normal conditions, and before and after off-normal (maintenance, unanticipated events) events, there are limited sensing options. Acoustical methods, primarily ultrasonics, are a key measurement technology with applications in non-destructive testing, under-sodium (components) imaging, thermometry and velocimetry. Here, the Kansas State co-PIs aim to demonstrate ultrasonic technology by addressing remaining issues in a new sodium test loop. In particular, ultrasonic velocimetry and thermometry, with focus toward improved SFR O&M will be investigated.

We propose a research project to address some of the principal technology issues related to sodium-cooled fast reactors; primarily concurrent development and demonstration of ultrasonic diagnostics linked to effective thermal convective sensing under anticipated normal and off-normal operations and maintenance.

The project will yield a better qualitative understanding and quantitative means to sense the thermohydraulic condition of sodium under varied flow conditions. This project supports the R&D Program Plan for the Sodium Fast Reactor (SFR),within the current Gen' IV roadmap and emerging GNEP missions. The scope of work will demonstrate and evaluate ultrasonic technologies and define instrumentation options for the SFR. This will maintain and extend the U.S. nuclear SFR knowledge base, as well as educate the next generation of professionals familiar with the SFR.

Introduction

Considerable fast reactor R&D and design engineering work on the sodium-cooled fast reactor (SFR) concept was undertaken in the 1960s, 70s and 80s in the United States, Europe (France, Germany, UK), and Japan. The experimental reactors, EBR-I and II (Stacy, 2000; Koch) Phenix/Superphenix and Joyo/Monju are testimony to this effort. Yevick (1966), Graham (1971) and Waltar (1981) are three notable reference texts. However, due to US non-proliferation policy, shifting national priorities and waning support for nuclear energy in the post-TMI/Chernobyl years, fast reactor R&D all but ceased by the early 90s. Since then, France and Japan have struggled to maintain activities. However, since announcement of the Bush Energy Plan describing the need to free heavy US dependence on foreign fossils fuel supplies, recycling of reactor fuel, linked to a new generation of fast reactors is now under consideration within the Global Nuclear Energy Partnership (GNEP). In particular, the R&D Program Plan for the Sodium Fast Reactor (SFR; draft, 2006), notes that the nuclear system concept is well-established and supported by dated, but adequate reactor engineering technologies, knowledge and experience base. There is however, a call to enhance the SFR economics (configuration simplifications, advanced energy conversion), update maintenance and operations (O&M) related technologies (in-service inspection and repair), verify inherent safety in design and advance simulations to the state-of-the-art.

The original selection of liquid sodium cooling over other competing media (lead and others) was based on two factors: 1) the doubling time of SFR can be significantly shorter than that of say, a Pb-Bi-cooled reactor as a result of the higher power density achievable in sodium cooled cores; and 2) Pb-Bi coolant, at the temperatures of interest, can be very corrosive to structural materials. Thus sodium, although well suited as the coolant, is known to be chemically reactive and (optically) opaque. As such, relative to existing LWR operations and maintenance (O&M) and in-service inspection (ISI) technologies,. O&M and ISI of SFR present engineering accessibility constraints. Thus in terms of thermohydraulic measurements under normal conditions, and before/after off-normal (maintenance, unanticipated events) events, there are limited sensing options. Acoustic methods, primarily ultrasonics, are a key measurement technology with applications in non-destructive testing, under-sodium (components) imaging, thermometry and velocimetry. It therefore serves, besides traditional application of thermocouples, a key phenomenological and technological platform upon which SFR will likely be realized.

The following sections provide summary information on a proposal to develop and demonstrate ultrasonic-based technologies via design, construction and operations of a small, university-based sodium loop facility.

Objectives, Ultrasonic Measurement Applications in Sodium

The basis of the proposed research focuses on the development of high temperature ultrasonic instrumentation for use *in sodium*. However, the ultrasonic method is equally applicable to other Gen' IV nuclear systems with liquid coolant such as Pb-Bi and molten salt.

With respect to velocimetry, we propose to demonstrate the applicability of ultrasonic Doppler velocimetry in conjunction with development of a prototype high-temperature ultrasonic transducer. Ultrasonic Doppler velocimetry is further explained below, but physically consists of a sensor (probe) and "electronics". The sensor, or transducer, is typically made from a piezoelectric material element and, converts electrical energy into acoustical waves and vice versa. As common commercial applications of ultrasonic transducers are at "normal" temperatures, <50°C, there is a particular need to develop transducers at SFR temperatures, ~500°-650°C. The velocimetric information is spatio-temporal along the line of wave propagation. Tokuhiro, Ara, Kimura, Hayashida and co-workers have summarized the status and application of ultrasonics for sodium at the Japan Nuclear Cycle Development Institute (1996a, b; 1997a,b; 1998, 1999, 2000).

In addition, as the rate of change of the acoustic (propagation) velocity with temperature in sodium is approximately 1cm/sec/°C, with modern developments in digital signal processing and data acquisition, it is in principle possible to resolve the spatio-temporal temperature distribution along the ultrasonic beam line by unfolding the echographic propagation time. The change in acoustic velocity fortuitously quasi-linear over the temperature range of relevance to the SFR. While this principle has been demonstrated, its applicability to SFR O&M remains open.

Finally, as echographic acoustics depends on back propagation of waves to its source, per reflection from "tracers" moving with the flow, the detected echo is related to the tracer concentration in the carrier liquid (i.e. sodium). As such, echography can serve as an indirect monitor of flowing oxides and particulate concentration monitor in (low concentration, small particle size) solid-liquid systems. From experience, PI Tokuhiro is aware that larger scale sodium loops always contain temperature-dependent impurities that serve as tracer particles for ultrasonic velocimety.

Based on this summary, the original aim of the project was to demonstrate ultrasonic measurement technology applications for the SFR as follows:

1. **First** design, construct and operate a new university-based, small, simple but purposeful sodium flow loop with inventory of approximately 5-6 liters. The loop should be so designed to develop, test and demonstrate ultrasonic technology solutions.
2. **Second** develop, test and demonstrate ultrasonic velocimetry, thermometry and particulate (oxides,

contaminants) concentration monitoring, with focus toward improved SFR O&M. That is, velocimetry, thermometry and concentration monitoring as diagnostic tools under steady and transient conditions.

3. **Third** address the energy conversion operating space by testing a compact, sodium to supercritical CO_2 (SCO2) heat exchanger. Generate convective heat transfer data, correlations and operational experience under steady and transient conditions. Assess the potential for plugging with respect to the compact heat exchanger coolant channel diameter.

Development of these instrument technologies will define cross-cutting applications for Generation IV and GNEP reactor engineering technology needs.

Description of Technical Need and Scope of Work
Proposed Sodium Loop

We proposed construction of a small sodium flow loop as schematically shown in Figure 1 and with characteristics shown in Table 1. The loop with total sodium inventory targeted at 5-6 liters consists of the following: 1) dump tank with thermocouple (TC), level indicator, relief valve and gauge, gas or vacuum line and fill port, 2) expansion tank with the same, except a fill port, 3) an electromagnetic (EM) pump to circulate the sodium, 4) cold trap to remove impurities and contaminants. The loop is additionally instrumented with two oxygen monitor (OM) sensors and two flowmeters (FM), one each for two test sections which can be accommodated as shown. This layout, as depicted, is planned to be completed in Year 1 with additional refinements to be defined and completed in Year 2. The loop accommodates two test sections, the main line will be a heated pipe section instrumented with a number of sensor ports for velocimetry and thermometry. This main line will be designed with ultrasonic velocimetry and thermometry in mind and not necessarily scaled to address a targeted convective heat transfer issue. However, every effort will be made reconfirm established convective heat transfer correlations under traditional flow configurations. Tokuhiro (1990) and Stoots et al. (2001) provide select references on heat transfer in liquid metals.

The addition of a compact heat exchanger, like the one under performance testing by Tokuhiro (2005) and projected as applicable to a Brayton cycle secondary loop will be installed and tested in Year 2. Although not shown, the supercritical CO_2 (SCO2) loop will consist of a pressurized CO_2 supply tank, small heat source (hot water and/or electrical) to reach the critical temperature-pressure range (31.1°C at 7.38MPa), a SCO_2 pump and flowmeter, all similar to that reported by Lomperski et al (2006). A brief synopsis of compact heat exchanger performance, in particular, the printed circuit heat exchanger (PCHE) is given below.

Sodium Loop

The loop will be placed in an enclosure and means to flood the volume with (cold) N_2-gas as smoke abatement will be implemented. Spill pans under tanks and connections will used, as well as protective wear and fire extinguisher intended for sodium. The co-PI, Tokuhiro, received basic training in sodium fire mitigation at JNC.

As only a select few universities operate (sodium or related liquid metal) or have the infrastructure to host a liquid sodium (or liquid-metal) thermohydraulics laboratory, the establishment of this new sodium loop will have significance and impact, concurrent with re-emphasis on the SFR. A sodium thermohydraulic laboratory is needed within the greater academic community in order to support SFR R&D in national laboratories and to educate the next generation of SFR engineers.

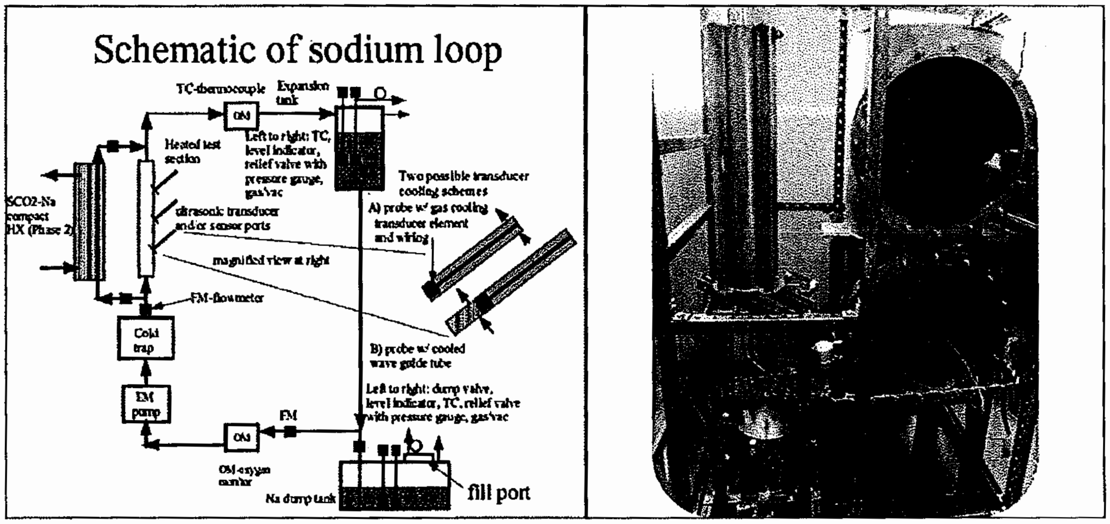


Figure 1. Schematic of proposed K-State sodium loop

Table 1. Sodium loop description

#	Feature	Target	Current
1	Maximum operating temperature	~500°-550°C	Approved to 150°C
2	Na-flow	0.5-1.0 m/s	1-10cm/s, buoyancy-driven
3	Na volume	Up to 3 liters	~10 liters
4	Na volume; expansion tank	Up to 3 liters	Up to 3 liters
5	Expansion tank volume	~5 liters	~ 5 liters
6	Na volume; dump tank	~6 liters	~ 6 liters
7	Dump tank volume	~12 liters	~ 12 liters
8	Loop piping	½" stainless steel	stainless steel

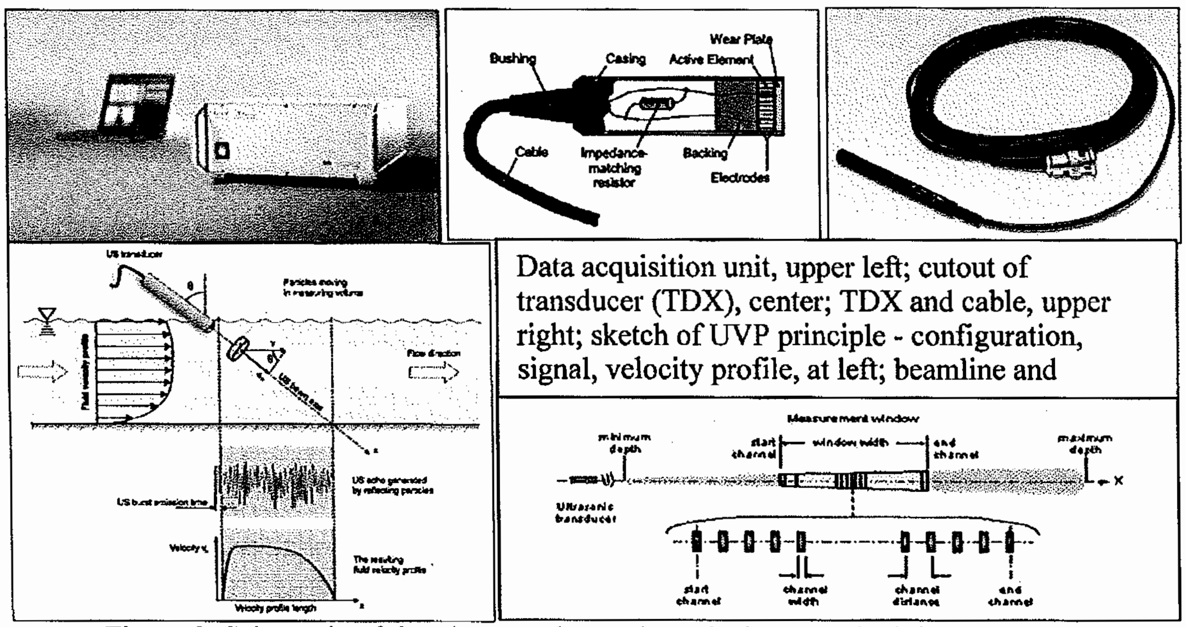
Ultrasonic Measurement Applications and Technology in Sodium

Ultrasound Doppler Velocimetry: Principles and Applications

Ultrasound Doppler velocimetry (UDV) is an acoustic echographic technique that detects both the time-of-flight (t) and Doppler-shift (f_D) information contained in reflectants (tracer particles or in-situ impurities) moving with a carrier liquid. A schematic of the principle is shown in Figure 2 for a common fluid. In a conventional application one ultrasonic transducer element is used, invasively or non-invasively, to emit a burst of acoustic waves. It is then switched to pick-up echoes. The Doppler shift, including the sign, provides information related to the velocity of the reflectant at the instant of detection (magnitude and direction with respect to the transducer). Furthermore, under the assumption that the reflectants move in unison with the carrier liquid; that is, with no appreciable slip between the reflectants and liquid, the velocity of the carrier liquid is known. This condition is realized by closely matching the density of the reflectant with that of the test media. Plastic particles on the order of 10-100 μm are well suited for example to use as reflectants in water systems. In cases where addition of tracers is impractical, including liquid metals, naturally existing impurities or oxides are contained in the liquid. Oxides-laden liquid metal systems are thus amenable to UDV. This (t, f_D) information is determined over multiple (spatial) channels, the number of which depends on the data acquisition system. A multi-point UDV thus generates a velocity profile of the velocity component *along* the ultrasonic beam. As the channels are repeatedly sampled by electronic means, we can gain spatial-temporal information of the flow. In the co-PI's case (Tokuhiro), the specific UDV device collects data at 128 spatial points (channels) over at least 1024 profiles in time. The number of profiles is in part only limited by the memory capacity of the data acquisition system.

The velocimeter used to date by Tokuhiro is manufactured by Met-Flow SA (Switzerland) and is known as the Ultrasound Velocity Profile (UVP) monitor. The UVP was largely developed by Y. Takeda at the Paul Scherrer Institute. Takeda has extensively documented the development and applications of the UVP for liquids (Takeda, 1985; Takeda, 1986; Takeda, Kobashi, Fischer, 1990; Takeda, Haefeli, 1991a, Takeda, 1991b; Takeda, Samec, Kobayashi, 1991c; Takeda, 1992a, Teufel et al.,1992b, Takeda, 1995). The UVP differs from other ultrasonic metering devices in that it repeatedly detects and over-samples the time-of-flight and Doppler-shift information over many channels, and thus generates spatial-temporal data as opposed to time-averaged data within a fixed spatial volume. This is further enhanced by the fact that the acoustic velocity in liquids, is substantially higher than in gases (c~1500-2500m/s vs. 300 m/s). This means that the UVP serves conveniently as a quasi-instantaneous velocity measurement tool.

The only other flow measurement option in sodium is use of a small permanent magnet or miniature EM flow meter; both use the Faraday effect to detect transport of electrically-conductive molten metal. Kapulla et al. (2000) used such a probe in a thermally-stratified Na mixing experiment while, Broc, Sannier, and Santarini (1983) studied use of Pb in a molten salt reactor. These probes only provide point velocity information and because the magnetic properties of probe material are temperature dependent, local temperature measurement and correction is needed. In that ultrasonic Doppler velocimetry provide velocity information along the beam line, it appears superior in velocimetry relative to the permanent magnet probe.



Data acquisition unit, upper left; cutout of transducer (TDX), center; TDX and cable, upper right; sketch of UVP principle - configuration, signal, velocity profile, at left; beamline and

Figure 2. Schematic of the ultrasound Doppler velocimetry principle and that used

The UVP has been tested in liquids noted at the Met-Flow SA Web-site [Met-Flow SA, 2000]. Water-based (c~1480 m/s at 20°C) applications have been investigated in many common flows (pipes, channels, tanks, rotating/oscillating). In addition, liquid metal flows (Hg, ferrofluids), including thermohydraulic mock-up facility for a PbBi-cooled spallation source (PSI). Finally, industrial flows (coal slurry, paper pulp) and oil/water flows have been documented.

Oxide and/or particle concentration and transport detection by UDV

Due to the fact UDV is an echographic technique, particulate impurities such as oxides that are acoustically "sampled" during transport through a beam line, if properly accounted, represent a measure of its in-situ concentration, as well as its "ensemble" average velocity. Thus if the distribution of oxide particles in flow of sodium includes a window of sizes detectable by UDV, we can in principle quantify the concentration and velocity of detected particles. In the anticipated applicaton with the transducer operating at 4 MHz, the operationally detectable range of particles is nominally 10 μm to 100 μm. This range can be expanded by using transducers operating at other frequencies, such as 2MHz and 8MHz. From past experience in other liquid metal systems (Takeda, 1987; 1998a, 1998b, 2000a, 2000b, Komatuzaki et al., 1995) oxides and particulates (insolubles) are common in liquid metal flow loops (JNC sodium loops) in the particle range given detectable at 4MHz.

By noting the detectable particle size distribution and concentration saturation level via calibration of the UDV to be used, the device can be applied to sodium flows. The accumulation of (echo) events gives the relative concentration of transported oxides along the ultrasonic beam during the sampling time, while measurement of the Doppler shift at the time of detection, when spatially- and temporally-averaged gives the ensemble average velocity of the oxides. We will assess the detectable particle size concentration using a calibration flow cell wherein the particle size and concentration can be controlled. We will then make a relative measurement in sodium at a measurement point of interest. Further, with positioning of multiple transducers along a flow loop, it may be possible to experimentally verify whether oxides (and/or particulates) are transported, for example from one region to another in a sodium loop.

High-temperature transducer

A UDV system consists of two key components, a UVP (or equivalent) for data acquisition/data processing and separately, a high-temperature transducer. For the projected high-temperature applications, prototype piezoelectric transducers have been custom-made by Toshiba (Ara, 1997) and in principle, are limited by the Curie temperature of the piezoelectric element. In the case of the Toshiba lithium niobate ($LiNbO_3$) transducer, this limit is ~650°C. These transducers as reported in Komatuzaki (1995) and Ohki (1997) have been tested up to 500°C for pipe-flow velocimetry and compatibility in sodium. CEA of France has also produced high-temperature transducers in-house, but has not reported on their applicability to velocimetry. To the co-PI's (Tokuhiro) knowledge, although Karasawa (2000) described an in-house (Toshiba) development of a new piezoelectric material with Curie temperature approaching 1000°C, much of this knowledge is commercially proprietary and highly dependent on the recognized technology need (i.e. an SFR order). It thus seem prudent to work with lithium-niobate (or similar) transducer element and investigate design means of isolating the thermal load on the transducer itself as shown via two schemes in Figure 1. That is, we will design (via CAD and/or CFD model) and construct prototype higher temperature transducers of one design or both as follows: 1) with gas or liquid cooling of the head region, and/or 2) with an acoustic impedance-matched wave guide that propagates the acoustic wave but at the same time, thermally isolates the head region.

Acoustic thermometry

As mentioned, the rate of change of the acoustic (propagation) velocity with temperature in sodium is approximately ~1cm/sec/°C and linear over the temperature range of relevance to the SFR. With conventional ultrasonic systems as described, the practical velocity resolution is on the order to 1-2mm/s. Thus, with modern developments in high-speed digital signal processing and data acquisition, it is in principle possible to spatio-temporally detect small changes in the reflected wave propagation time (forward or back scatter) to the transducer. Once measured, it is in principle possible to reverse estimate the local temperature at the time of reflection. Thus, the temperature distribution along the ultrasonic beam line can be unfolded. A demonstration of an ultrasonic thermometers was reported by Hayashida et al. (2000) using an acoustic wave guide. However, it remains to be seen if further resolution of the spatio-temporal, as well as the temperature scale, is possible such that it would be of significance to the SFR O&M operating space. In the proposed work, we plan to first reconfirm the working principle and then address the applicability and operating space of the ultrasonic thermometer.

Compact heat exchanger testing for Brayton cycle power conversion

Two key features used to improve the economics of the next generation SFR are: 1) plant simplifications to limit capital costs and, 2) thermal efficiency enhancement to reduce the cost per unit of power delivered. Both of these features can be realized with the supercritical CO_2 Brayton cycle, which has been proposed for power conversion in several Gen' IV nuclear systems. The use of a gas turbine cycle rather than a steam-driven Rankine cycle is expected to significantly reduce plant size, complexity, and cost. A key component in the Brayton cycle is a compact heat exchanger for high energy conversion efficiency. One promising concept is the printed circuit heat exchanger (PCHE by Heatric, 2006). At present however, there is no experience with large-scale PCHEs operating in a supercritical CO_2 Brayton cycle and their performance level in an actual power plant is uncertain. There is equally no experience using sodium and another heat transfer medium, such as supercritical CO_2.

However, Ishizuka et al. (2005) have conducted thermal hydraulic tests with a smaller 3 kW Heatric heat exchanger using CO_2. The hot and cold side pressures ranged between 2-4 and 6-11 MPa, respectively, with fluid temperatures between about 110 and 280°C. The CO_2 on the cold side was in many cases supercritical (critical point at 7.38 MPa, 31.1°C) though all tests were carried out far from the pseudocritical region where there are sharp changes in fluid properties with temperature. The effectiveness of the heat exchanger was found to be very high, ~99%, for all test cases. Pressure loss and heat transfer coefficients correlated well with Reynolds number and there were no notable differences between subcritical and supercritical conditions. However, an ongoing performance test of a 17kW PCHE by Lomperski et al. (2006) gave less dramatic results at conditions where the CO_2 outlet flow was in the pseudocritical region. These results are for water-SCO2 heat exchange, while high-and-low pressure SCO_2-SCO_2 heat transfer tests remain.

There is a large body of related research devoted to heat transfer of supercritical fluids in tubes and bundles; two examples include Pioro et al. (2004) and Pitla et al. (1998). Liao and Zhao (2002a,b) and Huai et al. (2005) studied single and simple flow geometries. These studies have observed complex behavior with both augmentation and deterioration of heat transfer coefficients in the pseudocritical region depending upon such factors as channel orientation, flow regime, and heat flux level. These findings are difficult to apply to the PCHE, especially considering that other studies have shown that the hydraulic and heat transfer characteristics of micro/mini-channels differ from those of conventional-sized channels (Peng and Peterson, 1996).

It remains to be seen, with the possibility of plugging of micro/mini-channels in a sodium-to-SCO2 compact heat exchanger whether sodium-to-SCO2 can be operated reliably and if not, whether a flow monitoring means, such as ultrasonic velocimetry, can be implemented. In that the acoustic velocity in solid phase is greater than that in the liquid phase for most elements, here again ultrasonic sensing and judicious signal processing may be able to detect the onset of solidification or "blockage" of a flow channel. This however needs to be demonstrated and will be addressed in the proposed work. Relative acoustic monitoring of two flow channels with a controlled solidification front or purposeful introduction of a blockage will be tried as a sensible investigative approach. The flow in both channels should change as soon as a flow blockage develops in one.

Summary

The application of ultrasonic measurement methods to the SFR will not only facilitate development of the SFR (and liquid-based) thermohydraulics, but identify promising ultrasonic technologies for implementation during the operations and maintenance functions of the next generation SFR. The applicability of ultrasonic techniques was earlier documented in development of SFRs in France, Japan and to a lesser extent in the UK. However, the state-of-the-technology needs to be updated and remaining issues addressed in order to bring the SFR nuclear system up to Gen' IV and GNEP performance standards. The current proposal re-addresses ultrasonic measurement development, application and demonstration in a new university-based sodium loop. In particular, we focus on ultrasonic velocimetry, thermometry and in-situ particulate matter concentration monitoring.

The K-State team, whose lead co-PI has past experience in this area, will investigate velocimetry, thermometry, particulate concentration and compact heat exchanger performance in a proposed sodium flow loop. The project will be effectively communicate with the Gen' IV and GNEP leads and revisit the state-of-technology in Japan and Europe, to facilitate the global effort.

Significance and Impact

At present only a few universities operate sodium or liquid metal loops, or have the infrastructure to host a liquid sodium (or liquid-metal) thermohydraulics laboratory. There appears to be no university laboratory with a focus on applications of ultrasonics in liquid metals and/or the SFR. Thus the proposed initiative to establish a new sodium flow loop is significance and has impact consistent with the renewed interest in the SFR. A sodium thermohydraulic laboratory is needed within the greater academic community in order to support SFR R&D effort at national laboratories. Under this proposal, K-State can begin to educate the next generation of SFR engineers.

With respect to described scope of work, the project will yield a better qualitative understanding and quantitative means to sense the thermohydraulic condition of sodium under varied flow conditions. This project supports the R&D Program Plan for the Sodium Fast Reactor (SFR), within the current Gen' IV roadmap and emerging GNEP missions. The scope of work will demonstrate and evaluate ultrasonic technologies and define instrumentation options for the SFR. This will maintain and extend the U.S. nuclear SFR knowledge base, as well as educate the next generation of professionals familiar with the SFR.

Project Timetable and Identified Tasks

In this section we first present the identified tasks in summary form. The project is planned to take 3 years and the annual tasks are as follows:

Year 1 Tasks: Design, construct and deploy sodium loop

The proposed sodium flow loop will be designed, constructed, deployed and tested in Year 1. Even for a small forced convection sodium loop the key components needed are: an electromagnet pump, a dump tank, a cold trap and an expansion tank. The components will come from suppliers and manufacturers known to the lead co-PI, and in consultation with sodium facility experts at ANL and associated national labs. Based on ANL's plan to operate a small sodium flow channel loop (Cho, 2006), the K-State loop is estimated at a Year 1 cost of $75K with an additional funds allocated for the UVP, prototype high-temperature transducers and loop components. The Year 2 fractional allocation will be for additional wares needed to refine the loop design and functionality. Upon completion of the apparatus, we will take delivery of sodium and inaugurate the loop. Initial shakedown tests will be conducted at lower operating temperatures (100°-450°C) to gain operating experience, to assess/establish operating procedure (including safety practices) and to define the initial test matrix. The test matrix will be based on an approach to confirm via a demonstration, velocimetry and thermometry measurement applications previously reported in sodium.

Probe and measurement method development will commence in parallel with loop design and construction. In order to accurately estimate the oxide and particulate concentration in a flowing sodium a separate calibration will be conducted in a calibration cell, using a common (transparent) liquid with known concentration of particles (nominally ~10 μm to~200 μm in size) added to make a solid-liquid solution. The calibration cell will be one or more of the following: 1) a stainless acoustic test cell intended for high-temperature liquid and/or 2) a mock-up test cell made from acrylic to permit visualization. The calibration test will be used to define the operating range of the particle size (characteristic echo) and known concentrations, as well as a limited mixture of particle sizes. The calibration cell will serve as a benchmark for characteristic echoes received from oxides and particulates in the sodium flow loop.

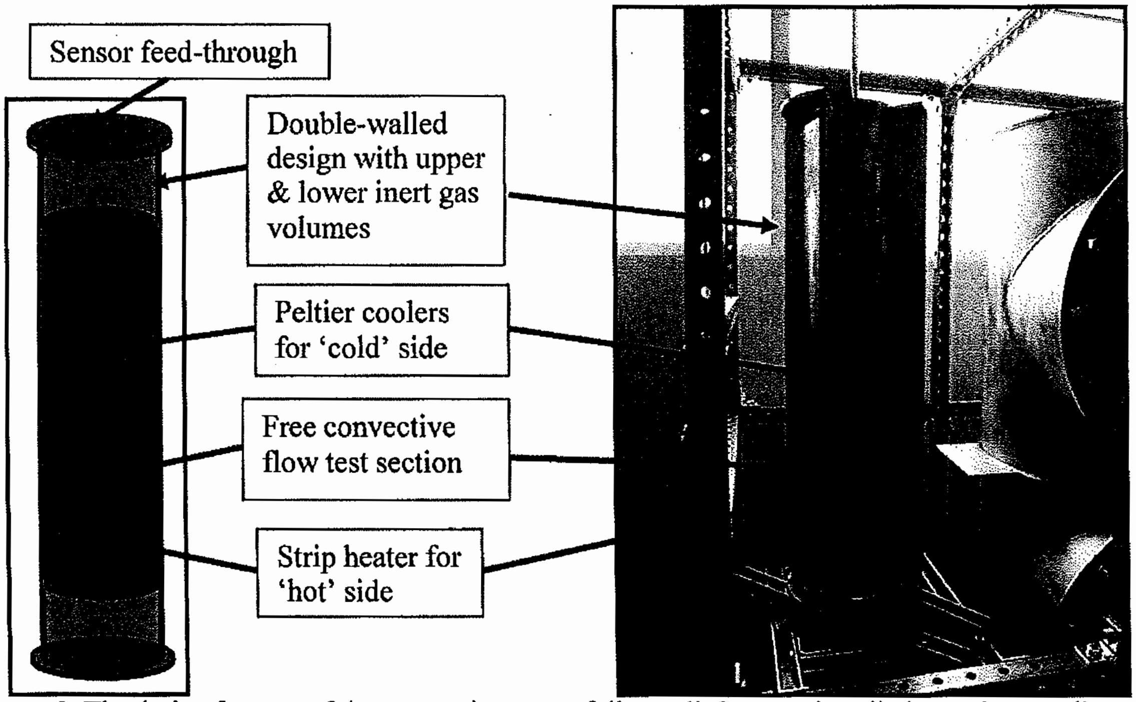


Figure 3. The design features of the test section are as follows: 1) Concentric cylinders to keep sodium from coming in contact with air upon any anticipated leak, 2) Free convective flow created by hot and cold sides - Peltier coolers on the cold side, Omega strip heaters on the hot, 3) Ultrasonic sensors and thermocouples inserted via 'Conax' fittings through penetration at the top. At right is the inner test section without the outer shell.

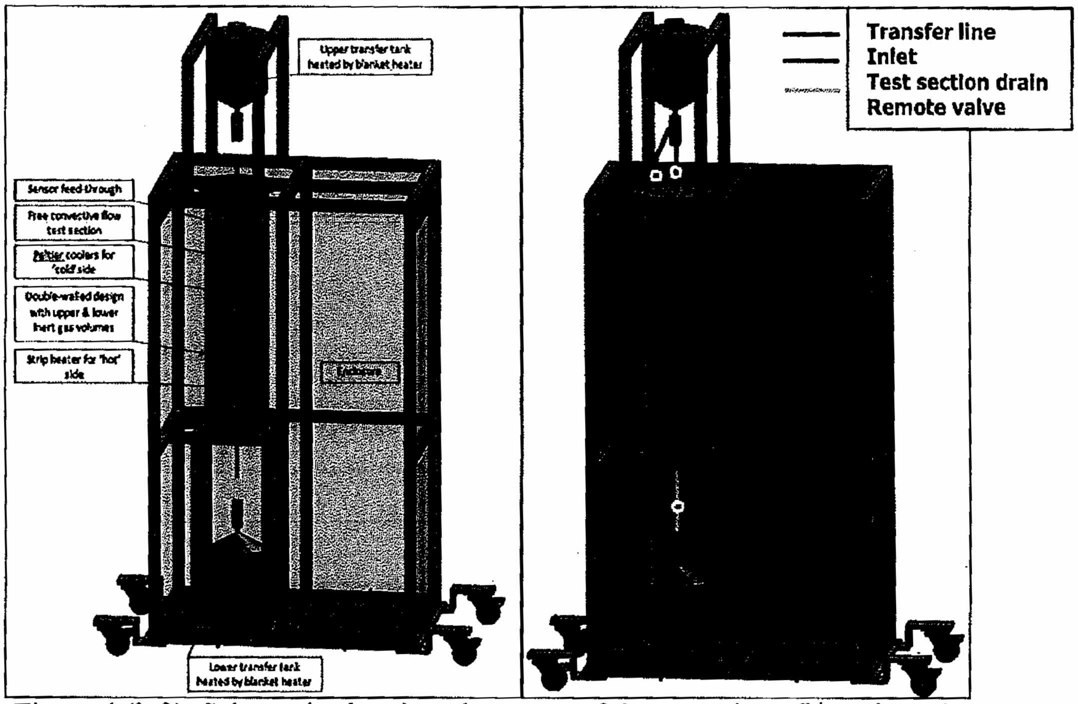


Figure 4 (left). Schematic showing placement of the natural configuration of natural convection experiment and transfer lines used.

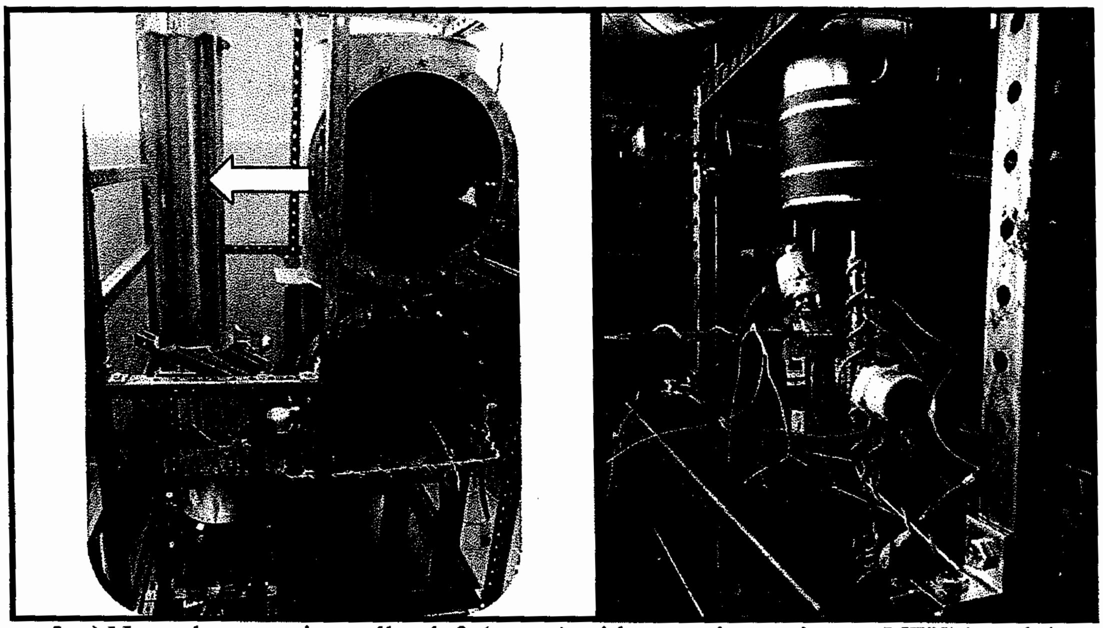


Figure 5. a) Natural convection cell at left (arrow) with second experiment (NEUP) at right and common sodium supply system, within compact enclosure (without sheet-metal panels). b) shows close-up of electro-valces, rope and wrap-around heaters for piping and tank.

Figure 6. Snapshot of natural convection experiment (arrow) and data acquisition systems (temperature, heaters and velocimeter) during shakedown testing.

Additional Components

In anticipation of access to the ANL sodium loop, the following components were designed and constructed. They are still available for eventual use in the designed flow loop.

Flow Test Section

This rectangular channel is designed with an insert (at left) to affix the ultrasonic transducer. Flow is intended from left –to-right. The figure additionally shows a ribbon heat to maintain the test section above the melting point of sodium. This rectangular flow test section is still available.

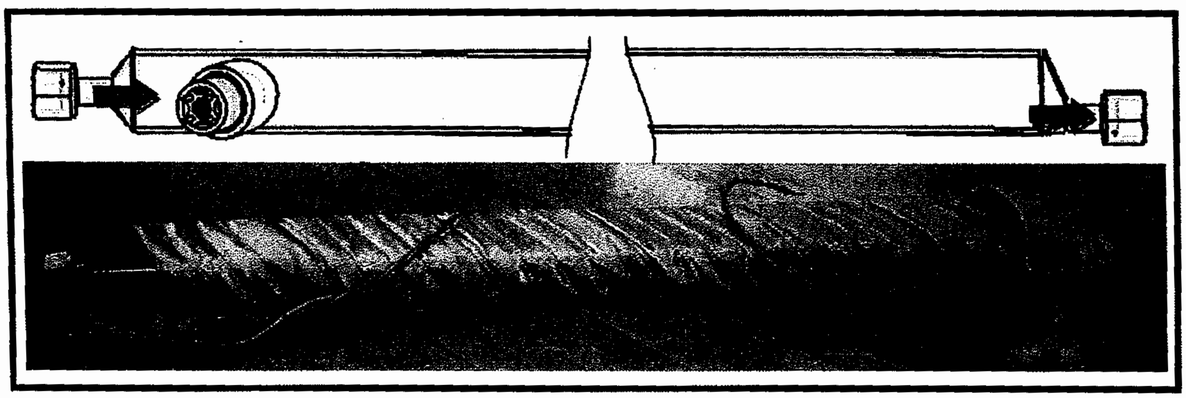


Figure 7. Schematic of flow test section with provisional location of ultrasonic transducer (top) and prototype test section with guard heater 'tape'.

Cold Trap and Heat Exchanger

A prototype cold trap, depicted in Figure 8, with 'cold finger' and a stainless mesh (to filter particulates) was designed and constructed. The cold trap works in hand with a small heat exchanger, shown in Figure 9, in order to control the particulate impurity (or tracer particles) and/or oxide content in the sodium. The particulates or oxides are needed in order to serve as reflecting surfaces for acoustic waves (ultrasonic).

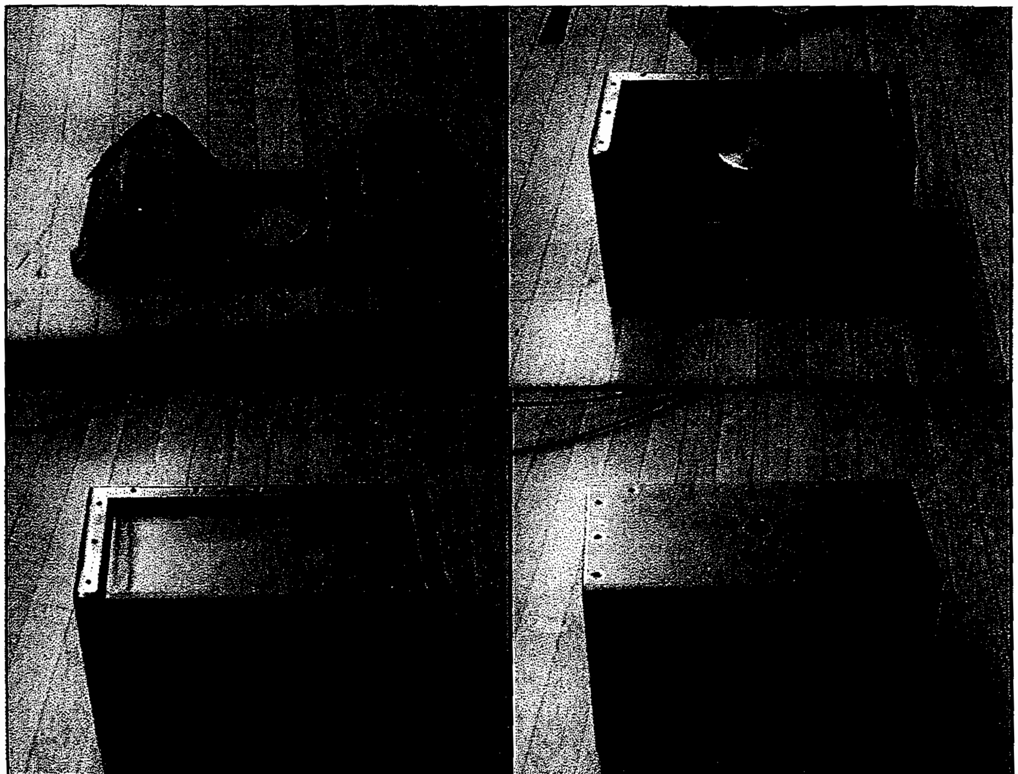


Figure 8. The prototype cold finger cold trap with mesh assembly at top, left, the inner configuration with cold finger, top right. The bottom left and right respectively show the inlet and outlet connections. This is available for use.

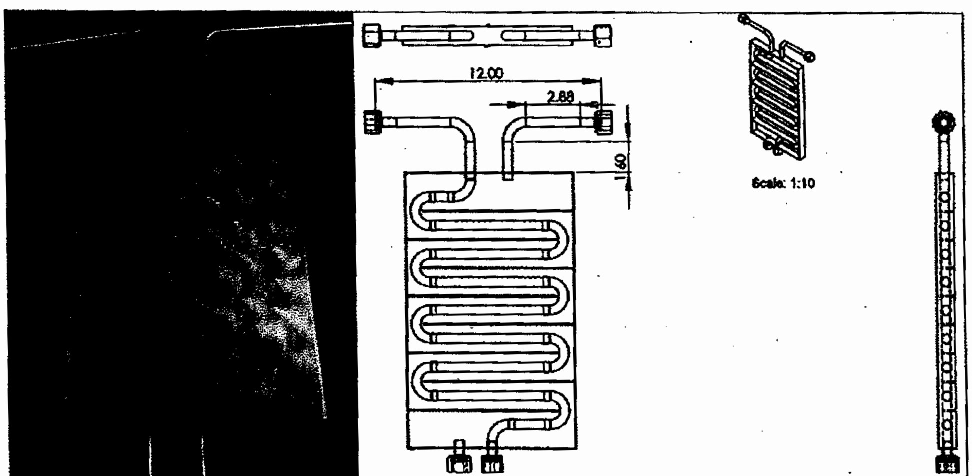


Figure 9. Prototype, stainless steel heat exchanger to be connected to the cold tap.

Year 2 Tasks: Addition of Compact Heat Exchanger and Ultrasonic Testing

It is anticipated that the loop will be completed, shakedown tested, filled with sodium, again shakedown tested and inaugurated by mid-calendar year, in Year 2. The initial Phase 1 experimental runs and data analysis will commence shortly thereafter. As time permits and the identified need arise after Phase 1, the loop will be refined from its basic configuration from Year 1. It is anticipated that additional loop sensors will be added to the loop. Subsequently, Phase 2 experiments and data analysis (non heat exchanger) will begin. At the same time, the compact heat exchanger test section, as well as the supercritical CO_2 loop will be prepared. Phase 2 runs will conclude with initial heat exchanger performance tests.

ANL's Momozaki et al. (2010) reported on a series of sodium flow experiments in small channels whose cross sections are configured as semicircles of 2, 4 and 6mm diameter. From Tokuhiro's work with Song (2007), Van Meter (2008) and ANL, printed circuit heat exchangers features acid-etched, diffusion bonded, semi-circular channels. The concern is the potential for plugging of the narrow channels by soluble/insoluble impurities in sodium. Momozaki et al. showed that if purity of sodium is carefully controlled, flow in even the 2mm channels could be maintain as it approached its melting temperature, ~100° to 110°C without plugging. As sodium oxide was added to the loop, the concentration of oxygen was controlled by varying the cold-trap temperature. The cold-trap essentially functions as an impurity filtration system wherein impurities solidify on surfaces below the melting point of sodium. When intentional plugging was induced by creating a cold region in the test flow section, plugging was observed. Plugging in the 2-mm test section occurred when the test section cold region temperature was 10-30°C below the cold trap temperatue. Unplugging of the plugged channel was realized through heating of the region.

In collaboration with Tranter (2009), Tokuhiro procured a prototype SCO_2 to sodium or water heat exchanger. The Figure below shows the conceptual construction of 'stacked' plates with high surface area to volume ratio to facilitate heat transfer. However, as liquid flow is not confined to small diameter channels; thus plugging is less an issue with impurity concentration for sodium applications. Impurity content in sodium is needed as tracer particles for ultrasound diagnostics and usually exists in larger scale sodium loops such as JAEA's. Because of logistical issues, this heat exchanger was not tested under this project. However, it will tested under another of the PI's DOE-NE projects.

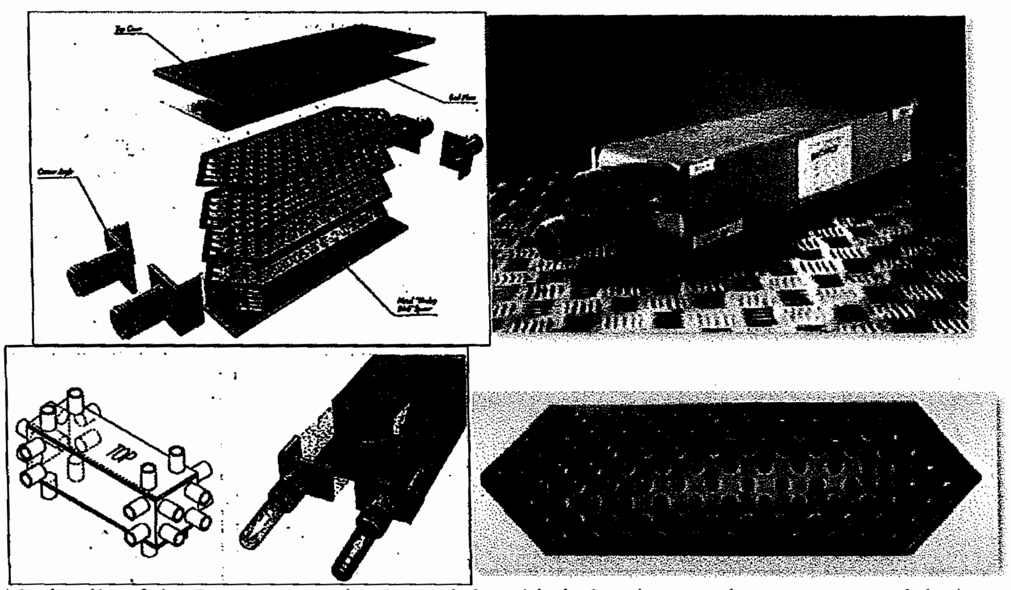


Figure 10. details of the Tranter Maxchanger mini-welded plate heat exchanger procured during project. Cf. http://tranter.com/Pages/products/mini-welded-exchanger/description-benefits.aspx

Year 3 Tasks: Phase 3 Experiments, Data Analyses and Reporting

In Year 3, we will complete any remaining data analyses from Phase 1 and 2 experimental runs and define remaining Phase 3 experiments, which we anticipate will be heavily based on heat exchanger performance and operational experience runs. We will then conduct Phase 3 experimental runs and analyze all data and measurement work. Phase 3 should also conclude heat transfer tests for the compact heat exchanger, to be followed by generation of correlations. We will archive data in a manner accessible to interested parties.

UDV Transducer Cooling Jacket

As noted, an ultrasonic transducer is used to measure the velocity of the water in natural convective flow along the hot side of the test section. The operational temperature limit of a Metflow 4 MHz transducer (tdx) used is 60°C (Delrin casing), but the bulk temperature of water will not exceed ~55°C. Therefore, during the water experiment, the transducer can be in direct contact with the fluid. If sodium is used, the bulk temperature for initial planned tests is anticipated to be ~140°C. Therefore, the transducer must be cooled in order to maintain the body at 60°C or lower; for the 60°C transducer, a cooling jacket is required. Even for Metflow higher temperature transducer rated to 150°C, a cooling jacket is required for any flow test above this temperature. A cooling jacket, designed by Britanyak (Figure 11) was welded into the inside cap of the cylinder for sodium experiments above 150°C. Argon or a similar inert gas from a pressurized source is fed through the small diameter tubing at the top of the cooling jacket and by Joule-Thompson expansion, cools the copper heat exchanger surfaces in order to maintain the transducer face below the desired temperature. Using pressurized air and the arrangement shown in Figure 11 (right), a proof-of-concept demonstration was complete using a hot-plate set at some ~150°C while the transducer's face was approximately 110°C.

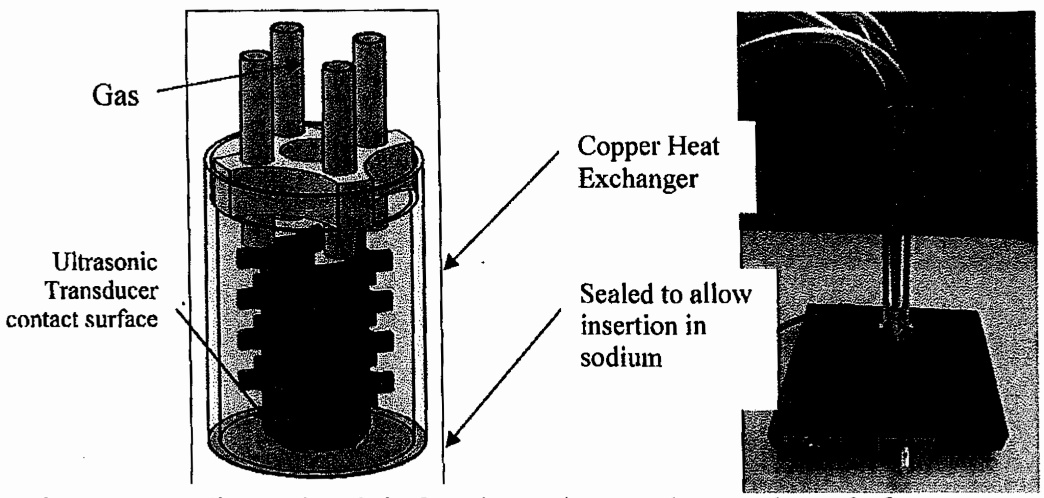


Figure 11. Cooling Jacket (left) for Ultrasonic Transducer and proof-of-concept at right.

CFD Simulations of Natural Convective Flow in an Enclosure

In order to anticipate natural convection experiments with UDV measurements, we used Fluent CFD with a standard k-ε turbulence model to simulate natural convective flow inside an idealized tall enclosure with water and sodium as heat transfer media. We summarize the results here. Table 2 summarizes the scoping CFD runs done. The CFD results were validated via comparison to long-standing natural convection heat transfer correlations, color temperature and velocity contours for correctness in the convective flow phenomena and finally, velocity profiles in order to assess magnitudes to expect when using UDV.

Table 2. Hot and cold temperatures applied to the sides of the Fluent model to induce flow

Constant Water Temp [°C]	[°C]	**Experimental Strip Heater Temp** [°C]	**Constant Sodium Temp.**[°C]	[°C]
Hot	Cold		Hot	Cold
75	45	80	150	120
65	40	70	140	115
55	36	60	130	110

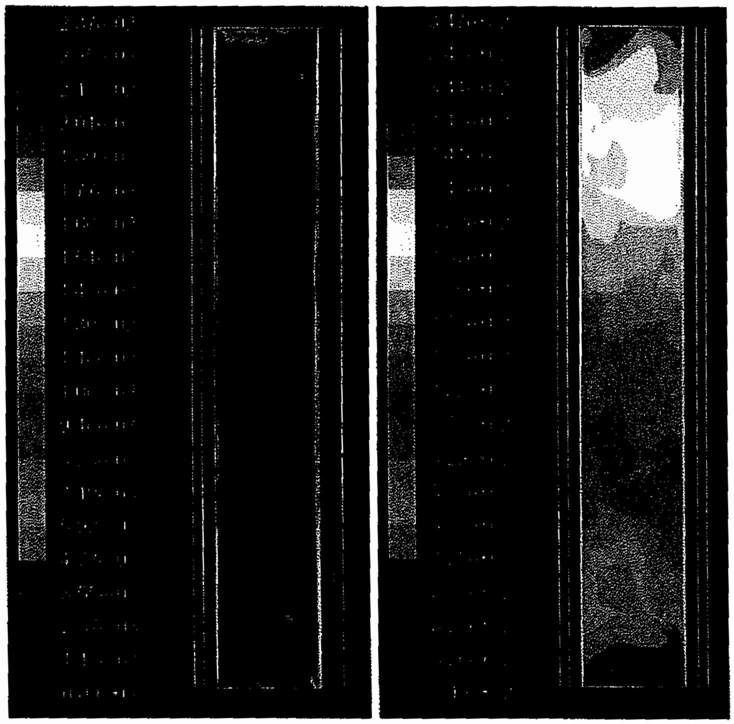


Figure 12. 75°C -45°C, " hot-to-cold wall", constant temperature, Fluent CFD velocity and temperature contours for water.

The velocity and temperature contours from the CFD simulations in water are shown in Figure 12. Although difficult to see, buoyancy-driven flow along the hot wall, upward (left) and cold wall, downward both define 'thin' boundary layers as expected. The flow field changes from predominantly axial to horizontal at the upper left and lower right corners. The temperature contour shows thermal stratification with quasi-defined isocontours as expected in a tall enclosure. To further explore the velocity field, profiles of the vertical component are shown in Figure 13 for eleven cross sections starting at the bottom of the fluid cavity. The fractional axial heights are as indicated. Other than near the top and bottom regions, where the flow changes directions, the expected velocity of water is approximately 2-2.5 [cm/s].

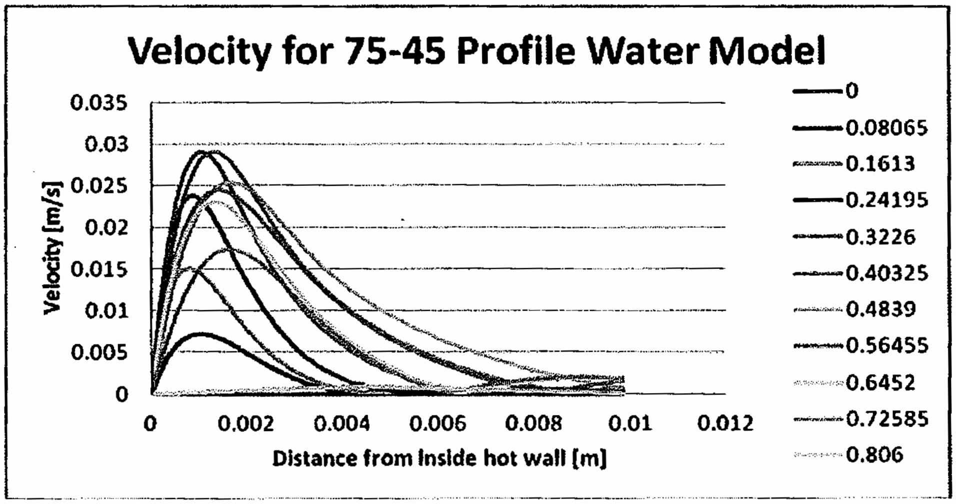


Figure 13. 75°C -45°C, "hot-to-cold wall", constant temperature, Fluent CFD velocity profiles with axial distance from bottom of the enclosure.

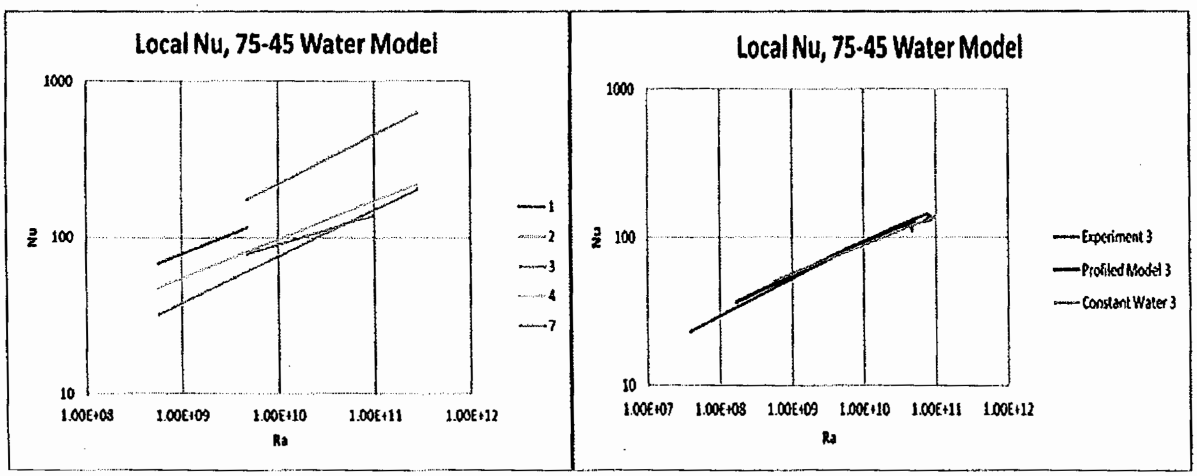


Figure 14. (left) Local Nusselt (Nu) versus the Rayleigh (Ra) numbers for a constant "hot-to-cold wall", 75°C -45°C, (right) Nu versus Ra for constant temperature model, compare to actual wall temperature and as calculated from initial experiments.

Figure 14 compares the local Nu versus Ra correlations when applied to the constant temperature differentially heated model. Nu correlations 1 and 2 (Churchill and Chu, 1975) are both for a vertical heated plate in an infinite fluid medium and plotted against representative correlations, "3, 4 and 7" attributed to Catton (1978), Bejan (2004) and Seki et al. (1978) respectively for natural convection in an enclosure. The right figure shows some initial experimental data that from CFD simulations under constant wall temperature difference as noted and 'profiled', representing estimates of Nu and Ra using the actual, measured temperature profile. One can see that the correlations have a range of values and that our apparatus generates heat transfer data in agreement with these accepted correlations.

Water Natural Convection Experiments

More recent heat transfer experiments have conducted in order investigate the onset of natural convective flow in the natural convection cell. As shown in Figure 15, the time-dependent development of natural convective flow generally follows trends relative to the traditional correlations. The transient flows per

UDV are largest at onset. Knowledge of this provides another means of characterizing the convective flow for sodium.

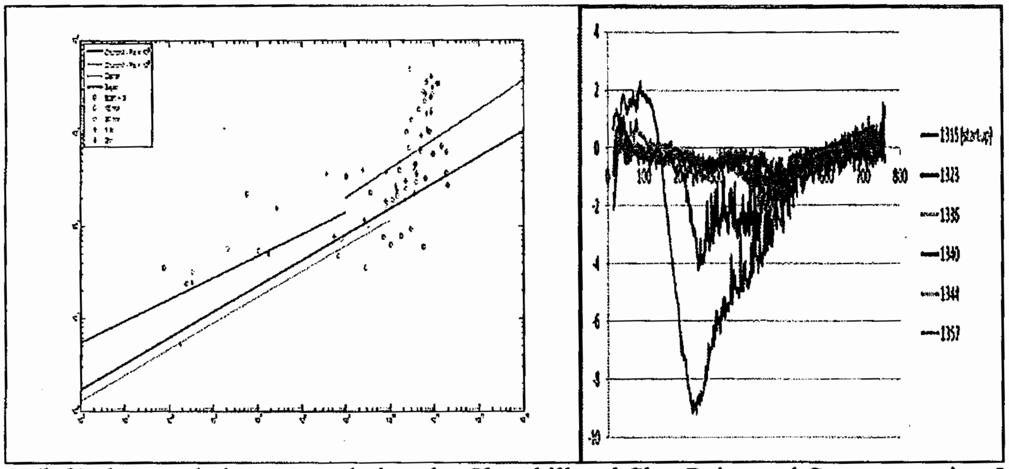


Figure 15. (left) shows relative to correlations by Churchill and Chu, Bejan and Catton, transient Nu-values estimated as steady-state is approached. (right) UDV measurements at intervals in time along the heated wall. Negative velocity indicates flow toward the transducer as expected.

Sodium CFD Simulations

Results for "hot-and-cold wall", 150°C -120°C, constant wall temperature

Additional CFD simulations were also done with the hot-and-cold walls held at constant temperature and then additionally simulating the actual temperature profile from the heater arrangement. The results are summarized below. Figure 16 show the velocity and temperature color contours for constant temperature and actual, measured hot-and-cold wall temperature conditions. With sodium having a thermal diffusivity approximately two orders of magnitude larger than water, the natural convective flow, in terms of the both the thermal and momentum boundary layers are much larger and prominent for sodium. Equally, the thermal stratification is also well-defined for constant temperature and reflective of hotter heater regions when using actual wall temperature profiles.

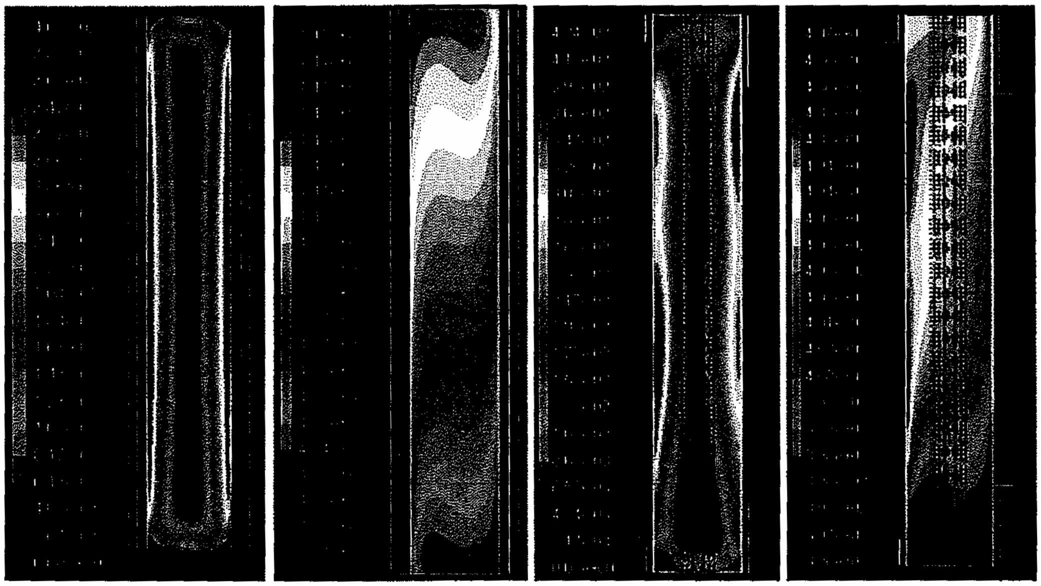


Figure 16. Velocity(L) and temperature(R) color contours for "hot-to-cold wall" at, constant, 150°C - 120°C temperatures (left two) and under actual temperature profiles (right two)

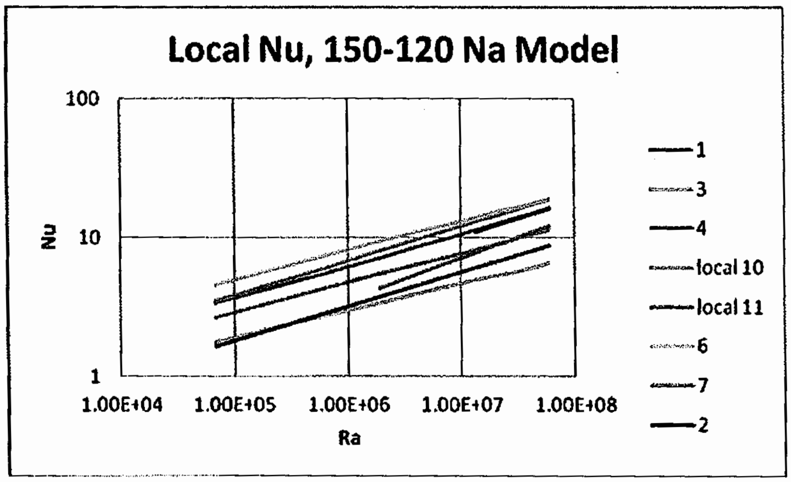


Figure 17. Local Nusselt versus Rayleigh numbers for "hot-to-cold wall" at, constant, 150°C -120°C temperatures

Figure 17 compares the local Nu- versus Ra-number correlations, under the constant temperatures as noted for sodium. It corresponds to the Figure 16 at left. As with similar representations for water, correlations "1, 2" (in legend) are attributed to (Churchill and Chu, 1975), "10" to (Bejan, 2004), and "11" to (Sheriff and Davies, 1978). All of these are for a vertical heated plate in an infinite fluid medium. Nusselt correlation "11" was correlated directly from experimental sodium data. Correlations "3, 4, 6 and 7" are from Catton (1978), Bejan (2004) and Seki et al. (1978) respectively and are each for natural convection in an (tall) enclosure.

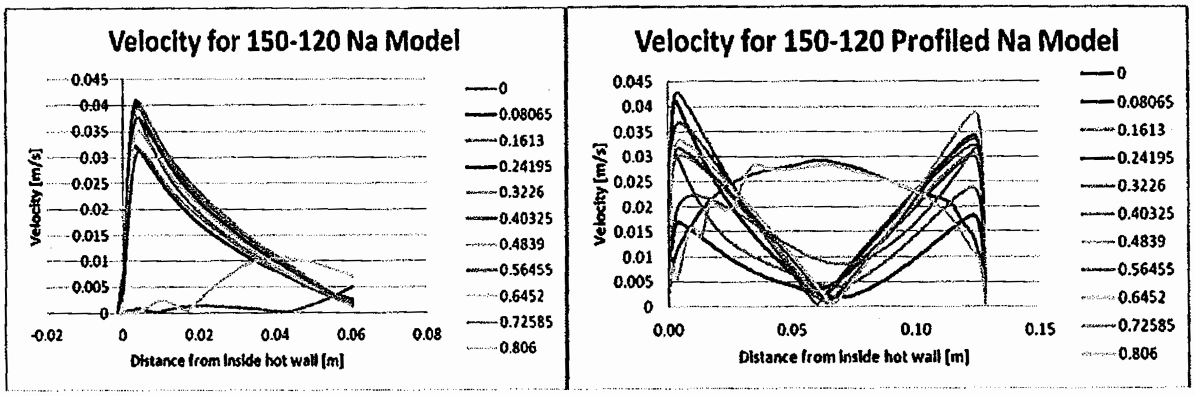


Figure18. Local axial velocity profiles for the "hot-to-cold wall", at constant, 150°C -120°C, temperatures (left) and axial profiles across the cavity (hot to cold sides), with actual temperature profile along the heated side.

Figure 18 finally shows the axial variation in the velocity profile, as predicted from the CFD simulation of natural convective flow with a "hot-to-cold wall", at constant, 150°C -120°C, temperatures (left). In contrast, we show at right, the profile from hot-to-cold walls across the cavity with the actual temperature profile along the heated wall. We note that in both cases that the approximate velocity is 3-4 [cm/s] with profiles near the top and bottom of the cavity accordingly different as the flow transitions to a predominantly horizontal (transverse) direction. These simulations provide information on what to expect when the experiments are conducted in sodium.

Conclusion, March 2013

Based on the description above, and relative to the Project Objectives, the following has been partially to fully accomplished:

4. **First** design, construct and operate a new university-based, small, simple but purposeful sodium flow loop with inventory of approximately 5-6 liters. The loop should be so designed to develop, test and demonstrate ultrasonic technology solutions.

   A nearly 10 liter volume, sodium flow loop has been designed, constructed and deployed. A natural convection test section has been tested with ultrasound Doppler velocimetry (and temperature) measurements and supported by CFD modeling and simulation results for both water and sodium. The facility has received various design, construction and deployment safety in design and operation approvals. Additional components have been developed and are ready to be integrated into the loop if a EM pump, sufficiently sized, can be found.

5. **Second** develop, test and demonstrate ultrasonic velocimetry, thermometry and particulate (oxides, contaminants) concentration monitoring, with focus toward improved SFR O&M. That is, velocimetry, thermometry and concentration monitoring as diagnostic tools under steady and transient conditions.

   Ultrasound Doppler velocimetry was tested and demonstrated, using transducers limited to 60°C and 150°C, not only for natural convective flows but for convective flow of thermal jet mixing in water and flashing single-to-two phase flows in a vertical pipe at at or above 100°C with the 150°C tranducers. Velocity information has been verified against CFD results for the former two flow configurations. Ultrasonic thermometry was not fully demonstrated but remains, in principle, possible from the acquired velocity signal. This approach alleviates hardware modifications. Particulate oxide control was not demonstrated because institutional barriers prevented us from taking delivery of and experimenting with sodium. The facility however, stands ready for sodium use.

6. **Third** address the energy conversion operating space by testing a compact, sodium to supercritical

CO_2 (SCO_2) heat exchanger. Generate convective heat transfer data, correlations and operational experience under steady and transient conditions. Assess the potential for plugging with respect to the compact heat exchanger coolant channel diameter.

The lead PI previously performance tested a commercial print circuit heat exchanger (PCHE) using water and supercritical CO_2 under another DOE-funded project. This was in collaboration with ANL. ANL also demonstrated that if the sodium is kept clean, plugging will not occur in characteristically small diameter channels such as that featured in the PCHE. However, plugging can develop if there is a cold spot along a heat transfer channel, relative to thermal condition of the cold trap, particulate removal system. Thus for the prototype water (or sodium) to air (SCO_2) heat exchanger procured for this work with perforated flow channel on layered plates, plugging is not expected. This heat exchanger will be leveraged and tested for another DOE-funded project. The lead PI has also studied the PCHE using CFD and proposed a method of design optimization method to optimize the design of heat exchanger based on identified application conditions. This methodology was partially verified using experimental data. Thus the CFD analysis has been verified and validated in a limited context.

Students Produced

On Design, Construction of the Sodium Experimental Apparatus and Initial CFD Simulations

- Caitlin Flynn-Harker, Experimental and CFD Study of Natural Convection, Mixed Convection and Ultrasonic Velocimetry in Water in Preparation for Sodium Technology Development, MS Project Report, University of Idaho, 2012.
- Matthew Cromwell, Building an Apparatus for High Resolution Thermal Jet Mixing Analysis of Liquid Sodium, MS Project Report, University of Idaho, May 2011.

On Natural Convection Heat Transfer and Velocimetry Experiments

- David Kim, David Kim, Transient natural convection ultrasonic velocimetry in water, University of Idaho, MS Thesis, expected in October 2013.

On Testing the Ultrasonic Doppler Velocimeter with 150°C Transducer in Thermalhydraulics

- Chris Bakken, Thermalhydraulic Analysis including Ultrasonic Doppler Velocimetry of Water-Cooled RCCS for NGNP, MS Thesis, University of Idaho, 2012.

On CFD Modeling, Simulation and Design Optimization of the PCHE Heat Exchanger

- Artit Ridluan, Development of Design Optimization Methodology using CFD as the Design Tool, as Applied to Printed Circuit Heat Exchanger, Ph.D. Thesis, University of Idaho, 2009.

Project Timetable

Events

1) Upon award received letter (April 13, 2007) from ANL NED Director, H. Khalil providing access to the sodium loop facility at ANL. Access has not been realized. It was not facilitated by NED staff.
2) Co-PI Hosni opted to remove himself as co-PI shortly after start of the project. Work began at Kansas State University in fall of 2007.
3) Co-PI Tokuhiro moved from Kansas State University to University of Idaho (UI) in June 2007 with part of the scope of work (SOW). Remaining parts of the work remained with co-PIs Babin and Beck at Kansas State University.

4) While waiting for access to the ANL sodium loop, initial work was on CFD modeling, simulations and design engineering of the compact heat exchanger with small flow channels.

5) Co-PI Babin left Kansas State University in December 2008. Subsequently, SOW remaining at Kansas State was transferred to University of Idaho. Co-PI Beck assumed role as Kansas State University point of contact.

6) Because access to the ANL loop and assistance on EM pump design was not forthcoming, design of the loop began at UI in 2008. A commercially viable EM pump is not readily available in the U.S.

7) Rest of the project SOW was transferred from Kansas State University to University of Idaho, in 2009 and a no cost time extension was requested during summer-fall, 2009, and approved. Without a viable EM pump, the loop design was transitioned to a natural convection loop during he 2009 timeframe. The loop as reported here was design, constructed in 2010-2011 and deployed in 2011 with incremental shakedown testing as subsystems were integrated into the loop.

8) Shakedown testing and resolution of issues with loop performance were ongoing in 2011-2012. Several satisfactory safety reviews were completed in 2011. A work stoppage order on sodium loop issued by CAES/INL staff, Mr. Paul Smith, in November 2012 for some 100 days. This was without efforts to discuss the situation with the PI. One of the lessons learned is that it is possible in this jointly operated 'center' that an INL staff who does not have subject matter expertise, academic experience nor knowledge of university-based DOE-NE can unfortunately have a severe impact on a project without any responsibilities for proposing a path forward in a timely manner. This had a significant impact on not being able to complete the SOW. At the same time, ongoing safety-related issues at INL, unrelated to the PI, had an unfortunate influence on this project. We see this as unfortunate.

9) Resumption of shakedown experiments in March 2013.

10) A FFRDC (PNNL) expressed potential interest in transferring the loop to their facility if the loop remained without sodium.

11) Returned unspent award to DOE Idaho Field Office, spring-summer, 2013.

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APPENDICES

Appendix A. Experimental Design

Experimental Design

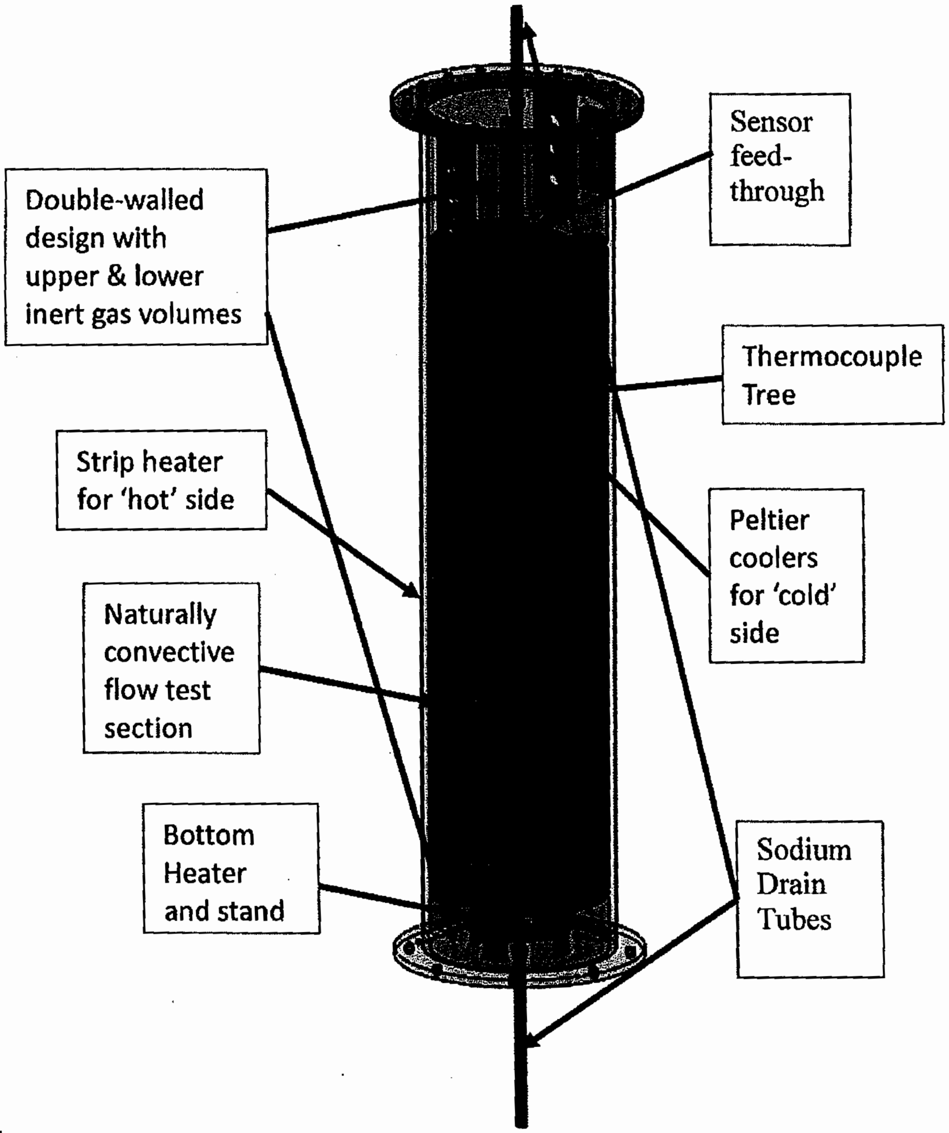
One of the main goals of this work was to design a natural convection experiment capable of handling water and sodium. Water does not present any challenges from a heat transfer or safety perspective; sodium does. Therefore, the experimental design was based on initial constraints and requirements determined by the sodium. Kern [XX], an INL employee and sodium employee was referred to for many of the options on how to handle sodium along with the references in the introduction of this paper. Due to the volatility of sodium and measures that need to be taken to ensure safety throughout the experiment, the following are the main precautions being taken to keep sodium from coming into contact with air or water.

- Sodium in all forms (solid or liquid) will always be contained with an inert cover gas (Argon).
- All portions of the experiment that may contain will have valves to keep them sealed from the air.
- Transferring the sodium in or out of the experiment will be done with a transfer tankin a glove box with an inert cover gas.
- The entire experiment will be in an enclosure that is capable of filling with gas, fire extinguisher fluid or sodium bicarbonate if a leak should occur.
- The base plate of the experimental enclosure will be .5" thick to act as a heat sink to solidify the sodium should a leak occur [Kern XX].
- The portion of the experiment where the natural convective flow will occur is double walled to maintain an Argon cover throughout the system and as an extra precaution against possible leaks [Lewis XX].
- Oxygen monitors will be used to ensure no leaks have occurred as they will detect the noxious gases that form from a sodium fire or argon indicating leaks in the outer cylinder of the test section.

2.1.1 The Test Section

The test section (the vessel that hosts the experiment) consists of two concentric cylinders; one nested inside the other to provide a "buffer" to hold any unanticipated leak of liquid sodium. The melting temperature of sodium is 98°C; thus, sodium is solid at room temperature. The experiment will be done with liquid sodium, in the range, 110°-150°C with higher temperature operation based on cumulative operational experience. At these temperatures the sodium will not be a problem corrosively for the materials used [Piping Materials for LMFBR [XX]]. 316 Stainless steel is used for all components that could come into contact with sodium as it does not react with sodium, is frequently used in commercial sodium applications and is recommended [Fanning XX Cottrell and MannXX Konomura, Mamoru, and Ichimiya [xx] Furukawa, Yamamotoa, Nihei, and Iguchi [XX]].

The test section (figure XX) includes: an inside cylinder onto which all measurement and temperature control devices are attached and in which the experiment takes place, and an outside cylinder that serves as a containment in case of any leaks. For the sodium experiment the outside cylinder is filled with Ultra High Purity Argon (Ar) as a cover gas to prevent contact between sodium and air (oxygen) if a leak from the inside cylinder occurred during the experiment. It has a bottom cap welded on, a flanged top, and ports to allow tubes and wires into the outside cylinder. The inside cylinder contains the experimental fluid. The natural convective movement of fluid is thus self-contained in the inner container. The inside cylinder has two capped ends welded into place that extend to the sides to keep the cylinders concentric and protect the temperature elements fixed to each side. IDAPA 17 Boiler and Pressure Vessel Safety Specific Rules [XX] identify what containers need to be certified as ASME pressure vessels and which containers are exempt from being certified. Some of the defined exemptions from being certified are vessels that are less than five cubic feet in volume at 250psig, have an inside diameter of less than six inches with no limitations on pressure, or low pressure vessels that are operating at working pressure not exceeding 15psig. The inside cylinder is within all of these exemption limits, and the outside cylinder is within the low pressure limit. A stand is positioned on the bottom cap of the outside cylinder to hold the inside cylinder while allowing room for a bottom heater and gas flow. Tubes penetrate the test section's outer cylinder via a plugged port and has been welded to the inside caps to allow the sodium to flow in and out of the test section. Wires and gas are also fed into the outer cylinder with high-temperature plugs. The individual components attached to the inside cylinder are detailed later in this



chapter.

Figure A1. Natural Convection Test Section

During the experiments completed for this work, water was used. Microspheres were added to the water to act as reflecting particles to measure the flow with the UVP. The microspheres used are 36 µm in diameter with a density of 20 kg/m^3[Akzo data sheet XX] and are 551Du80 made by Expancel. To ensure the microspheres didn't clog the tubes and valves for sodium the water tests only consisted of the above setup in the enclosure. The water and microspheres were poured into the test section before a test and drained into a separate container after each test to keep the microspheres from settling in the test section. The water flows in the test section due to natural convection. The cool side of the inside cylinder has Peltier Coolers with heat exchangers that were cooled using compressed air. The bottom and hot side of the cylinder are heated by a ring heater and a strip heater respectively. A "tree" of thermocouple sensors is immersed in the sodium in order to measure its bulk temperature. The temperatures for the hot and cold side are measured at multiple points along the strip heater and coolers; the difference of the wall to bulk temperature and the heat flux is needed to calculate the heat transfer.

The following has been designed for when sodium will be used as the convecting fluid. Containers for transporting the sodium to and from a glove box were placed above and below the test section; these storage tanks respectively serve as the upper and lower storage tanks for sodium (thus called the upper and lower storage tanks) (Appendix XX). These storage tanks were designed in collaboration with Cromwell. The storage tanks have valves on both fluid and gas line connections to prevent air from entering them once the sodium has been transferred to them in a glove box. The storage tank with sodium is placed above the test section, heated, and the valve opened to drain the sodium into the test section. The transfer tanks are heated by blanket heaters wrapped around the tanks. The valve between the test section and lower storage tank remains closed while a test is performed. Once an experiment is finished, the valve beneath the test section is remotely opened so the sodium drains from the test section into the lower storage tank where it is allowed to solidify. To ensure no clogging in the tubes a small amount of gas is turned on opposite to the desired flow direction for short bursts during the drain and the pipes are heated with rope heaters. The gas bursts cause a bubble to be pushed back through the tube dislodging any sedimentation. When an experiment is repeated, the lower tank is heated in order to melt the sodium; cover gas pressure is then increased to "push" the liquid sodium back up to the upper transfer tank where it drains back into the test section. Only 2-3 psi are needed to push the sodium into the test section or upper tank. Figure XX demonstrates how the sodium would flow throughout the system.

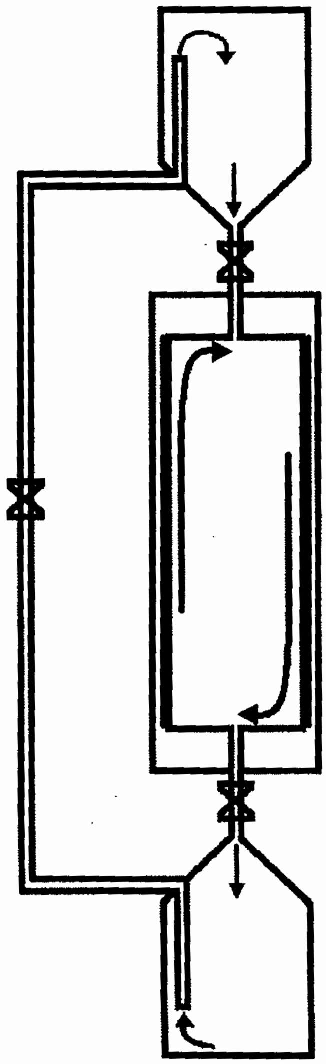


Figure A2. Sodium Flow within test section, transfer tanks and connecting tubing

2.1.2 Cooling the Transducer

In this experiment an ultrasonic transducer is used to measure the velocity of the water in natural convective flow along the hot side of the test section. The operational temperature limit of a Metflow standard line 4 MHz transducer (tdx) that is used is 60°C, but the bulk temperature of the water will not go above 55C. Therefore, during the water experiment, the transducer can be in direct contact with the fluid. If sodium is used, the bulk temperature would be max 140°C. Therefore, the transducer must be cooled in order to maintain the body at 60°C or lower, this would require a large amount of cooling and a higher temperature transducer was deemed a better option. The second Metflow transducer has a 150°C operating temperature limit. A cooling jacket, designed by Britanyak[XX], has been welded into the inside cap of the cylinder in case the sodium experiments are attempted at temperatures above 150°C. Argon or a similar inert gas is fed through the small diameter tubing at the top of the cooling jacket and cools the heat exchanger surfaces in order to maintain the transducer face and nearby casing below the desired temperature.

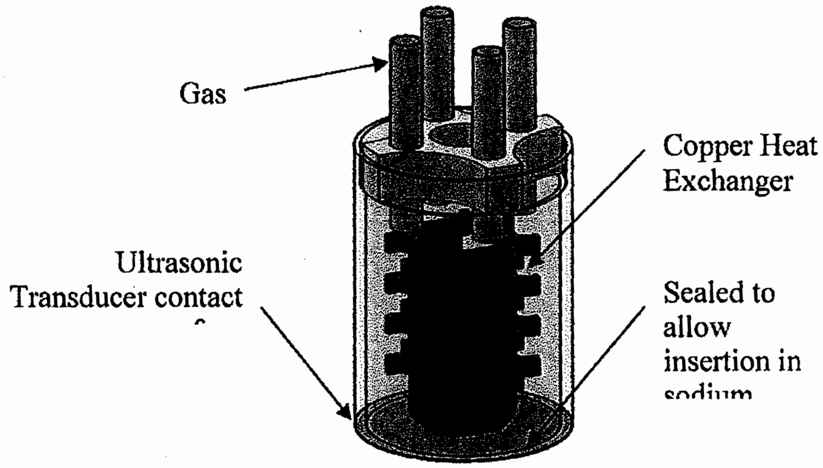


Figure A3. Cooling Jacket for Ultrasonic Transducer

A second transducer will be in a second feed through to produce more data and to compare to the main transducer. This second feed through (Figure XX) allows for varied quantity of sodium and guaranteed submersion in the working fluid by making use of a tube to have the transducer contact surface about 5.75 inches below the inside cap. The end of the tube has .002 in thick stainless foil laser welded to the end to protect the transducer from the working fluid, but still ensure maximum acoustic transmission when used in conjunction with ultrasonic gel. Finally, the feed through has a threaded fitting welded to the top, which used with a sodium compatible thread sealant (Reactor seal No. 7) ensures that the inside cylinder is sealed during testing. Since there is no way of cooling the transducer in this feed through, it can only be used with high temperature ultrasonic transducers and only when the sodium is kept below 150°C.

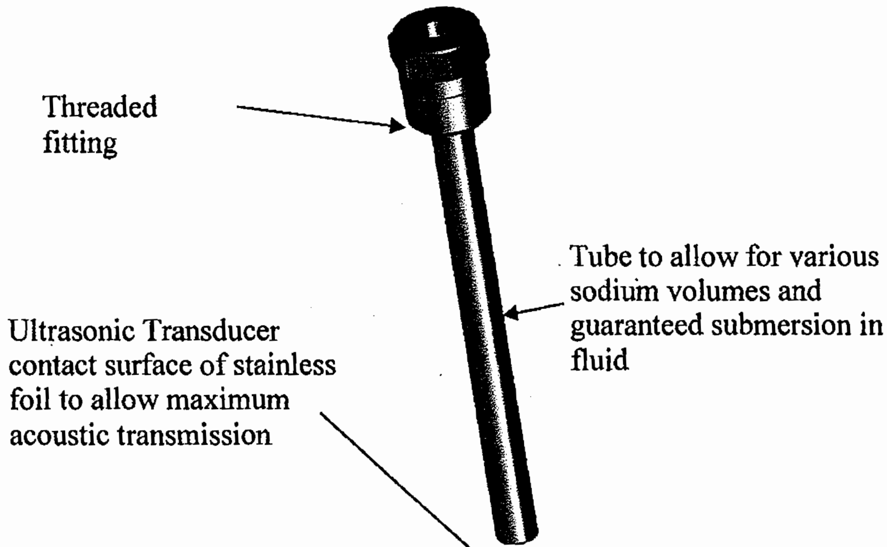


Figure A3. Ultrasonic transducer feed through

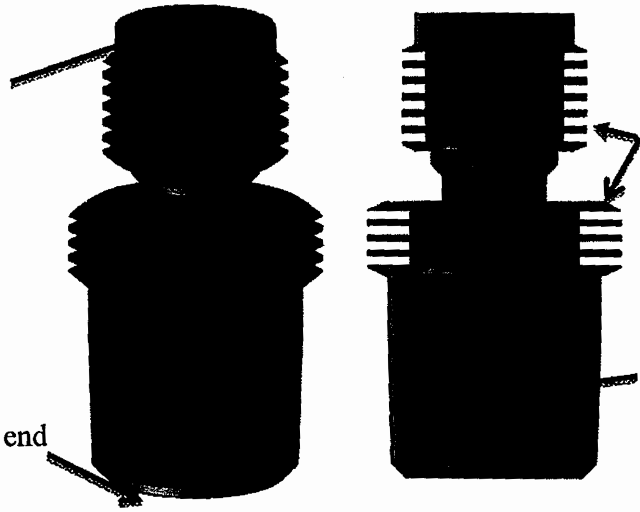


Figure A4. Swagelok feed through with fins for transducer cooling

A third feed through was designed with limited cooling (Fig XX). It consisted of a Swagelock tube fitting with a threaded end. Fins were machined into the length above the inside cap to cool the fitting. The idea for this feed through was that the transducer would go through the feed through and be pushed flush against a piece of stainless aluminum that would be welded against the end of the feed through. The main problem with this fitting was the wetting of the surface of the feed through for acoustic transmission. The threads allowed the fitting to go most of the way through the female threads on the inside cap, but this would still require the working fluid to be above the bottom of the inside top cap and there be some sort of pressure vent alongside the feed through to allow the fluid to properly wet the surface. Additionally, the fins did not adequately cool the inside of the fitting. Therefore, this fitting is not to be used.

2.1.3 Controls

There are multiple parts of the experiment that are controlled or measured. To know what is going on within the system we need to know the temperature profile throughout the sodium. Thermocouples are used to measure the temperature along the hot side, cold side and in the thermocouple tree inside the cylinder. The thermocouples all have fiberglass insulated wires to withstand temperatures they might see during sodium experiments. The thermocouple tree consists of a 0.049inch sheath welded to the inside cylinder cap that extends almost to the bottom of the cylinder that houses a long fitting that can hold up to 31 equally spaced thermocouples against the sheath near the hot wall where the transducer will be measuring flow. During the experiment 16 thermocouples are used in every other slot because it gives a good picture of the temperature distribution and because the insulated wires on 31 thermocouples would take up more space than exists in the sheath. From these three positions we will be able to extrapolate the temperature across the enclosure. Similarly, thermocouples will be placed inside the cooling jacket and on other parts of the system in order to monitor what is happening throughout the system. The data from the thermocouples will be measured with National Instruments (NI) Data Acquisition (DAQ) hardware plugged into a computer and NI Labview software. The NI DAQ works by combining a switch and a multimeter and was bought by a different student. The switch has 128 channels that it reads one at a time at a speed of 900 channels per second. The digital multimeter reads the voltage difference between each wire of each thermocouple and sends the data per channel to labview, where the NI-DMM/Switch Express virtual instrument splits the signal to be read and displayed. The switch coding Labview to read and record the channels proved challenging and the author was assisted by Phillippi [XX], a NI engineer in writing that portion of the code. The code (Appendix XX) exports temperature data for each thermocouple in a generic format that can be opened in Excel while displaying the temperature numerically for easy system monitoring.

The heaters and peltier coolers will all be controlled with Tempco Temperature Controllers. The controllers for the heaters plug directly into a wall outlet and create a feedback loop by reading the temperature of the heater with a thermocouple and adjusting the power to the heater to maintain the desired temperature. The wiring for these temperature controllers is in Appendix XX, there are three 15 Amp and two 8 Amp heater temperature controllers. Table XX shows the heaters and power requirements used in experiment. The cooler temperature controller works similarly but requires external power. The peltier coolers are wired in series and connected to the external power supply, the temperature controller and a switch.

Table 1 Experiment heaters and power requirements

Heater	Qty	Watts	Max Temp	Purpose
Omega 3 ft OMEGALUX® Rope Heaters	2	125	482 C	Heat sodium tube sections between transfer tanks and test section
Omega 10 ft OMEGALUX® Rope Heaters	1	500	482 C	Heat sodium tube sections between transfer tanks
Omega Flexible Silicone Rubber Fiberglass Insulated Heaters 6x24"	2	720	232 C	Heat transfer tanks
SNH Series Strip Heater 28.75" long	1	1000	649 C	Heat hot side of experiment
A Series Ring Heaters 3.97" OD	1	500	1200 C	Heat bottom of experiment

The cold side of the experiment is cooled by thirteen high temperature peltier coolers made by TE Technology. They cool through an electrical differential inside the cooler creating a temperature differential with the cool side against the test section. The coolers are rated up to 150 C but their hot side must be cooled to keep the coolers from overheating. Therefore heat exchangers are places on the hot side. The heat exchangers are cooled by compressed air for the water experiments and argon for sodium.

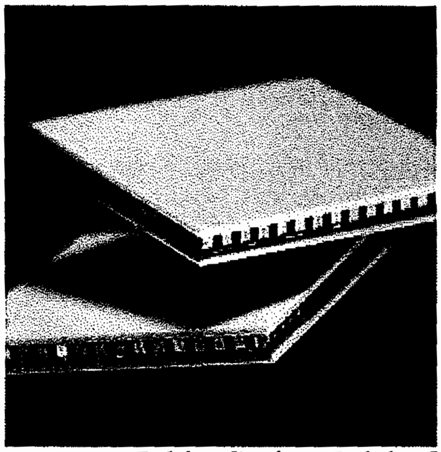


Figure A5. High Temperature Peltier Cooler Modules [Te Technology XX]

The controls not temperature related are the fluid and gas loops. The fluid loop has several manual valves that are in place to keep the system components sealed during transfer of sodium. The fluid loop also has two actuated valves manufactured by Triad Process specifically for use with sodium (Figure XX) that can be opened or closed remotely during the experiment. The actuated valves are in place to keep the fluid in the main test section, transfer tank, or to open the path between the transfer tanks to refill the main test section from the lower transfer tank. The gas loop has pressure gages, flow gages and manual valves throughout the loop but outside of the enclosure to allow full control during sodium experiments. The gas manifold as different legs in which the gas to each transfer tank, the test section, the heat exchangers, the cooling jacket, and the inside cylinder can be turned on, off or flow adjusted to the desired level for each component. Figure XX shows the gas manifold used to control where the gas to individual components can be turned on or off, monitored, and controlled with adjustable valves.

Figure A6. Triad actuated valve for fluid loop

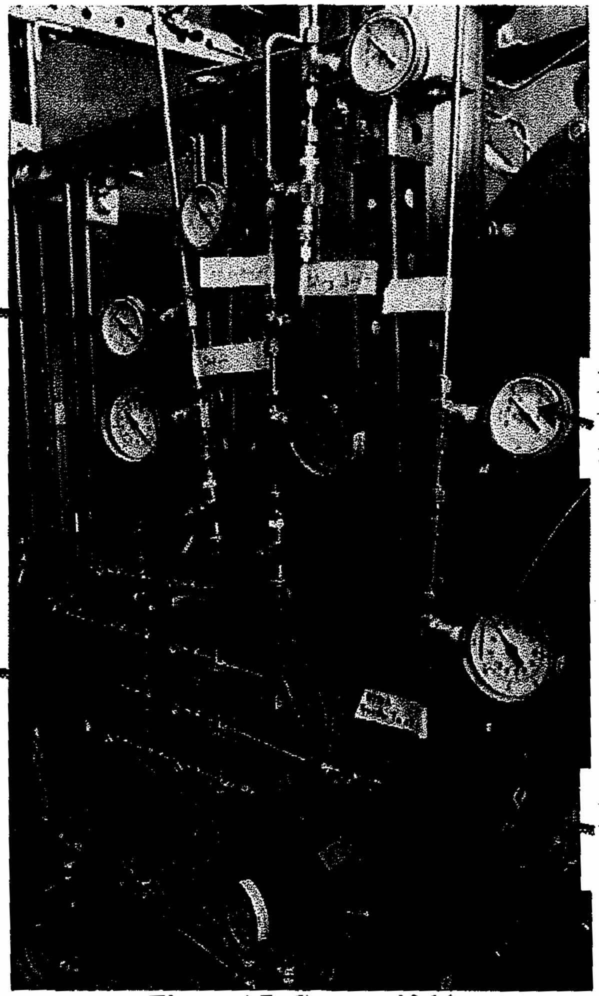


Figure A7. Gas manifold

A dry run was performed to determine how much gas it will take to fill the test sections and cool the peltier coolers and transducer cooling jacket. One 300 ft^3 tank of high purity argon will last for almost a day of testing. During a sodium experiment, a second tank must be connected so it can be used if needed. Pressure will be measured before running any experiment to ensure there will be enough argon for the experiment and monitored during the experiment. Prior to beginning an experiment, the system will be filled with argon. As sodium drains into the inside cylinder the pressure out of the cylinder will be monitored to be slightly below the pressure in the transfer tank to make sure the sodium will drain, but also to make sure no air comes back up into the inside cylinder. After the inside tank is filled with sodium all valves except those for cooling will be shut off. The level of gas flow will be constant during the experiment cooling the cooling jacket and heat exchangers on the peltier coolers. The pressure of the system will not exceed 5 psi.

2.1.4 The Enclosure

An enclosure to house the entire test setup as well as a second experiment of Dr. Tokuhiro's was designed and then built (Figure XX). The main purpose of the enclosure is to create a controllable barrier between the experiment and the surrounding environment. The enclosure frame was created out of Unistrut channels – making the enclosure easy to assemble and sturdy in nature. The walls of the enclosure are made of air ducting material, sheet metal, as an inexpensive way to cover the outside of the enclosure. The bottom of the enclosure has been made of half inch steel plate. The purpose of the bottom of the enclosure is to provide a heat sink for any unexpected sodium leaks. Solid sodium is less reactive than liquid sodium and the heat sink is considered adequate to remove enough heat from the sodium to solidify it [Kern XX]. A stainless sheet metal catch pan was placed under the lower transfer tank to contain any possible leak. The height of the enclosure was limited by the door heights in the CAES building so it could be removed from the room if it is needed. In order to provide for the height of the experiment, the enclosure includes an extendable portion to house the upper transfer tank. The secondary purpose of the enclosure was to make the experiment portable within the deflagration room. In order to maximize the height of the enclosure, dropped z-brackets were designed to connect the casters to the enclosure.

Inside the main enclosure is a second, smaller Unistrut structure to hold the test section and transfer tank. The structure attaches to the outer enclosure to keep the experiment steady. The lower transfer tank bolts to the bottom of the inside structure, while the test section bolts to the top of the structure.

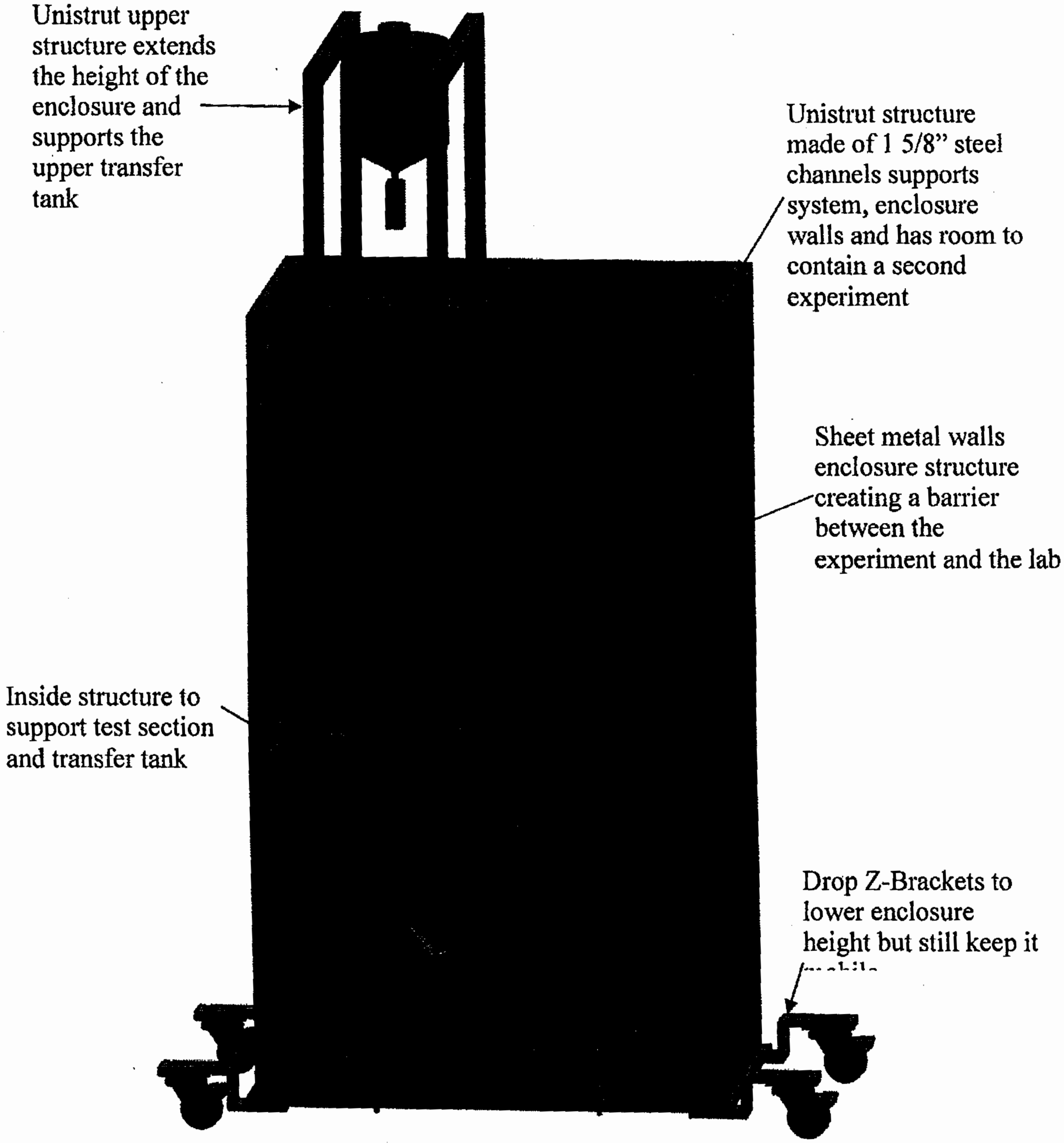


Figure A8. Test Setup Enclosure with several walls removed

2.2 Experimental Procedure

The first stage of experimenting was to put water in the system with gas and fluid loops intact but without nesting the cylinders to ensure fluid movement and all other controls were working properly. The second was in nested cylinders, gas but no fluid loop to test the natural convective flow of water. The second stage includes a variety of ultrasonic and flow tests.

In the first stage test steps for sodium are practiced. The upper transfer tank is placed inside a glove box loaded with around 25lbs of water to simulate the weighted section with sodium. The transfer tank is then carted from the glove box to the Deflagration room in the Fluids Laboratory. Once in the Deflagration room two ropes are attached to the transfer tank that is connected to the top of the enclosure. Two people pull the ropes to lift the tank while a third person guides the tank into position above the rest of the transfer tank. Once all gas and fluid loop connections are made, the water is drained into the test section by opening the valves between the two and the gas in and out valves to relieve the pressure. Fluid movement is simulated throughout the system by using argon pressure controlled with valves. If the water is in the bottom tank, it is pressurized and the fluid flows up into the upper transfer tank and then down into the test section. After an experiment is run, the valve to the lower transfer tank it opened and the water is allowed to drain into the lower transfer tank. While in the main test section the water was heated by the strip heater and temperatures were monitored inside and outside of the tank to ensure all were functioning properly. Ultrasonic tests were performed in this setup, but due to the lack of particles in water no usable data was obtained.

In the second setup the system was disassembled and a team from West One nested the inside cylinder onto a stand inside the outer cylinder and then both cylinders were lifted onto the stand in the enclosure where they were bolted in place. All gas lines, heater cords, and thermocouple wires were fed through the outer cylinder feed throughs. Plastic microspheres were added to the water. The microspheres used are 36 μm in diameter with a density of 20 kg/m^3[Akzo data sheet XX] and are 551Du80 made by Expancel. These microspheres have negligible slip in water flow but allow the ultrasonic signal to reflect and therefore make the water flow readable to the UVP. Due to the concern that the microspheres might clog the valves and fluid loop, and because the fluid/pressure loop had already been demonstrated the transfer tanks were not included in the second setup.

During the second stage of the experiment it was discovered that the UVP was reading an unexpected data profile over any velocity data. The experimental results section will demonstrate this profile. Table XX gives a description of the tests performed. Where applicable the tests are analyzed thermodynamically. The test performed on a stir plate (figure XX) consisted of water with microspheres in a clear plastic container with an oblong magnet in the bottom to create the flow due to the interaction between the magnet and stir plate mechanism. The tests in the plastic tube consisted of a one meter long plastic tube with one end capped and filled with water and microspheres and took place in the CAES Deflagration Room or the author's home. The test in the plastic natural convection experiment took place in the CAES Analytical Chemistry Lab in a preexisting experimental setup that consisted of a 1.2 m tall, 0.55 m wide but only .04 m in depth rectangular enclosure filled with water and microspheres. On either end of the enclosure there were two aluminum tubes through which water was pumped at two different temperatures. The walls between the tubes were clear plastic so the flow could be observed.

Table 2 Experiment Summary for UVP performance

Test	Location	Flow
1	Test Section	Natural Convection with varied temperature difference between the hot and cold sides
2	Small plastic container on stir plate	Transducer used to measure velocity across the flow induced by the stir plate
3	Test Section	No flow- just measure stationary water with microspheres
		Handheld vertical movement - should demonstrate all particles moving towards or away from the transducer at the same speed
4	Plastic tube in Deflagration Laboratory	No flow- just measure stationary water with microspheres
		Handheld vertical movement - should demonstrate all particles moving towards or away from the transducer at the same speed
5	Plastic tube in a house away from CAES	No flow- just measure stationary water with microspheres
		Handheld vertical movement - should demonstrate all particles moving towards or away from the transducer at the same speed
6	Test Section	Natural Convection with varied temperature difference between the hot and cold sides adjusting software parameters: number of repetitions, gain start and gain end
7	Test Section	Natural Convection with varied temperature difference between the hot and cold sides while trying to control electrical noise by grounding/ungrounding the UVP, the NI DAQ, the temperature controllers, the enclosure and then by letting the system reach steady state, shut off anything electrical in the lab besides the UVP then measuring the flow
8	Plastic Natural Convection Experiment	Natural convection flow between two plastic plates with the UVP measuring along the hot wall.

9	Test Section	Mixing Convection experiment. The system was allowed to reach steady state, bubbles were added at the bottom of the hot wall and allowed to flow for several hours to allow the system to become as steady as it could become, then the bubbles were shut off and the flow was allowed to become steady again. The UVP was used to measure flow during each of these steps.

The experimental procedure for sodium testing was also developed. For sodium tests the experimental apparatus is fully assembled and sealed before sodium can be delivered. The experimental apparatus (lower tank and test section) will be purged of air with inert gas (Argon). The sodium is delivered in sealed containers with inert gas cover and will be placed in a glove box. Then the procedure outlined for the first test will be applied to get the sodium to the enclosure. The upper transfer tank is installed and all gas and fluid loop lines connected. The valve from the test section to the upper tank is opened. Once the transfer tank with the sodium is installed above the test section the areas of the enclosure that were open to allow installation of the tank will be covered with sheet metal so that the enclosure is fully covered. The test section will be heated above the melting temperature of sodium to about 110°C. Then the upper storage tank containing solid sodium, which is encased with electrical heaters, is heated until above the melting temperature of sodium allowing the liquid sodium to drain into the test section.

Prior to and during the experiment itself, steady-state conditions are established by monitoring the temperature of the test section and upper and lower storage tanks with time. Once at steady-state, temperature and velocity data is recorded while monitoring said components. After an experiment is completed, the lower tank is heated and then the actuated valve is opened allowing the sodium to drain into the lower tank. Once the sodium is drained the heaters will be turned off to allow the sodium to solidify in the lower storage tank. If the lower tank is below, 98°C, then the sodium is in solid form. To start a new experiment the heaters to this lower tank will be turned on and the temperature monitored until above it is 98°C but below 150°C. At the same time, the heaters to the upper tank and test section are also turned on to attain the above temperature. 2-3 psi of pressure is added in the lower tank to transfer liquid sodium into the upper tank through the line connecting the two.

Appendix B. Cooling Jacket Research and Design

As with any technology, UDV instruments have limits of appropriate application. A notable challenge is that most ultrasonic transducers are limited to about 60 °C. Developments in materials and manufacturing have let to some commercially available high temperature transducers that are capable of operating at temperatures up to 150 °C and 250 °C. However, these high temperature transducers are much more expensive and the common 60 °C transducers have been used here. This necessitates the design and fabrication of a protective jacket that will enable the transducer to operate at elevated temperatures and protect it from the harsh sodium environment. Another limitation is that acoustic signals tend to be weak compared to the power required to produce the signal. This is true in most acoustic phenomena. For example, the efficiency of speakers may be only 1 or 2%. Consequently, the signal tends to attenuate rapidly when different material layers are introduced between sensor and test medium. Because of material compatibility issues, the material of choice for shielding against liquid sodium is stainless steel. If appropriate coupling materials are used to acoustically connect the transducer, while still providing insulation to the transducer, a large portion of the signal can be transmitted. The degree to which this transmission occurs is described by a transmission coefficient (T_i). It is important to note that for measurable levels of sound to return to the device, the wave must be transmitted through each layer twice.

It was originally assumed that the transducers required a layer of insulation to protect them from the elevated temperatures. As the system was analyzed, it was realized that results were unsuitable for the given parameters; specifically, porous media is generally formed with a large percentage of volume filled with air and so, good insulators are generally very poor acoustical transmitters. Mohammadi et al. investigated transmission loss through a triply layer panel. The triply layer panel had two solid layers with a middle layer of air or liquid. Theoretical models were compared with experimental results, and Mohammadi concluded that for a middle layer of air and a frequency above 780 Hz there is high transmission loss of the acoustic wave (Mohammadi, 2009). This means for the present research with the use of 4MHz transducers air gaps will not allow for effective acoustic transmission. Mohammadi also demonstrated that fluid density is an influential parameter in the transmission loss values. Different fluids with similar densities produce similar results.

Eckert et al. investigated the issue of acoustic transmission through stainless steel while studying sodium flow through a square duct under a magnetic field (Eckert, 2002). Eckert determined that there are three major requirements for effective acoustic transmission. These are 1) effective coupling between the transducer face and the solid barrier, e.g., stainless steel wall, 2) proper barrier thickness for maximum transmission, and 3) effective wetting (coupling) between the barrier and the fluid of interest [Eckert, 2002]. All three of these requirements are related in the fact that in order for there to be effective transmission of sound waves through layers of different materials the difference in the acoustic impedances between each layer must me minimized. In order to minimize the impedance between layers, or maximize the transmission coefficient, Eckert uses the equation below.

$$T_i = \frac{1}{\sqrt{1 + \frac{1}{4}\left(m - \frac{1}{m}\right)^2 \sin^2 \frac{2\pi d}{\lambda}}}$$

where T_i is the transmission coefficient, m is the ratio of acoustic impedances between layers; in this case liquid sodium and steel, d is the thickness of the steel plate, and λ is the wavelength in the plate. It should be mentioned that this equation assumes that the steel plate and incident wave are perpendicular to each other. In Eckert's experiment he coupled the transducer face to the steel plate using silicon grease. He also assumed that the impedance of the silicon grease ($Z_{gr} = 1 * 10^6\ Ns/m^3$) and liquid sodium ($Z_{Na} = 2 * 10^6\ Ns/m^3$) were approximately the same. This is a valid assumption because the impedance of both sodium and grease are equally small compared to that of stainless steel ($Z_{st} = 45 * 10^6\ Ns/m^3$). Using the above equation Eckert determined the plate thickness, d, which maximized the transmission coefficient, T_i, was 2.21mm.

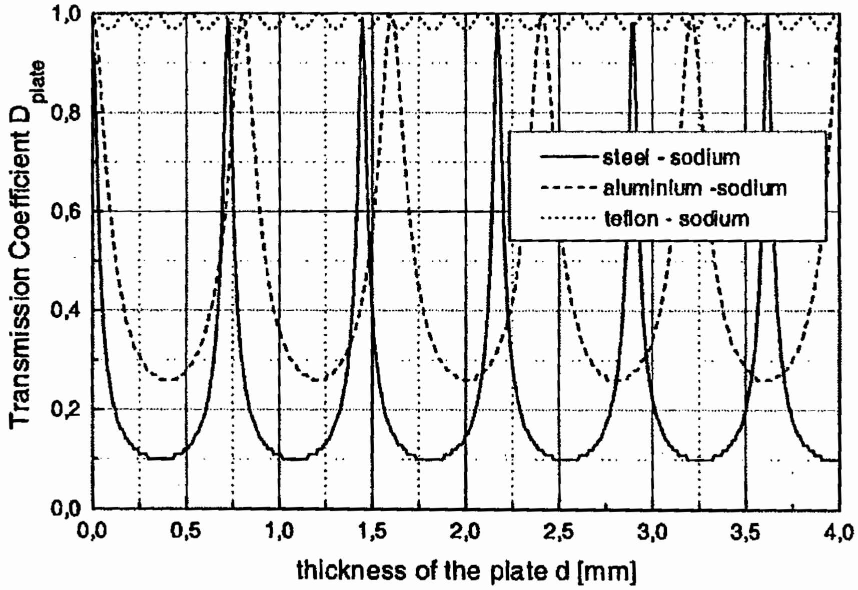


Figure B1.. Eckert Plot of Ultrasonic Transmission Coefficient (Eckert, 2002)

Due to the large impedance of stainless steel the resonance peaks are very strong and narrow. Outside of the peaks only about 10% of the wave is transmitted through the steel plate.

In this research it is proposed to use an array of transducers to provide a planar mapping of both temperature and velocity within the flowing sodium. As noted earlier, it is critical to achieve a high T_i. This can be achieved by coupling the transducer to the protective jacket wall using gel or grease, and by properly sizing the jacket wall. Theoretically, it is possible to have nearly perfect transmission through an appropriately sized wall. However, as seen in Figure the very narrow resonance peaks make it difficult to obtain with reasonable manufacturing tolerances. Still, it is possible to have near 90% transmission with reasonable tolerances.

Using the equation above for the transmission coefficient by Eckert et al., the transmission coefficient with sodium at 127C and water at 20°C is determined to be greater than 90% with a wall thickness of 2.17mm. This wall thickness agrees well with the 2.21mm used by Eckert at higher sodium temperatures. Figure 2 shows the transmission coefficient as a function of wall thickness under experimental temperatures for both sodium and water.

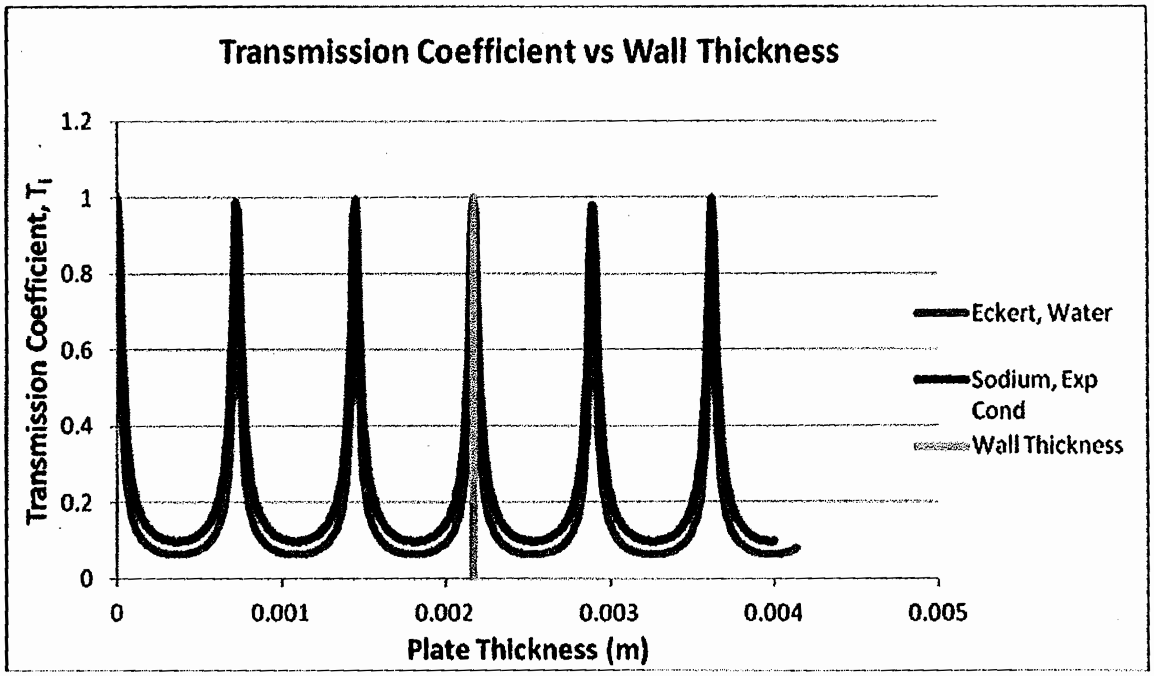
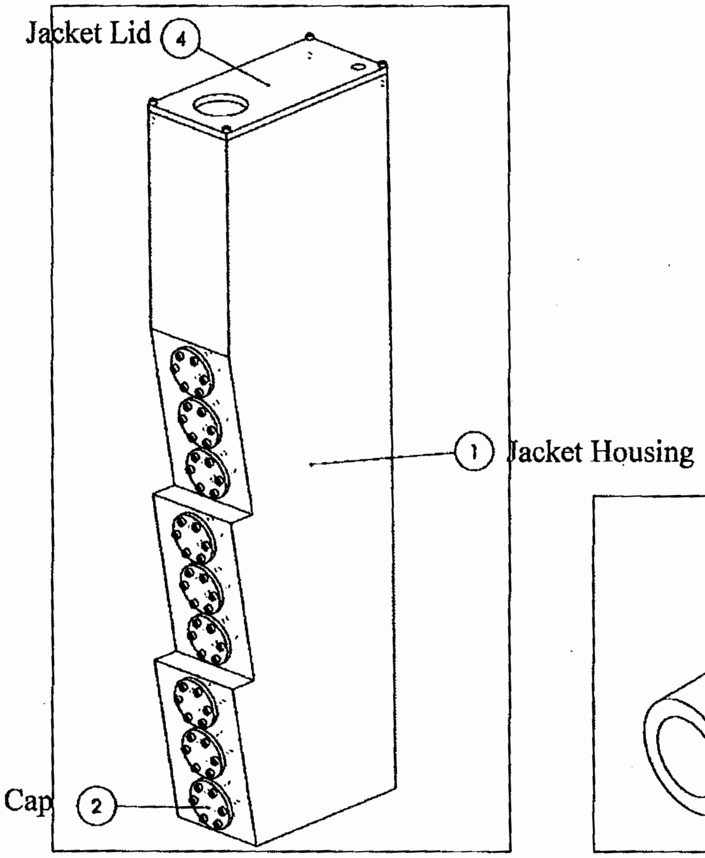


Figure B2. Transmission Coefficient as a Function of Wall Thickness for Experimental Temperatures

In this research an array of transducers is used to capture a plane in the flow field. A single jacket housing is used where each transducer may be acoustically coupled to its own "cap" and then attached to the housing. This ensures good coupling between all the transducers and the transmission wall of the cap. This also allows for the cap wall to be machined separately from the rest of the jacket. See Figure B3 for a sketch of the jacket design and transducer cap.



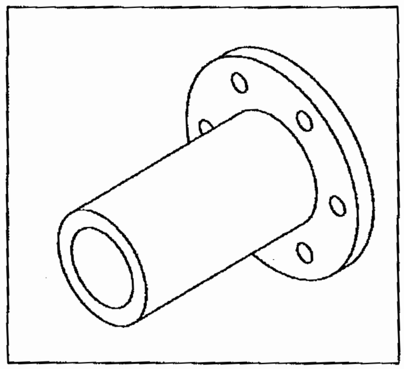


Figure B3. Transducer Jacket Design with Cap Shown Separately and Enlarged

References:

1. Eckert, S., & Gerbeth, G. (2002). Velocity Measurements in Liquid Sodium by Means of Ultrasound Doppler Velocimetry. *Experiments in Fluids*, *32*, 542-546.
2. Mohammadi, N., & Mahjoob, M. J. (2009). Transmission Loss of Multilayer Panels Containing a Fluid Using Progressive Wave Model: Comparison with Impedance Progressive Model and Experiments. *C.R. Mecanique*, *337*, 198-207.

Appendix C. Letter from ANL

Dr. Hussein S. Khalil
Director

Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439

1-630-252-7266 phone
1-630-252-4780 fax

April 13, 2007

Dr. Akira Tokuhiro
Kansas State University
Mechanical & Nuclear Engineering
3002 Rathbone Hall
Manhattan, KS 66506

Dear Professor Tokuhiro:

Subject: **NERI Project on Experimental Development and Demonstration of Ultrasonic Measurement Diagnostics for Sodium Fast Reactor Thermal-Hydraulics**

On behalf of Argonne's Nuclear Engineering Division, it's a pleasure to express our strong support for the Kansas State University NERI project "Experimental Development and Demonstration of Ultrasonic Measurement Diagnostics for Sodium Fast Reactor Thermal Hydraulics" which was recently selected for an award by DOE (Project Number 07-037). The proposed development and demonstration of ultrasonic diagnostics for sodium-coolant thermal-fluidic behavior and the testing of sodium-to-supercritical carbon dioxide (sCO_2) heat exchangers will greatly advance the development of the Advanced Burner Reactor (ABR) for actinide management as part of the Global Nuclear Energy Partnership (GNEP).

As part of the GNEP/ABR studies at Argonne, we have initiated an experimental project to provide baseline data for the evaluation of potential sodium plugging in narrow flow channels such as might be encountered in a compact heat exchanger. The construction and assembly of the test apparatus is now nearing completion. The apparatus includes a sodium loop made from ½-inch stainless steel tubing, three test sections, expansion and dump tanks, two electromagnetic (EM) pumps, three EM flow controllers, five EM flow meters, a cold trap, and associated Argon and vacuum systems.

The Argonne sodium loop will become operational soon. Upon completion of our planned sodium plugging tests, this facility can be employed for testing and demonstration of the proposed ultrasonic measurement diagnostics. We will be pleased to make this facility available to you and the Kansas State University research team, consistent with Argonne's programmatic commitments and requirements related to environment, safety and health protection. In addition, we would be interested in collaborating with KSU on testing of a sodium-to-sCO_2 compact heat exchanger. As you know, Argonne is already collaborating with Kansas State University on testing of a printed-circuit heat exchanger (PCHE) for sCO2-to-water and sCO2-to-CO2 heat exchange as part of a previous NERI project.

The proposed collaboration between Kansas State University and Argonne is ideal in that it would maximize the benefits from an experimental facility already existing at a National Laboratory, while at the same time providing university students the opportunity to interact and gain experience working with Laboratory staff experienced in fast reactor and sodium-coolant technology.

Sincerely,

HSKhalil

Hussein S. Khalil
Director, Nuclear Engineering Division

Appendix D. Tranter Maxchanger Heat Exchanger Prototype Specification

H E A T   E X C H A N G E R S ▲ H E A T   E X C H A N G E R S

TRANTER®
The heat transfer people

Welded PHE Specification

Date		Tranter Reference #	
Request Date		Item #	
Customer Name		Sales Engineer	
Street Address, City, State, Zip Code			

Specify Product (If Preferred)	☐ Ultramax	☐ Supermax	☐ Maxchanger

	Hot Side		Cold Side		
Fluid Name	Supercritical CO_2		Water		63
Flow Rate	0,1077	GPM	0,1467	GPM	52
	315	lb/hr	112,5	lb/hr	
Select One	☒Gas	☐Liquid	☐Gas	☒Liquid	
	Inlet Temp	Outlet Temp	Inlet Temp	Outlet Temp	
°F	95	93,2	115	109	
Specific Heat (Btu/lb*°F)	1,2621	1,494	1,0	0,999	
Specific Gravity					
Thermal Conductivity (Btu/hr*ft*°F)	0.024	0,026	0,369	0,367	
Viscosity (cp)	0,02135	0,0217	0,584	0,6203	

Operating Pressure	1073	PSIG	20,0	PSIG	
Pressure Drop	1,14	PSI	2,24	PSI	
Heat Exchanged (if known)					
Design Pressure	3147	PSIG	1218	PSIG	34
Maximum Design Temperature	1650	°F		°F	
Minimum Design Temperature		°F		°F	

Material of Construction	316L stainless steel	SS 316L	31
ASME Code Stamp/Design (Select One)	☒Yes	☐No	

Operation Specification				
Select One	☒Closed Loop Sys.	☐Batch	☒Closed Loop Sys.	☐Batch
Select One	Cyclic Operation?			
	☐Yes	☐No	☐Yes	☐No
If Yes,	Number of Cycles Per Day?			

Environment Specification				
Ambient Temperature			°F	
External Vibration	☐Yes		☐No	
Insulation	☐Yes		☐No	
Space Limitation	☐Yes		☐No	
If Yes, Please Specify		Length (inches)		Height (inches)
Location of Installation (City, State)				

Market/Industry	☐ Automotive	☐ Chemical	☐ Food/Beverage
	☐ HVAC	☐ Marine	☐ Petroleum/Gas
	☐ Power/Utilities	☐ Ethanol/Biodisel	☐ Other
NOTES:			

Tranter, Inc., 1900 Old Burk Highway, Wichita Falls, TX 76306
Ph: 940-723-7125, Fax: 940-723-5131, http://www.tranter.com

H E A T E X C H A N G E R S ▲ H E A T E X C H A N G E R S

TRANTER®
The heat transfer people

2-Phase Specification

Date		Tranter Reference #	
Request Date		Item #	
Customer Name		Sales Engineer	
Street Address, City, State, Zip Code			

Specifiy Product (If Preferred)	☐ Ultramax	☐ Supermax	☐ Maxchanger

	Hot Side		Cold Side	
Phase Change: Specify One**				
None				
Evaporation				
Condensation	Super-critical CO_2		water	
Fluid Name				
	Name	Flow Rate (lb/hr)	Name	Flow Rate (lb/hr)
Sub-Component #1 ☐ Liquid ☒ Vapor		315		
Sub-Component #2 ☒ Liquid ☐ Vapor				112.5
Sub-Component #3 ☐ Liquid ☐ Vapor				
Sub-Component #4 ☐ Liquid ☐ Vapor				
Total Flow Rate (lb/hr)				

19 Inlet Temperature	95	°F	115	°F
19 Outlet Temperature	93.2	°F	109	°F

Specific Heat*	1.2621	Btu/lb*°F	1.0	Btu/lb*°F
Specific Gravity*		****		****
Thermal Conductivity*	0.024	Btu/hr*ft*°F	0.369	Btu/hr*ft*°F
Viscosity*	0.02135	cp	0.584	cp

Operating Pressure (Required)†	1073	psig	20.0	psig
Pressure Drop	1.14	psi	2.24	psi
Design Pressure	3134 psi		1204 psi	
Design Temperature	392 °F		392 °F	35
Heat Exchanged (if known)				

Material of Construction	316L stainless steel	SS316L	31
ASME Code Stamp/Design (Check One)	☒ Yes	☐ No	

Market/Industry	☐ Automotive	☐ Chemical	☐ Food/Beverage
	☐ HVAC	☐ Marine	☐ Petroleum/Gas
	☐ Power/Utilities	☐ Ethanol/Biodisel	☐ Other

NOTES:

*To Be Completed Only For Single Phase (All Liquid or Vapor), Special Fluids
**For Condensation/Vaporation, If Available, Please Supply A Separate "Heat Release Curve"
† Operaing Pressure Is Require (Phase Change Fluid Streams)

Tranter, Inc., 1900 Old Burk Highway, Wichita Falls, TX 76306
Ph: 940-723-7125, Fax: 940-723-5131

Appendix E. CAES Sodium Natural Convection NERI-037

CAES Center for Advanced Energy Studies	SODIUM NATURAL CONVECTION NERI-037	Identifier:	CAES –P–024	
		Revision:	0	
		Effective Date:	TBD	Page 1 of 32

ACTIVITY PRINCIPAL INVESTIGATOR, LAB LEAD, and SPONSORING ASSOCIATE DIRECTOR

PI(s): Akira Tokuhiro
LL: Rob Podgorney
AD: Bob Smith

ACTIVITY LOCATION BY LAB ROOM NUMBER
Deflagration room Lab 114

Principal Investigator, Laboratory Lead, and CAES Safety Officer Approvals

Print Sign

Principal Investigator: Akira Tokuhiro ______________________ Date: ________

Print Sign

Laboratory Lead: Travis McLing ______________________ Date: ________

Print Sign

CAES Safety Officer: Kristi Moser-Mcintire Date: ________

RESEARCH STAFF

David Kim, M.S. Student of Nuclear Engineering, University of Idaho
Nathan Seaver, M.S. Student of Mechanical Engineering, University of Idaho

MAJOR EQUIPMENT USED IN ACTIVITY

1) Labconco Protector Glove box (to initially transfer sodium as delivered to Na-storage tank)

These pages contain general comments that will need to be tracked and vetted with the commenting SME. For now, they're just something to think about in general terms so a productive dialog is more likely.

From Jim Durrant (Industiral Safety)

- c. What pressure will the system operate at? Has anyone looked into pressure safety issues including use of compressed argon gas cylinders?
    - The system will operation at a max p of 5 PSI
- e. Is pressure system assemblers training needed?
    - We don't believe so, but would appreciate your advice
- There is a conflict between administrative control #5 and the hazard of sodium in the hazard section and in the PPE section.
    - Jim – please help us resolve the conflict as you see it, we intone covered shoes as having no exposed skin.
  - What are "covered shoes"?
    - Is your terminology "substantive foot wear" we just need to understand the appropriate term
- (2) Task #2: There are more hazards and administrative controls to consider. Are you using lead(Pb) solder? What are you doing to control lead fume exposure? What about Chemical Hygiene training relating to lead. Electrical safety training needs to be included.
- Task #4: Who is performing the hoisting and rigging? There are specific training for each task. Additional hazards exist when performing H&R activities. The existing hazard section needs to be re-written.
  - Jim – this is a small floor mounted lifting device. We may need some help with the appropriate controls. It's the same equipment used for Gannon's PV
- Any ladder work? Any elevated work above 4 feet?
  - Yes, we do anticipate elevated work from a ladder, but feet never above 4 ft
- Any need to operate a 480V breaker or disconnect?
  - No
-

1. PURPOSE/SCOPE/APPLICABILITY (include activity abstract and objectives)

We propose to demonstrate ultrasonic technology in a small sodium-based natural convective heat transfer experiment to address some of the principal technology issues related to sodium-cooled fast reactors. Specifically, we propose concurrent development and demonstration of ultrasonic measurement diagnostics linked to effective thermal convective (flow) sensing under anticipated "normal" and "off-normal" reactor operations and maintenance. The scope of work will demonstrate and evaluate ultrasonic technologies and define instrumentation options for the SFR and yield a better qualitative understanding and quantitative means to sense the thermohydraulic condition of sodium under varied flow conditions.

Sodium, although well suited (qualified at EBR-II) as the heat transfer medium for the Sodium Fast Reactor (SFR), is chemically reactive and (optically) opaque. As such, sodium presents engineering accessibility constraints relative to Light Water Reactor (LWR) operations and maintenance (O&M) and in-service inspection (ISI) technologies. That is, the optically transparent nature of water presents a different set of challenges; chemical reactivity and opacity are not apparent. Thus in terms of thermohydraulic measurements under normal conditions, and before/after off-normal (maintenance, unanticipated events) events, there are limited velocity and temperature sensing options. Acoustic methods, primarily ultrasonics, are a key measurement technology with applications in non-destructive testing, under-sodium (components) imaging, thermometry and velocimetry. Here, the co-PIs proposes to create a natural convective sodium flow to demonstrate ultrasonic technology as a means to measure the velocity and temperature of the fluid. No pump is required to circulate the fluid because it is caused by natural convection.

1.1 Research Activity Description (include activity approach)

1.1.1 Introduction

The international sodium fast reactor R&D effort, most recently summarized in the R&D Program Plan for the Sodium Fast Reactor (SFR), rests on relatively well-established technologies and reactor engineering knowledge and experience base. Thus, within the context of renewed interest in the SFR and the closed fuel cycle, the majority of the R&D issues that remain are technology performance and demonstration related issues, rather than feasibility of concepts. Both under the Generation IV and Global Nuclear Energy Partnership (GNEP) objectives, there is a need to re-address SFR realizability in terms of design concept economics, in-service inspection and repair, verification of inherent safety and updated analyses (i.e. advanced simulations).
Sodium, although well suited as the heat transfer medium for the SFR, is chemically reactive and (optically) opaque. As such, sodium presents engineering accessibility constraints relative to LWR operations and maintenance (O&M) and in-service inspection (ISI) technologies. In terms of thermohydraulic measurements under normal

conditions, and before/after off normal (maintenance, unaticipiated events) events, there are limited velocity and temperature sensing options. Acoustic methods, primarily ultrasonics, are a key measurement technology with applications in non-destructive testing, under-sodium (components) imaging, thermometry and velocimetry. Here, the PI (Tokuhiro and UI students) aim to demonstrate ultrasonic technology through the following:

1) design, construct and operate a new university-based, small, simple but purposeful sodium flow loop with inventory of *up to* ~10 liters.
2) develop and demonstrate ultrasonic velocimetry and thermometry, with focus toward improved SFR O&M. That is, velocimetry and thermometry as diagnostic tools during normal and off-normal operations.
3) test a compact, sodium to supercritical CO2 heat exchanger and generate convective heat transfer data, correlations and operational experience under normal and off-normal operations. (NOTE: this is reproduced from the original proposal but will addressed separately if conducted at CAES)

As further described, the project will yield a better qualitative understanding and quantitative means to sense the thermohydraulic condition of sodium under varied flow conditions. This project supports the R&D Program Plan for the Sodium Fast Reactor (SFR), within the current Gen' IV roadmap and emerging GNEP missions. The scope of work will demonstrate and evaluate ultrasonic technologies and define instrumentation options for the SFR. This will maintain and extend the U.S. nuclear SFR knowledge base, as well as educate the next generation of professionals familiar with the SFR (Hill, 2010).

1.2 Equipment Description

1.2.1 Vessels (upper and lower storage tanks and test section)

The test section (the vessel that will host the experiment) consists of two concentric cylinders; thus, one nested inside the other to provide secondary containment. The melting temperature of sodium is 98°C; thus, sodium is solid at room temperature. The experiment will be performed with liquid sodium in the range of 110°-200°C. Further the annulus hosts sensors for as described in controls section below. The outside cylinder will be filled with argon as a cover (barrier) gas to prevent contact between sodium and air (oxygen). It will have a bottom cap welded on and a flanged top (Figure 1). The inside cylinder will contain the liquid sodium, the natural convective flow of which is the intended experiment. The movement of sodium is thus self-contained in the inner container. The inside cylinder will have two capped ends welded into place that extend to the sides to keep the cylinders concentric. A stand will be positioned inside the outside cylinder to keep the inside cylinder at the proper height.

The entirety of this assembly is called the 'test section'.

Containers for transporting the sodium to and from a glove box will be placed above and below the test section; these 'storage tanks' respectively are named and will serve as the upper and lower storage tanks for sodium. The upper tank is used for transferring the sodium from the glove box and filling the test section. The lower tank is a requirement for being able to drain the test section any time. The sodium will be delivered in solid form, inside a (plastic) container filled with inert gas; the sodium thus has to be transferred to a stainless steel storage tank in order for it to be melted into liquid form and drained into the test section. This can be done with stainless steel tongs. During sodium transfer to the storage tank, the sodium will be transferred to the storage tanks with Argon cover gas. The storage tank will have valves and (gas-line) connections to keep the sodium sealed while allowing for safe connection to the test section. The storage tank with sodium will be placed above the test section, heated in order to melt the sodium and the valve opened to drain the sodium into the test section. The valve between the test section and lower storage tank will remain closed during this time. Once an experiment is finished, sodium will be drained into the storage tank and allowed to solidify. When an experiment is to be repeated, the lower tank will be heated in order to melt the sodium; cover gas pressure will then be increased to 'push' the liquid sodium back into the test section (with line in-between open). Only a difference in pressure of 3-5 psi is needed to push the sodium into the test section or upper tank. A feed tube will penetrate the test section's outer cylinder via a feed-through (fitting) and will be welded to the inside caps. Wires and gas will be fed into the outer cylinder with high-temperature plugs.

The sodium will flow due to natural convection. One side of the inside cylinder has Peltier Coolers while the bottom and other side of the cylinder are heated by a ring heater and a strip heater respectively. A 'tree' of thermocouple sensors will be immersed in the sodium in order to measure its 'bulk' temperature. The wall temperature will be measured from the 'wall-side'; the difference of the wall to bulk temperature, and the heat flux is needed to estimate the heat transfer.

1.2.2 Transducer Cooling

An ultrasonic transducer will be used to measure first the velocity and subsequently the temperature of liquid sodium in natural convective flow along the hot side of the test section. The operational temperature limit of one type of transducer (tdx) that will be used is 60°C and therefore must be cooled in order to maintain the 'body' at this temperature or lower. A second type of transducer has a 150°C operating temperature limit. Figure 3 shows the cooling jacket that will be welded into the inside cap of the cylinder. Argon gas will be fed through the small diameter tubing at the top of the cooling jacket and will cool the heat exchange surfaces in order to maintain the transducer 'face' and nearby casing. Testing of this 'tdx cooling jacket' can and will be done separately and without sodium prior to the experiment.

1.2.3 Controls

There are multiple parts of the experiment that are controlled or measured. To know what is going on within the system we need to know the temperature profile throughout the sodium. Thermocouples are used to measure the temperature along the hot side, cold side and in the thermocouple tree stuck inside the cylinder. From these three positions we will be able to extrapolate the temperature across the enclosure. The data from the thermocouples will be measured with National Instruments (NI) Data Acquisition hardware plugged into a computer and NI Labview software. Similarly, thermocouples will be placed inside the cooling jacket and on other parts of the system in order to know what is happening throughout the system. The heaters and peltier coolers will all be controlled with Tempco Temperature Controllers. The controllers for the heaters plug directly into a wall outlet and create a feedback loop by reading the temperature of the heater and adjusting the power to the heater until to maintain the desired temperature. The wiring for these temperature controllers is in figure 4, there are 7 temperature controllers in use - three 15 Amp, three 10 Amp and one 8 Amp heater temperature controllers. This is done by placing a thermocouple on the heater being controlled, and the controller adjusts the power to the heater until it reaches the temperature programmed into the controller. The cooler temperature controller works similarly but requires external power as can be seen in figure 5. The max temperature the system will see during this experiment is 200C.

The only controls not temperature related are the actuated valves and the argon gas. There are several actuated valves for the argon gas system and one in the sodium loop. Each one is simply plugged into an outlet and opened and closed with a switch. The gas loop has pressure gages and manual valves throughout the loop. A dry run will be done to understand how much gas it will take to fill the test sections and cool the peltier cools and transducer cooling jacket. The longest test expected will be eight hours and pressure will be measured before running any experiment to ensure there will be enough argon for the experiment. The level of gas flow will be constant during the experiment, some gas will be used to fill the system, and higher levels of flow will be used to cool the cooling jacket and heat exchangers on the peltier coolers. The levels of gas will be setup at the beginning of the experiment and left on once the enclosure is sealed. The actuated valves on the gas system seal the argon in and out of the inside cylinder just in case the inside cylinder needs to be sealed. The pressure of the system will not exceed 10 psi.

In the event of a power out or surge, the power outlets located at the fume hood have a backup generator source. Thus, all sodium and gas valves are to be plugged in to there so that in the event of a black out control of the flow of sodium and argon could be directed to shut down.

1.3 Project Steps

1.3.1 Build and Shakedown testing in preparation for sodium work:

1) Solder all heater, thermocouple wires and circuits
2) Construct and install lower transfer tank and test section in enclosure

a. Cut and bend pipes
b. Tighten fittings
c. Putty and seal components together
d. Feed wires through containment
e. Connect ventilation tubes from system into fume hood
f. Build enclosure
g. Attach argon cylinder to work table

3) Heater testing: plug in heaters and thermocouple to temperature controllers
4) Thermocouple testing to ensure reading properly
5) Glove Box test to make sure weighted transfer tank can be handled going in and out of glove box
   a. Place 10 L deionized water into transfer tank
   b. Lift weighted (~45 lb) transfer tank into in materials lab glove box and orientate it where it could be worked on
   c. Remove transfer tank from glove box
6) Install lower transfer tank
   a. Transfer weighted transfer tank from materials lab to fluids lab on cart
   b. Installation of lower transfer tank will be placed at a slight angle to help ease of connection of all joints
   c. Connect all joints to gas and water loop
7) Deionized water shakedown and leak test
   a. All heaters will be turned on
   b. Water will be drained into test section
   c. Initial UVP measurements taken
   d. Water will be pushed into upper transfer tank
   e. Water will be drained into the lower transfer tank
   f. The rest of the water will be removed by heating the system and allowing it to evaporate
   g. The system will then be flushed with denatured alcohol to remove traces of water then heated to 140F to aid the evaporation of the alcohol
8) Nest cylinders within each other
   a. This step will be completed by a separate company
   b. Have stand prepared to hold nested cylinders
   c. Lift inside cylinder with shop crane (Appendix B)
   d. Lift outside cylinder around inside cylinder, place both on stand
   e. Use crane to lift nested cylinders onto enclosure stand

1.3.2 In preparation for the test(s) below and delivery of the sodium, there are a number of steps as follows:

1) For UI (PI) to order the sodium with full knowledge of CAES personnel.
2) For UI and CAES to be ready to take delivery of sodium and to have a location for interim storage.
3) Ensure sodium fire safety equipment is in place with personnel who are versed in using the equipment.
4) Electrical work to be reviewed
5) Prior to sodium delivery, the experimental apparatus will be fully assembled.

6) Sodium Transfer will be practiced prior to delivery
7) Transfer Sodium into Glove Box
    a. Place Sodium containers into glove box
    b. Place transfer tank in glove box
    c. Fill glove box with Nitrogen
    d. Open sodium containers and place sodium in transfer tank with the aid of glove box gloves and stainless tongs
    e. Close transfer tank.
        i. The transfer tank will weigh ~50lbs
    f. Remove nitrogen from glove box
    g. Remove transfer tank and other materials from glove box
    h. Strap transfer tank to cart.
8) Install lower transfer tank
    a. Connect tubes to test section
    b. Connect transfer tank to enclosure
    c. Connect all joints to gas and water loop
    d. The blanket heater and carriage heater around the transfer tank will be heated until they reach115°C.
    e. Once given ~1hr to melt and fill the test section the gas valves from areas containing sodium will be shut off
        i. External temperature will be monitored from the NI-DAQ in to see if additional time is required
    f. Experimental Procedure
        i. Temperature throughout system will be monitored at all time
        ii. UVP data will be take every half hour
        iii. Gas pressure will be monitored through
9) If the sodium is in the lower storage tank (after occupying the test section).
    a. We will assume that the sodium has solidified in the lower storage tank. If the lower tank is below, 98°C, then the sodium is likely in solid form. Thus, we will turn on the heaters to this tank and monitor its temperature until 115°C.
    b. At the same time, the heaters to the upper tank and test section will also be turned on and attain the above temperature.
    c. Pressurize the lower tank to no more than 5 psi to transfer liquid sodium into the upper tank through the line connecting the two.
10) Prior to and during the experiment itself, we will estimate steady-state by monitoring when the temperature of the test section becomes steady. We will record thermohydraulic data while monitoring the system.
11) In order to terminate the experiment, the liquid sodium will be drained into the lower storage tank while the tank is heated. Once the sodium is drained, the heaters of the system will be shut off.

1.3.3 The section below correspond 1.3.2 above

For UI (PI) to order the sodium with full knowledge of CAES personnel

1) The procurement of sodium should be coordinated with CAES responsible staff and delivered with full knowledge of CAES occupants and staff responsible for safe delivery.

For UI and CAES to be ready to take delivery of sodium and to have a location for interim storage

1) CAES responsible staff should be ready to take delivery of sodium.
2) In case there is not a means to immediately transfer sodium into the prepared storage tank as proposed, CAES should be prepared to provide an interim storage means.

For UI and CAES to have on-hand, sodium fire safety equipment with personnel who are versed in using the equipment

1) Verify that sodium fire safety equipment with personnel versed in use of said equipment is present when sodium is delivered to CAES and present, as deemed needed, when handling of sodium is going on.

Preparation of the experimental system components for initial assembly

1) Unless otherwise authorized, testing/experimentation will be done during regular CAES working hours.
2) Have the testing enclosure on hand and in a finished and ready state as possible.
3) Verify or fix the outside cylinder (of the test section) to stand of the testing enclosure.
4) If not already done, attach the Peltier Coolers, ring heater and strip heater to the Inside Cylinder. Verify fixtures if already present. The functional status of the coolers and heaters should be verified separately and prior to these tasks.
5) Lower the Stand and Inside Cylinder into Outside Cylinder.
6) Connect the Cooling Jacket tubing to locations needed and planned. Again, the functional status of the Cooling Jacket should be verified separately and prior to these tasks.
7) Assemble and connect the thermocouple tree in the Inside Cylinder.
8) Feed wiring and gas-line tubes through the stoppers in the wall of the cylinder and fix into place.
9) The top of the inside cylinder will be bolted into place and the feedthrough will be installed to the tubes feeding through the top and bottom of the outside cylinder.
10) Lift nested cylinders into testing enclosure and secure with bolts.

Operational start-up and transition to steady-state; monitoring the temperatures and velocity,

1) Verify that the outside cylinder is secured to the stand of the testing enclosure.
2) Verify that the Peltier Coolers, ring heater and strip heater are secured within the Inside Cylinder.
3) The above steps will be needed before initial filling of the test section with sodium.

4) Once the test section has been filled with sodium, the test section tested and later, the sodium drained into the lower tank, the sodium will have to be refilled in the test section from the upper tank.

5) Once the sodium is in the test section, the heaters and Peltier coolers turned on, monitor the temperature measurement points in time to determine approach to steady-state.

Establishing steady-state conditions and recording/acquisition of thermohydraulic data while monitoring the experiment and,

1) Steady-state is defined as approach to a steady, quasi-constant temperature change at most, if not all, of the temperature measurement points of the test section. Steady-state is anticipated to be approximately 0.5°C or less change in temperature over a 15 minute period. This is an initial estimate of steady state and is when we will begin taking velocity measurements.

2) The (Met-Flow SA) Ultrasonic Doppler Velocimeter (UVP) should be turned on to acquire velocity data of the naturally convecting sodium in the test section. The Met-Flow UVP has already received approval for use in CAES.

3) Recording/acquisition of temperature and velocity data should be repeated for some 30 minutes.

Shut down procedure of the experimental system:

1. Turn on or verify that the electric heating 'blanket' of the lower tank, as well as the valve on the sodium line connecting the test section to the lower tank has been remotely opened. Re-confirm that the lower tank contains an inert gas atmosphere but near atmospheric pressure.
2. Maintain the sodium bulk temperature at approximately (above) 150°C.
3. Once the connecting line to the lower tank and lower tank itself is above 98°C but below 150°C, remotely open the bottom Sodium Valve in order to allow the liquid sodium time to drain from the test section into the lower tank.
4. Once the sodium drains into the lower tank, turn off power to the test section but monitor the temperature to affirm 'cool-down'.
5. Remotely close sodium valves to isolate liquid sodium in the lower tank.
6. Turn off power to the heaters of the lower tank. Let the sodium solidify over time, unless the sodium is to remain in liquid form for the next experiment.
7. If the sodium is in the lower tank and at near room temperature, the test section and the upper and lower sodium tanks may be removed for storage at this time or remain in the testing enclosure for further work if needed.

Analysis:

Data from the ultrasonic transducer and thermocouples will be acquired using a commercial data acquisition device, stored on a PC and archived. Analysis of the data will be done separately and out of the experimental area.

2. RISK AND CONTROLS

Table 2.1 Risks and controls

Task: 1 Installing and setting up equipment	**Hazard(s)**	Muscle strain, twisting, falling, pinching, Chemicals used in construction: metal duct sealant, Sauereisen ceramic cement, graphite based thread sealant, stainless putty, dielectric grease. Elevated work installing equipment. Power Tools Cuts from sharp edges
	Engineering Control(s)	
	Administrative Control(s)	1) Work limited to 50 pound lifting limit or 1/3 of body weight whichever is less 2) When placing items or moving equipment, ensure that three point contact is constantly maintained with both feet solidly on the ground 3) Use appropriate tool for job 4) Keep tools in good working condition 5) No sodium will be present during this initial installation and setup of equipment. 6) A lifting device must be used to install large equipment. This may be an overhead crane, or other similarly capable ground based item. Max assembly weight is approx. 250 lbs. 7) Keep loose clothing or hair tied back when using power tools
	PPE	• Leather or cut resistant gloves when working with sharp objects • Eye protection, long pants, covered shoes must be worn at all times in the lab. • Rubber gloves need to be used when using all putties and greases
	Special Instruction(s)	All employees using the loop should read and understand the MSDS for sodium. This is to be included in the MSDS binder in the Fluids Lab.
	Task Specific Training	Hand and Power Tool Training

Task: 2 Setting up electric equipment	**Hazard(s)**	Electrical Shock/Solder Burn
	Engineering Control(s)	1) All wires connections will be wrapped in electrical tape, and 2) Wires will be held be alligator clips while soldering to keep hands from hot components
	Administrative	1) Basic soldering and electrical knowledge is required

	Control(s)	2) No electrical components will be handled while plugged in 3) Insulated tools when contacting electrical components
	PPE	
	Special Instruction(s)	
	Task Specific Training	

Task: 3 Testing Heaters	**Hazard(s)**	Burn from Heaters, contact with denatured alcohol Fire, electric shock
	Engineering Control(s)	
	Administrative Control(s)	1) Heaters will be tested only when isolated on test fixture or cement floor and no handling will be allowed until heater has cooled to below 100F 2) Surface temperature of heater will be measured by infrared thermometer before approached or handled
	PPE	Thermal resistant gloves, GOGGLES & SHIELD; LAB COAT & APRON; butyl Rubber or neoprene GLOVES
	Special Instruction(s)	VENT HOOD and CLASS B EXTINGUISHER when working with denatured alcohol.
	Task Specific Training	

Task: 4 Nesting Cylinders and fixing them to frame	**Hazard(s)**	Manual heavy lifting can cause injury from lifting objects that are too heavy Injury from dropped objects
	Engineering Control(s)	
	Administrative Control(s)	1) A crane will be used to fix one of the cylinders to limit the amount of lifting that has to be done once. 2) After cylinders are nested and temporarily placed on a stand both cylinders will be lifted together with crane to transfer to enclosure stand
	PPE	Steel-toed shoe covers and substantial shoes must be used Leather gloves should be used if possible
	Special Instruction(s)	
	Task Specific Training	

Task: 5	**Hazard(s)**	Contact with sodium, sodium 'fire', associated caustic fumes after delivery

Sodium in CAES	**Engineering Control(s)**	1) Sodium is delivered in sealed bottles under Argon. All transfer of sodium from shipping containers to the upper tank is to be done in a glovebox under cover gas. 2) Valves control the atmosphere of the transfer tank while installation is finalized. 3) Use of Argon or similar inert cover gas in sealed containers prevents air from contacting sodium. 4) Solid phase sodium is less prone to fire than liquid phase. Melting temperature is 98°C and use of the glovebox requires that objects never come close to this temperature. So, sodium will exist in a solid phase
	Administrative Control(s)	1) A measuring device such as a thermometer or thermocouple will be used to ensure that the glovebox never reaches more than 35 °C. 2) Not more than 50 lbs shall be lifted at once by one person. 3) Industrial valves will be closed prior to transport ensuring that air does not infiltrate container. Argon is denser than air and will prevent infiltration.
	PPE	Leather glove when potential for contact with sodium exists, safety glasses, long pants, lab coat and covered shoes.
	Special Instruction(s)	1) Open assemblies must not be left unattended for any reason. 2) Apparatus shall be purged with Argon gas prior to transfer of solid sodium into the said storage tank. 3) Any smoke or unusual odors should be reported to the person operating the equipment and preventative action like emptying the test section into a transfer tank, dumping sand into the enclosure, filling the enclosure with argon or using a sodium fire extinguisher should be taken to isolate and contain any sodium leak. 4) Sand buckets attached to enclosure in case of any observed 'smoldering smoke' from sodium, the sand will be used to cover any spilled sodium. 5) Keep Class D fire extinguisher for sodium on hand and ready to use.
	Task Specific Training	Read MSDS for Sodium. Other training as specified in Appendix. Complete glovebox training as required.

Task: 6 Sodium Transport and Charging (filling) of Natural	**Hazard(s)**	Contact with sodium, sodium 'fire', caustic fumes
	Engineering Control(s)	1) Solid sodium contained in a stainless steel storage tank will be transported (moved) from the glovebox to the natural convection loop test section. 2) The rig will be heated above the sodium melting point (98°C) and contain inert gas.

Convection Loop		3) The storage tank will be encased with heating elements to melt the solid sodium. The temperature of the tank will be monitored and determined to be well above 98°C before transfer of liquid sodium into the natural convection test section. 4) Valves seal the atmosphere in the transfer tank while installation is finalized. 5) Use of Argon cover gas in sealed containers prevents air from contacting sodium. 6) Solid phase sodium is less prone to fire than liquid phase. Melting temperature is 98°C and gloveboxes require that objects never come close to this temperature.
	Administrative Control(s)	1) Movement of the solid sodium from the glovebox to the test section will be conducted during a day and time when there are a minimum of occupants in the building. 2) Not more than 50 lbs shall be lifted at once by one person. Transport will be carried out using a low center of gravity cart of similar conveyance with emergency equipment in a state of readiness. 3) Valves on the sodium storage tank will be closed prior to transport out of the glove box. This is to insure that air does not infiltrate the storage container.
	PPE	Nitrile gloves inside a leather glove, safety glasses, long pants and covered shoes.
	Special Instruction(s)	1)Thoroughly practice the transfer procedure with a surrogate material first. Be sure to discuss and reaffirm understanding of the procedure by team members. 2) Open assemblies must not be left unattended for any reason. 3) Apparatus should be purged with Argon or similar inert gas prior to transfer of solid sodium into the said storage tank. 4) Any smoke or unusual odors should be reported to the operator and preventative action should be taken to isolate and contain any sodium leak. 5) Keep a bucket of sand with hand shovel on hand in the glovebox in case of any observed smoldering smoke from sodium. 6) Keep Class D or similar fire extinguisher for sodium on hand and ready to use.
	Task Specific Training	Read MSDS for Sodium. Other training as specified in Appendix. Complete glovebox training as required.

Task: 7 Test Procedures at	**Hazard(s)**	Overheating vessel, sodium leak and subsequent fire during operation
	Engineering	1) Vessel will have an independent temperature controller with

Start-up and Initiation of Operating Conditions	**Control(s)**	adjustable set-point to turn off the heater upon a temperature (current, voltage) limit. The initial temperature limit will be above the sodium melting point (~98°C) but kept low (~150°C) until operational experience is gained and the test section is judged to be operational at higher temperatures. 2) Containment for the test section will remain charged with Argon (or another inert gas) even while in operation. It will be vented to the fume hood only. 3) Thermocouples will be used to monitor inside temperatures of devices and enclosures. 4) The thermal mass of the outer containment is designed to be large enough to quickly solidify liquid sodium leaks if they occur. A heat sink is provided as well as a spill tray that will contain any spread of liquid sodium. 5) All structural parts are rated for high operating temperature. 6) Periodic temperature checks at fittings of the sodium lines taken by temperature laser gun. The system's lines should be maintained at an operating temperature of 110°C. Higher than expected temperatures would indicate a gas leak and shut down should begin immediately.
	Administrative Control(s)	1) At least one operator shall oversee each test run with a second present or in the building with knowledge of the experimental operation. 2) The assembly is to be kept within the secured deflagration room of the CAES Fluids Lab during all procedures involving electrically-generated heat. 3) Sodium shall not be stored or transported in anything except a sealed container with inert cover-gas. 4) Several buckets of soda ash will be kept at hand to smother smoldering or burning materials should there be a vessel failure. 5) A Class D, recommended fire extinguisher for alkali metal fires is to be kept outside the deflagration room.
	PPE	Heat resistant gloves are required when handling items >124°F.
	Special Instruction(s)	1) Keep a bucket of sand with hand shovel on hand in the glovebox in case of any observed „smoldering smoke" from sodium. 2) Keep Class D or similar fire extinguisher for sodium on head and ready to use. 3) Carry-out shutdown with a lab partner.
	Task Specific Training	General sodium handling awareness.

Task: 8	**Hazard(s)**	Freezing of sodium in tubing or valves impairing operation

Shut Down	**Engineering Control(s)**	The design of the, loop and the sodium therein contained is (mostly) gravity driven to drain into volumes (tanks) where further, expansion of volume is safely accomplished as sodium solidifies. This minimizes accumulation of sodium in the loop piping. Tubes and valves are also heated to minimize accumulation of solidified sodium.
	Administrative Control(s)	We anticipate that once sealed, fittings should not be disturbed. If it becomes necessary to open any sealed connections, a review processes will be undertaken to minimize likelihood of sodium contacting air.
	PPE	Heat and sodium resistant- gloves and protective gloves and safety glasses should be used. A temperature sensor should measure the surface temperature of suspected hot surfaces.
	Special Instruction(s)	Carry-out shutdown with a lab partner.
	Task Specific Training	General sodium handling awareness.

3. WASTE GENERATION

No test material waste is to be expected from this project. Sodium will be reused for a separate experiment. The seal for the cap and the seals for the feed-through may need to be replaced if the lid of the experiment needs to be opened.

Type of Waste	Anticipated Volume	Container Type	Disposal Responsibility
1) flange seals/ feedthrough seal	< Liter	bag	Dispose in Garbage if not laden with sodium
2) denatured alcohol	Several liters	Jug	ISU will dispose. Contact Kristi Moser-Mcintire, Michael Shaltry or Joanna Taylor

List any special needs/requirements for storage and handling and disposal of wastes. Sodium-laden waste must stored, handled and disposed of in accordance with adapted practices of INL personnel who have experience in sodium disposal. Only small quantities (<0.5 liter) are expected at any one time. Generation of sodium-ladened waste is to be avoided at all phases of the work. See additional pertinent comments in Section 4, Emergency Procedures.

If a spill occurs, how will it be cleaned up? For spills of liquids other than sodium, using wipes and disposed of in trash. Water spills are not anticipated since it will not be used, for safety consideration, in the presence of sodium.

4. EMERGENCY PROCEDURES

The general safety as well as emergency management approach is as follows:
1) Communicate to 1st responders that water cannot be used.

2) Keep water sources out of reach.

3) Non sodium-use fire extinguishers and especially those with higher pressure nozzles cannot be used since they may further disperse the sodium mass.

4) Since sodium in contact with air (oxygen) smolders in time, an effective mitigating action is to deny access to air. This can be done by the following:
   a. Throwing soda ash on the mass of sodium. Keep soda ash nearby.
   b. Flood the basin of the enclosure with inert gas.
   c. Keep sodium appropriate fire extinguisher ready to use. Discharge into cabinet as needed.
   d. After initial containment, maintain sufficient gas or airflow to vent smoke that is generated.

5) Once the sodium fire is under control, keep the sodium-laden materials in a temporary storage enclosure and/or container. Plan a means for disposal according to ISU and CAES practices.

5. EXIT STRATEGY

The apparatus will be further used by graduate student, on the NEUP 321 (2009-2012) project under Akira Tokuhiro. This document for NEUP 321 will be submitted separately. The apparatus will be used by future graduate students working on the NERI(2007-2011) and NEUP 321 projects. If funding is no longer available for the project, the apparatus will be stored outside of the CAES building by Akira Tokuhiro and CAES staff.

6. SUPPORTING DOCUMENTATION

Additional Documents Supporting this Project Plan

6.1 References:
None

7. DRAWINGS AND DIAGRAMS

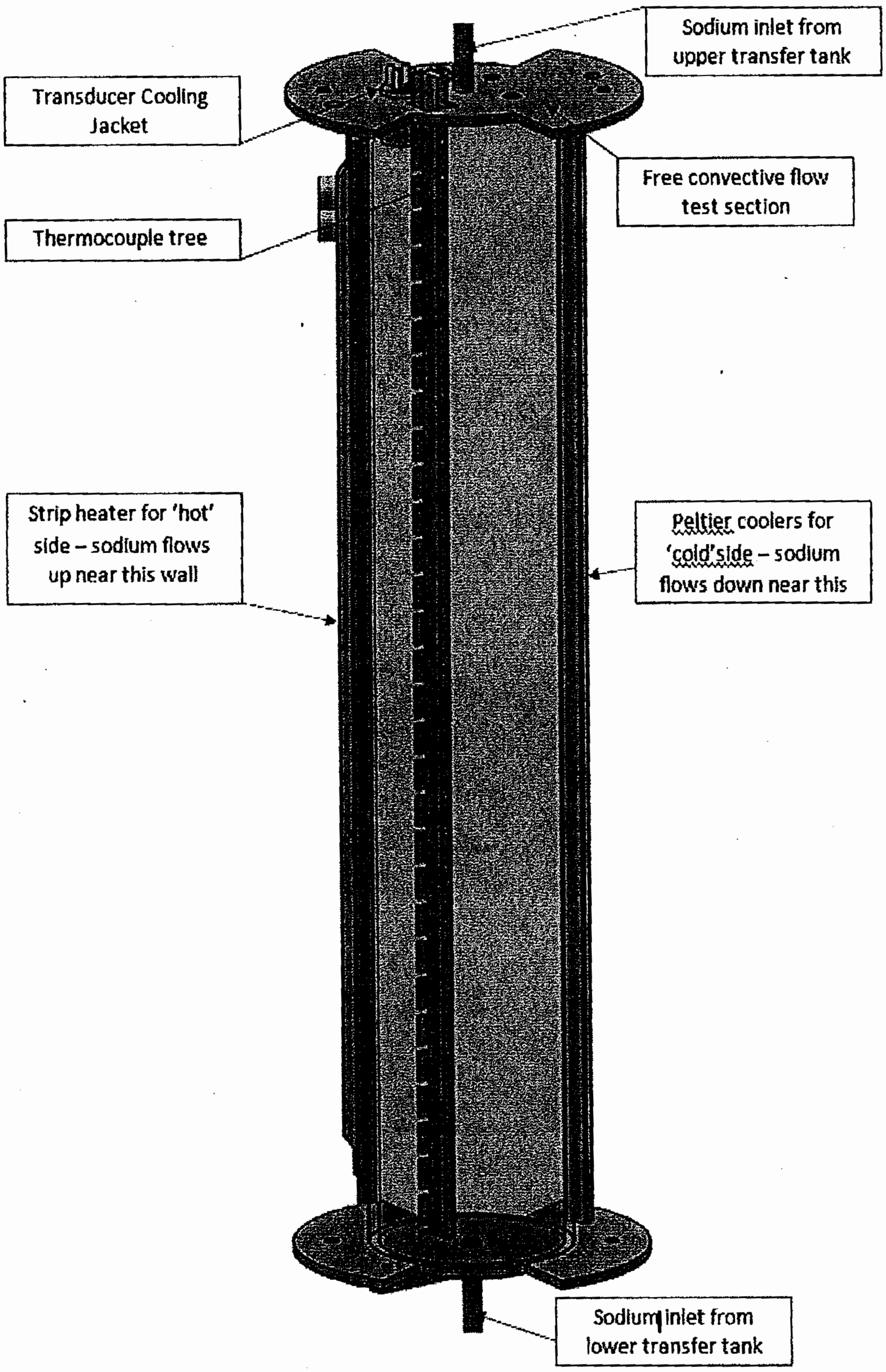


Figure 1. The inside cylinder and components to create the natural convective flow.

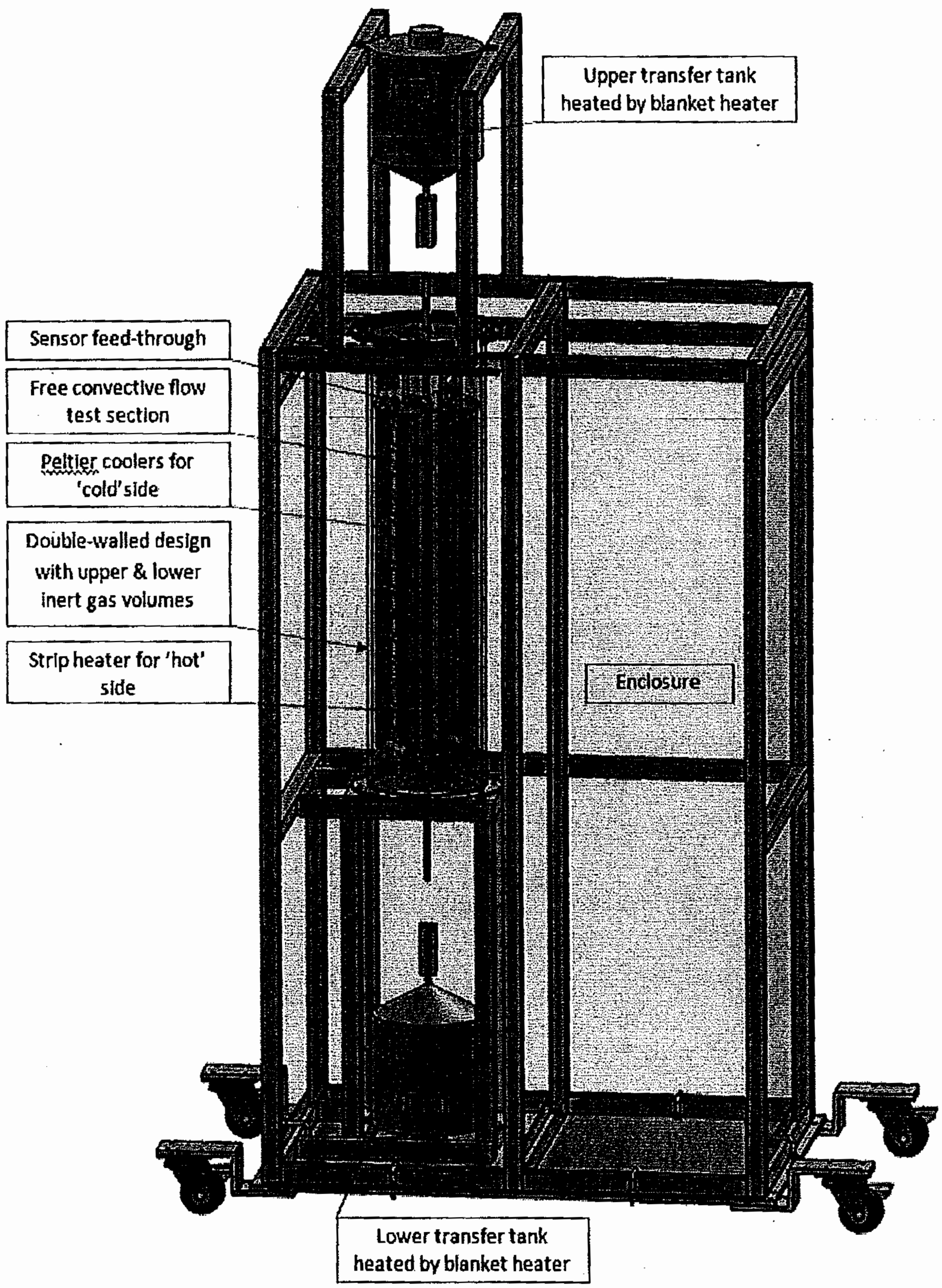


Figure 2: The design features of the test section are as follows: Double walled cylinders to keep sodium from coming in contact with air upon any anticipated leak; free convective flow created by hot and cold sides - Peltier coolers on the cold side, strip heater on the hot; sensors fed through the top of the inside cylinder; upper and lower transfer tanks in line with test section; all located in enclosure.

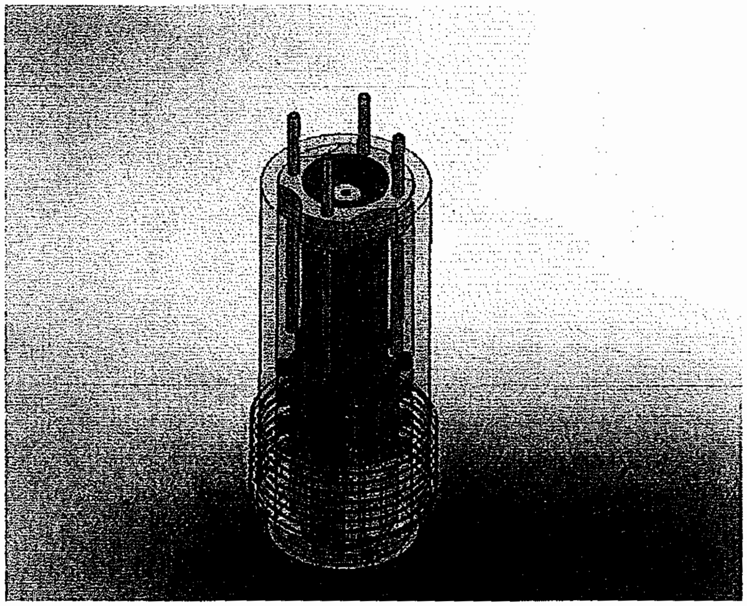


Figure 3. Current design of ultrasonic transducer for velocimetry and thermometry with a cooling jacket.

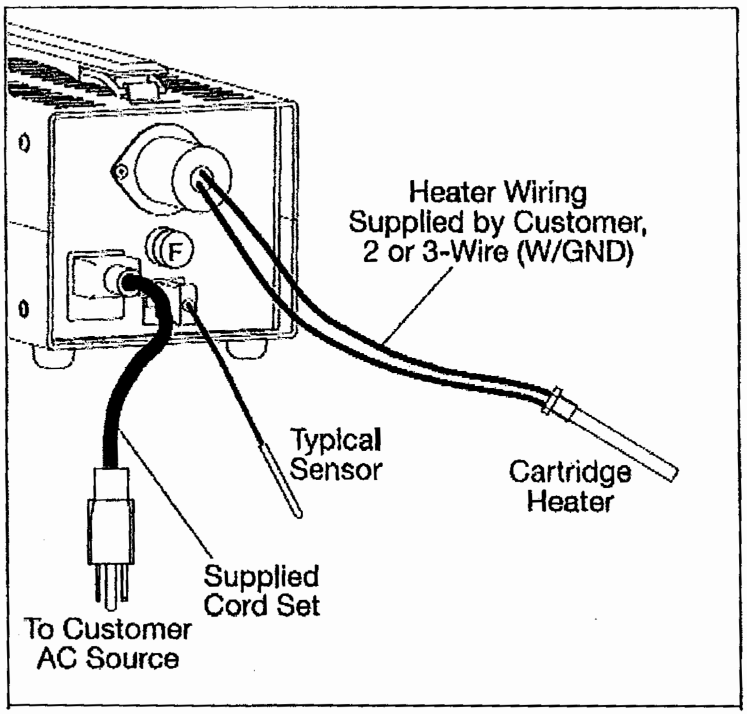


Figure 4. Wiring for heater Tempco Temperature Controllers

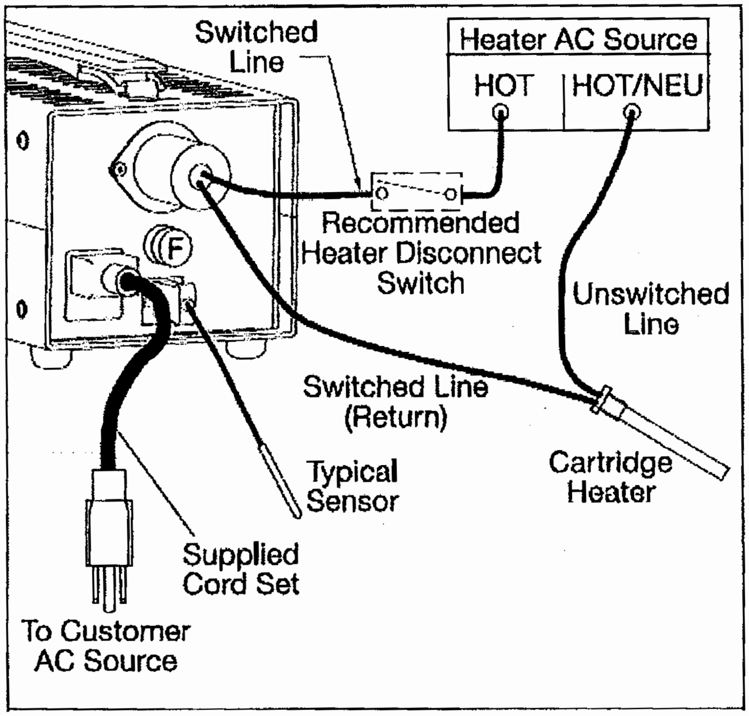


Figure 5. Wiring for peltier cooler Tempco Temperature Controllers

8. APPENDICES

Appendix A, Chemical Inventory

Appendix B, Electrical schematics

Appendix C, References

9. DOCUMENT COMMENTS

This document is a living document. Please provide recommendations below so that your inputs can be reviewed and incorporated into the next revision of this document.

Contributor Name	Document Section	Comment	Date

Appendix A

Chemical Inventory

Supporting Information: Chemical Inventory (Chemical hazards are captured in the body of the Project Plan - this section only provides a list of chemicals used in execution of the plans identified above.)

Name	CAS Number	NFPA/ Known Hazards	Maximum Storage Volume	Comments
Sodium (Na)	Not yet assigned	Health 3 Fire 3 Reactivity 3	8-10 liters	
Industrial Argon	7440-37-1	Health 0 Fire 0 Reactivity 0 USDOT 2.2	~50 ft^3 per test	
Metal-Duct Sealant	100304	None	(2) 5lb	
Sauereisen Ceramic Cement	NA			
Graphite Based Thread Sealant	????-??-?			
Durabond 7032 Stainless Putty	744-002-0	Health 1 Fire 0 Reactivity 0	1 lb	Effects Of Overexposure Skin Contact: Repeated contact with metallic nickel can cause nickel sensitivity and allergic skin rashes.
Super Lube® Silicone Dielectric Grease	63148-62-9 68611-44-9 025322-69-4	Health 1 Fire 1 Physical 0	400 g	May cause skin or eye irritation
Denatured Alcohol	64-17-5 141-78-6 108-10-1 67-56-1	Health: 2 Fire: 3 Reactivity: 0 Contact Rating: 2	10 L	Lab Protective Equip: GOGGLES & SHIELD; LAB COAT & APRON; VENT HOOD; butyl rubber or neoprene GLOVES; CLASS B EXTINGUISHER Storage Color Code: Red (Flammable)

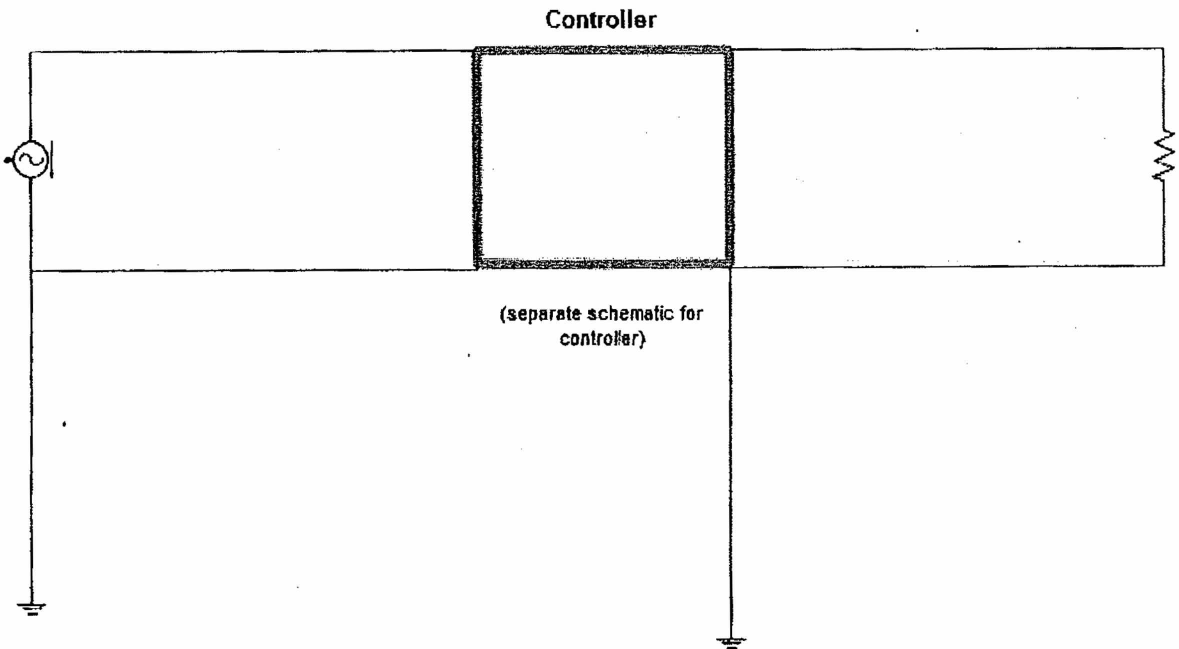
Lenox Rosin Core Solder	7440-31-5 7440-50-8 65997-06-0	Health: 1 Flame: 0 Reactivity: 0		
RectorSeal No. 7 Pipe Thread Sealant	123-42-2 141-78-6 108-10-1	Health: 2 Fire: 3 Reactivity: 0 PPI:B	1 pt.	Safety glasses and gloves required

Appendix B

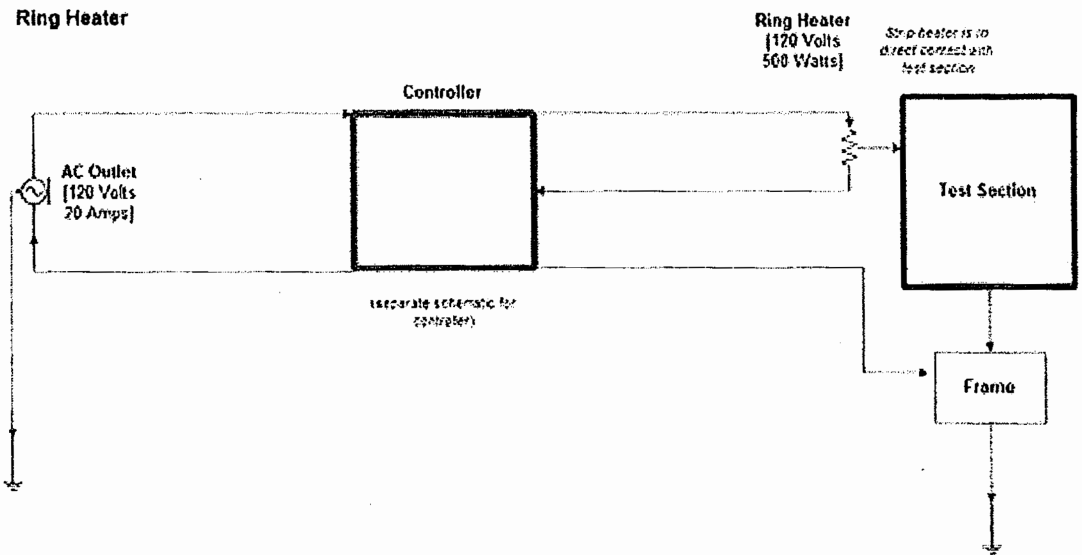
Strip Heater x2

120 Volts
4.2 Amp

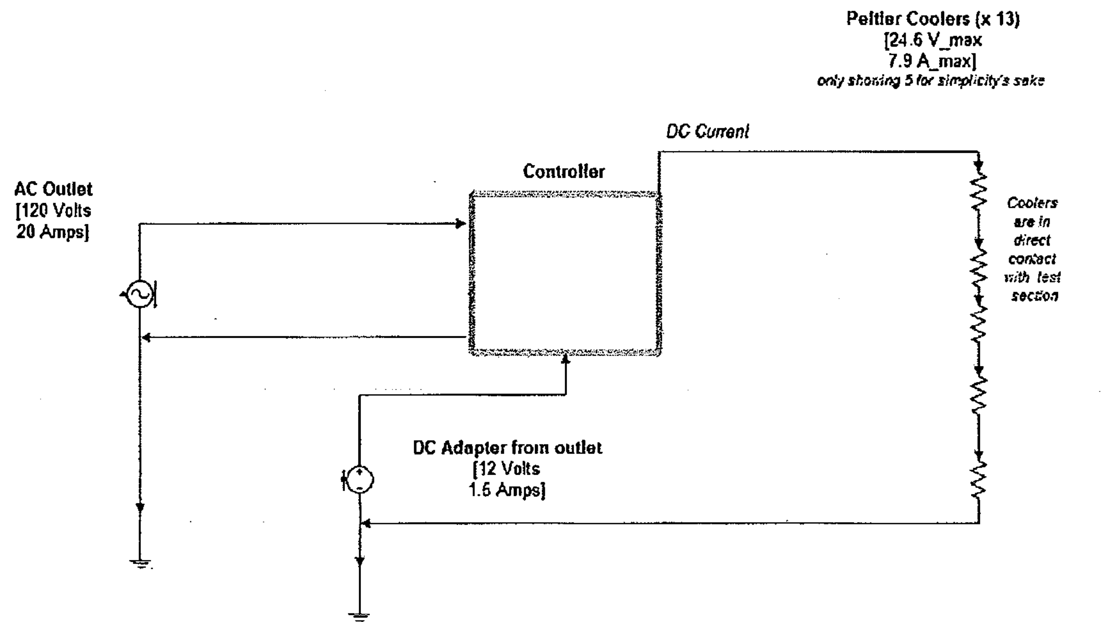
500 Watts



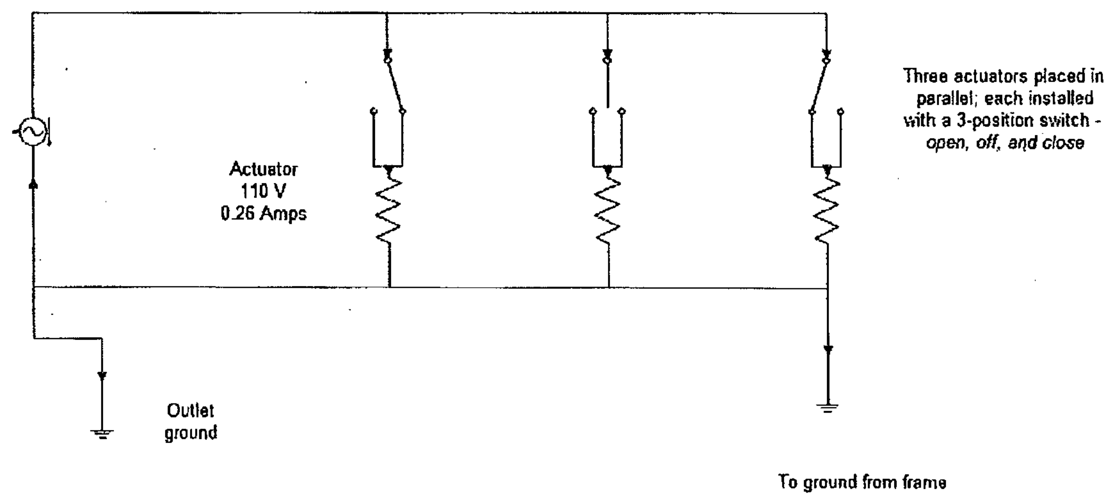
Ring Heater



Peltier Coolers



Actuator + Electronic Valve



	SODIUM NATURAL CONVECTION NERI-037	Identifier:	CAES –P–024	
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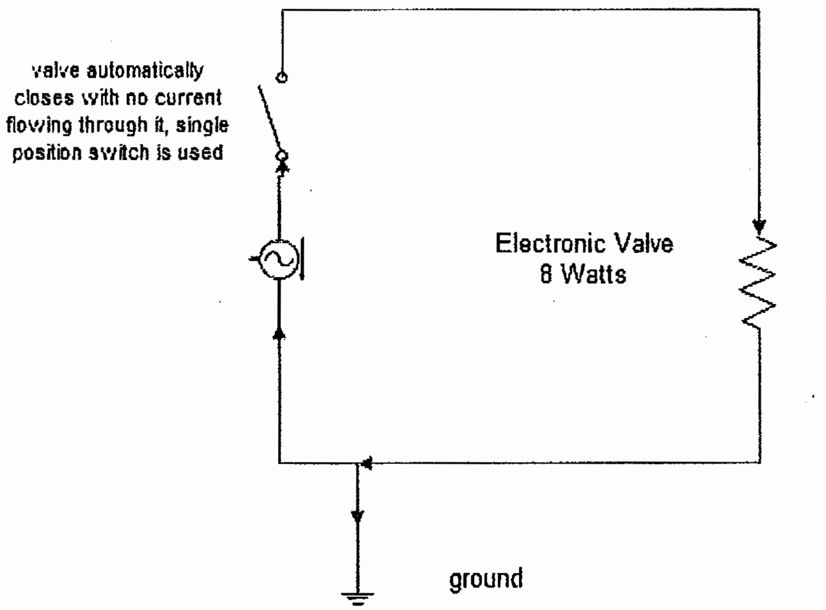
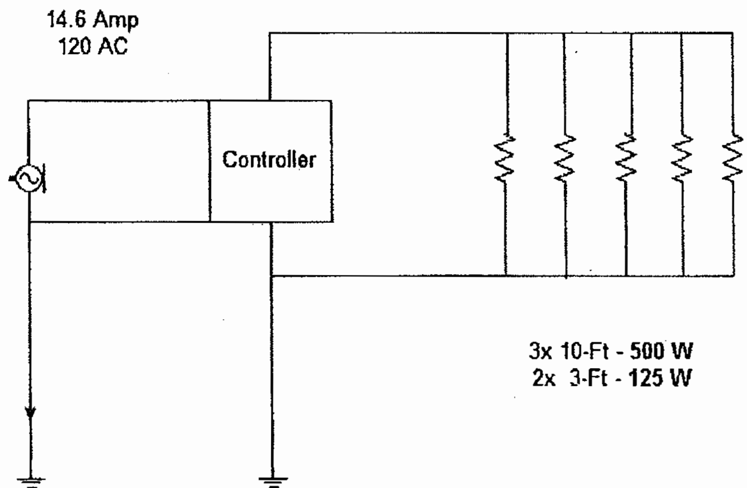
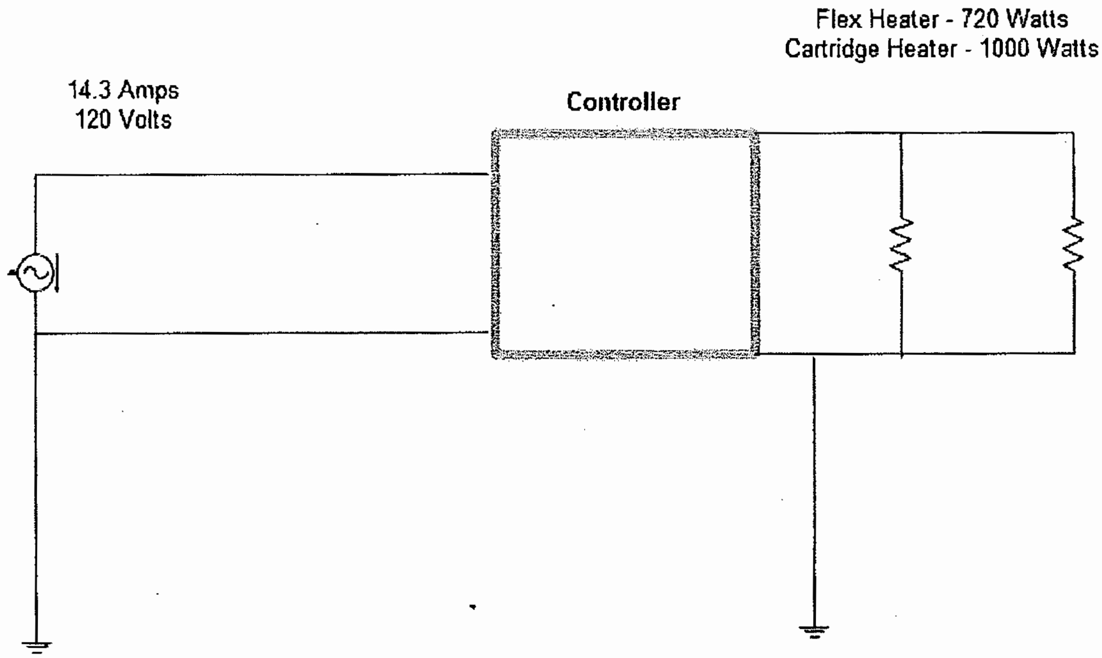
Electronic Valve (Gas Line)



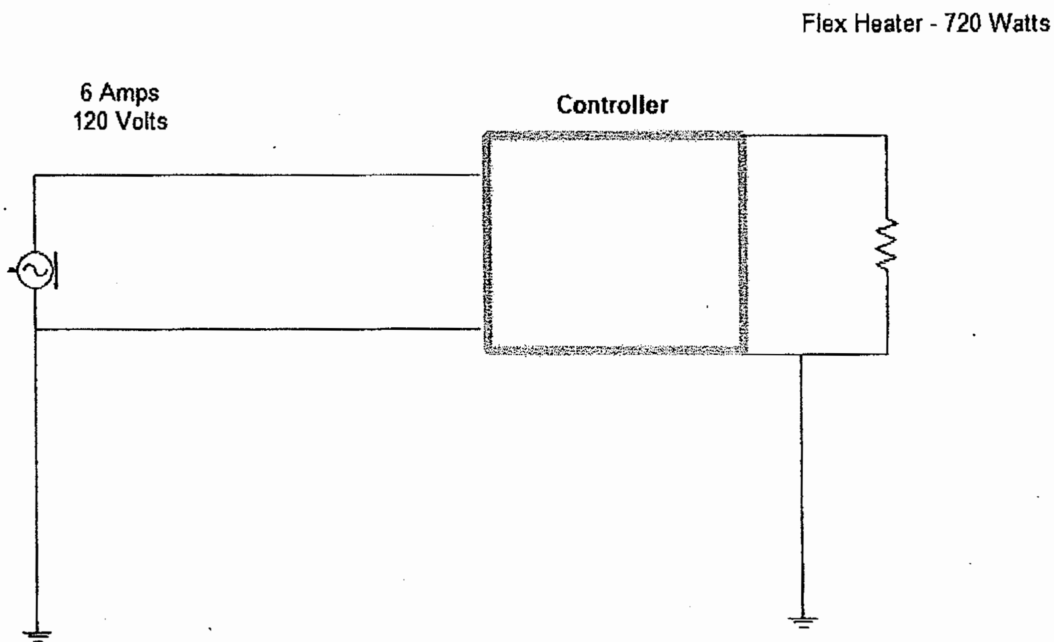
Rope Heaters



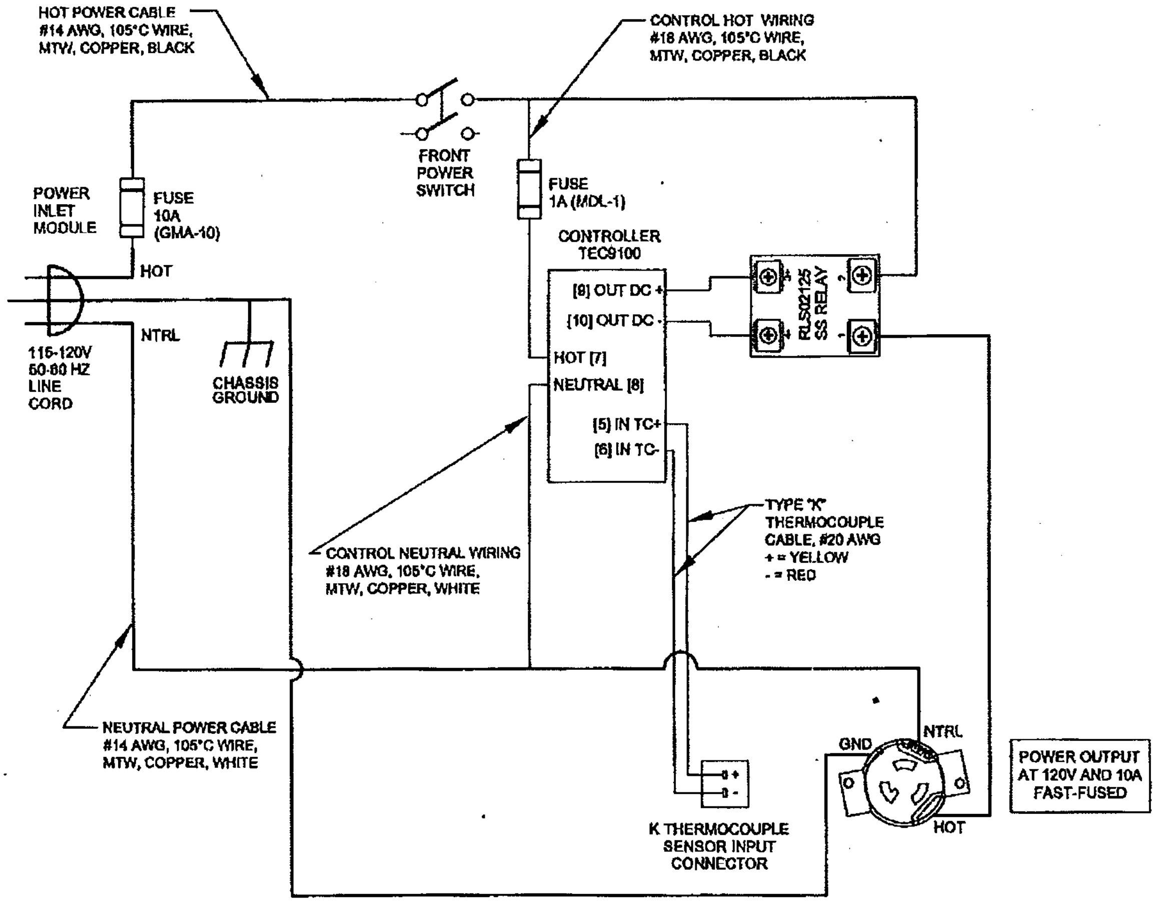
Lower Transfer Tank



Upper Transfer Tank

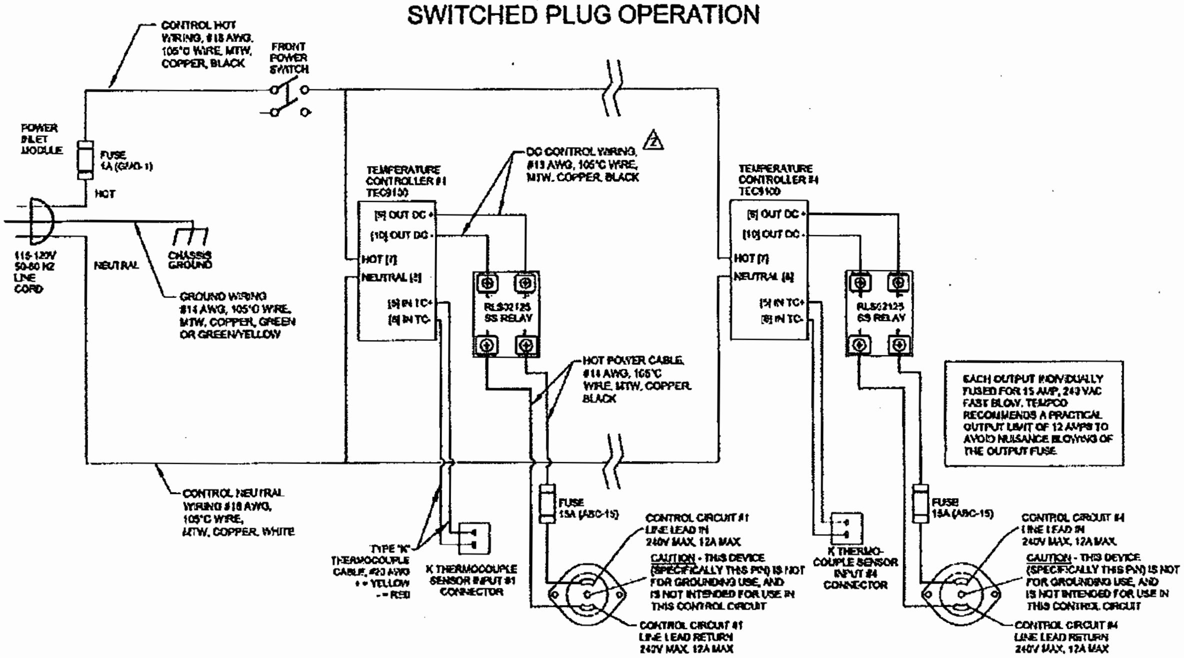


TPC10008 CIRCUIT DIAGRAM K THERMOCOUPLE, 120V POWER THRU CONSOLE DESIGN



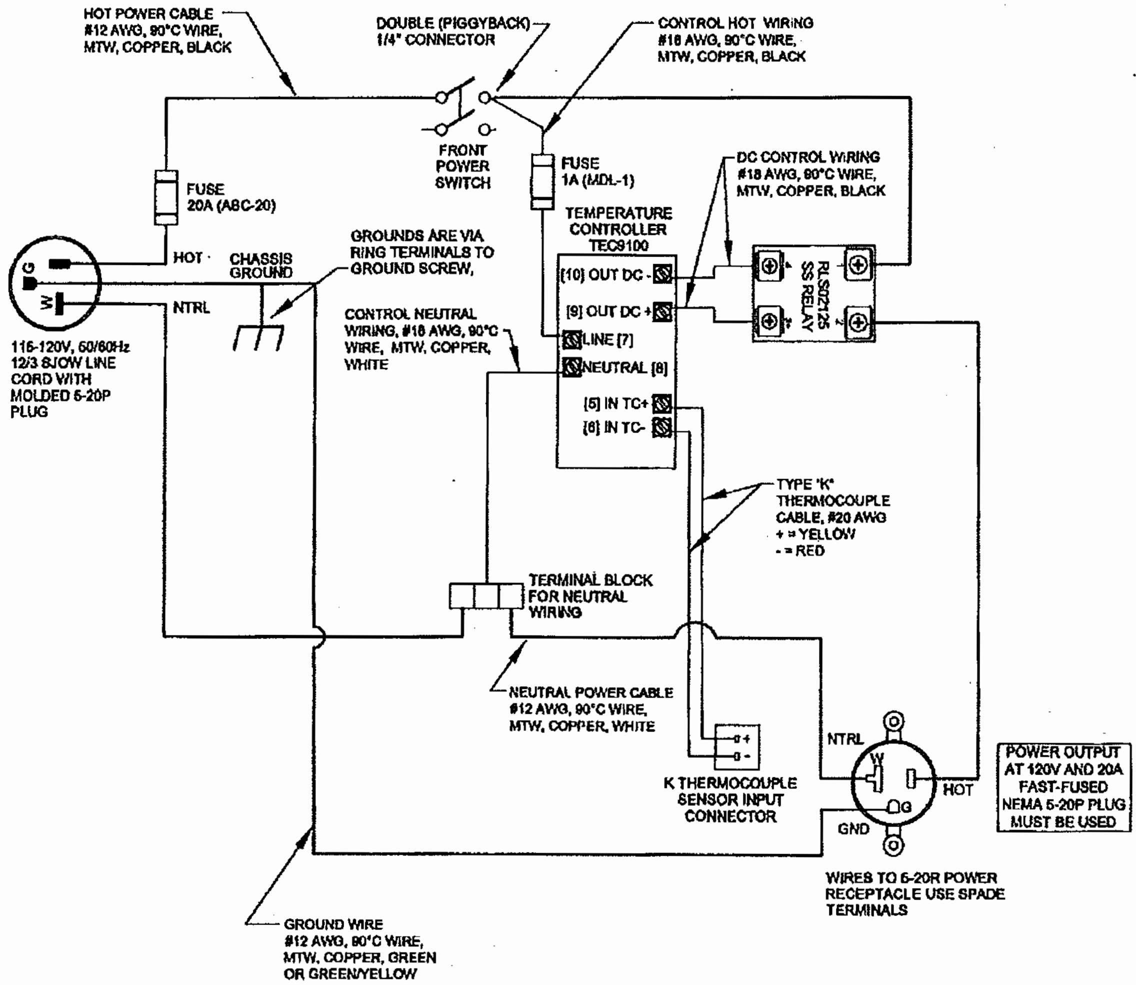
This specified controller (practical limit of 8 Amps) will be used for the strip heaters, and ring heater

TPC40002 CIRCUIT DIAGRAM
K THERMOCOUPLE, 120V POWERED CONSOLE
SWITCHED PLUG OPERATION



This controller will be used to monitor operating temperatures of the peltier coolers

TPC10029 CIRCUIT DIAGRAM
K THERMOCOUPLE, 120V POWER THRU CONSOLE DESIGN



These temperature controllers (practical limit of 16 Amps) will be used to control rope heaters, and transfer tanks.

Appendix C

References

1) DOE, NEUP09-321, Data Collection Methods for Validation of Advanced Multi-Resolution Fast Reactor Simulations, with U. Tenn. – Ruggles, ANL – Pointer, NEUP, $912,317.
2) DOE, NEUP07-037, "Experimental development and demonstration of ultrasonic and remote diagnostics for sodium fast reactor thermohydraulics", Department of Energy, Nuclear Energy Research Initiative, $549,730
3) R. Hill, ANL, Fast Reactor Curriculum Workshop, August 30-31, 2010 at Argonne National Laboratory

Appendix F. CAES Water Testing (Shakedown) for the Sodim Loop_Phase 2

CAES	WATER TESTING (SHAKE DOWN) FOR THE SODIUM LOOP_PHASE 2	Identifier: CAES – 1 Revision: 1 Effective Date: 2-27-2013	Page 1 of 15

ACTIVITY PRINCIPAL INVESTIGATOR, LAB LEAD, and SPONSORING ASSOCIATE DIRECTOR

PI(s): Akira Tokuhiro
LL: Travis McLing
AD: Bob Smith

ACTIVITY LOCATION BY LAB ROOM NUMBER: Fluids Lab (Room 117)

Principal Investigator, Laboratory Lead, and CAES Safety Officer Approvals

	Print	Sign	
Principal Investigator:	Akira Tokuhiro		Date:
Laboratory Lead:	Travis McLing		Date:
CAES Safety Officer:	Kristi Moser-McIntire		Date:

RESEARCH STAFF
David Kim
Nathan Seaver
John Downing

MAJOR EQUIPMENT USED IN ACTIVITY
Natural Convention Loop and Force Convention Loop

1. STATUS OF THE LOOP AND ADDITIONAL WORK TO BE DONE

This section addresses the state of the sodium loop in preparation for eventual experimentation using sodium (3/12/13). Listed are current processes and/or tasks, and (if applicable) conditions to be met and completed before the beginning of water testing. The water testing includes the heating of loop components with resistance heaters as well as leak detection. Cooldown is passively achieved with all heaters turned off. The reader should understand rudiments of 'process control' and 'experimentation' per short description below.

Process Control

Process control is here defined as actions taken to prepare the experimental equipment or 'apparatus' to a targeted thermal-physical condition. This targeted condition is often anticipated via a strategic matrix of conditions to be met, based on appropriate knowledge of the operational space of the equipment. During the 'startup' phase of the process control, safety measures are to be confirmed, monitored and re-confirmed with the end objective to reach the targeted condition. The experiment, defined below as experimentation, cannot be conducted unless all safety measures are confirmed.

In thermal-physical equipment, like the one here, there will be a startup procedure and a shutdown/cooldown procedure during which confirmation of safe processes are of importance. However, once the targeted condition is reached, safety concerns are monitored in the background as the experimentation is conducted. A schematic diagram is shown below of the three step process. It is important to make a distinction between *Process Control* that is safety-related and *Experimentation* which proceeds on confirmation of meeting safety conditions.

Experimentation

Experimentation is here defined as the phase of ongoing experimental runs wherein the safety of the equipment during the startup phase of the process control has been completed and the targeted condition is reached. Experimentation consists of measurements linked to the research objective and is thus, separate from process control. Measurements are taken typically under steady-state thermal-physical conditions or under known rates of change. Safety measurements are taken constantly throughout the experimentation phase to ensure that it will be safe to interact with the apparatus. In the event that process control aspects of the process are no longer satisfied, it will be considered as an off normal event and handled as outlined in the *Risk and Controls* section of this document.

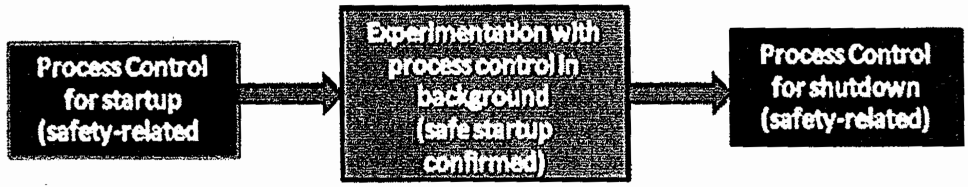


Figure. Flowchart of Safety-Related Process Controls relative to Experimentation

1.1 Natural Convection Experiment

A) Instrumentation

1. Thermocouples
    a. Check connectivity, placement and readings
        i. Thermocouples attached to temperature controllers for the strip heaters and ring heater are for process control, and therefore safety related
        ii. All thermocouples not identified in (i) are for experimentation purposes.
2. Heaters
    a. Wattage provided by heaters are able to reach and maintain an internal experimental temperature of 175 C.
        i. To be verified at the conclusion of the water shakedown testing. This is a safety related function.
    b. Wattage supplied via transfer tanks and rope heaters are sufficient to melt sodium and maintain as liquid.
        i. To be verified at the conclusion of the water shakedown testing. This is a safety related function.
3. UVP-DUO
    a. Verify UVP assembly and data collection within the test section
        i. Moving transducer in quiescent water up and down
        ii. Induced forced convection via bubbly flow

B) Sealing the test section (all Safety-Related)

1. Placement of outer cylinder
    a. Contact Westone - moving company place test section into outer cylinder
    b. Route thermocouple and electrical wires through outer cylinder ports
    c. Apply sealant to the ports
2. Connect natural convection test section to sodium loop
    a. Route gas lines
        i. Heat exchangers/cooling jacket (G-3)
        ii. Cover gas (G-4)
        iii. Gas Outlet
    b. Route sodium lines
        i. Transfer line (S-1)
        ii. Natural convection inlet (S-2)
        iii. Natural convection drain (S-4)

3. Seal the outer cylinder
    a. Place lid onto the outer cylinder
    b. Screw the lid on
    c. Plug and apply rector sealant around inlet and drain (S-2 & S-4)

1.2 Forced Convection Experiment

A) Instrumentation

1. Thermocouples
    a. Install thermocouple tree and confirm connectivity and readings inside test section.
        i. Thermocouple tree is for data collection only
    b. Install process control thermocouples
        i. Thermocouples attached to temperature controllers for rope heater, and ring heater are for process control, and therefore safety related
        ii. All thermocouples not identified in (i) are for experimentation purposes.
2. Temperature tests
    a. Wattage supplied via ring and rope heaters are sufficient to maintain an internal temperature of 175 C.
        i. To be verified at the conclusion of the water shakedown testing. This is a safety related function.
3. UVPs
    a. Mount them in the cooling jacket that is mounted to the actuator trolley.
        i. UVP transducers are for data collection purposes.

2. OPERATING PROCEDURES FOR VARIOUS ACTIVITIES

The following activities will be performed once the system is satisfactorily assembled per Section 1 of this document (*Status of the Loop and Additional Work to be done*). Aspects of this section can be distinguished as either Process Control or Experimental procedures. Process control procedures that are safety-related are noted below. These will be highlighted in color red to make them readily apparent. Parts of this document that are related to the steps taken to obtain data are thus part of Experimentation. Steps including "XXs" or "TBD" indicate that these fields will be determined during testing.

2.1 Leak and Residue Detection

- ☐ Place a sign on the door stating that there is an experiment in progress.SR
    - The sign will state the type of test (e.g. Leak test)
    - The sign will state the researchers name and contact info (phone number, email)
- ☐ Remove the Lower Transfer Tank (LTT) from the system by undoing the piping on the outflow side of the LTT's valves, uncoiling the rope heaters from the LTT, disconnecting

the blanket heaters that are mounted on the LTT, and removing the strapping that holds the LTT in place.

- ☐ Measure the weight of the empty tank using the digital scale in the Fluids Laboratory (CAES 113). The scale was moved to the Fluids Laboratory from the Analytical Chemistry Laboratory (CAES 210) and will need to be returned upon project completion.
- ☐ Ensure all of the tank's manual valves are closed (turn directions are labeled) and remove the gasket clamp and cap found on the bottom of the tank (See Figures 3, 4).
- ☐ Fill the LTT with ~9 L of tap water by measuring with a large open beaker found in the Fluids Laboratory (CAES 113) and pouring it in through the port opened in the bottom of the LTT (See Figure 4). This will require two people because one person will need to hold and secure the tank upside down while the other fills it with water.

- ☐ Replace the gasket cap and secure the clamp. Securing the clamp is done by tightening both sides evenly until they are very snug.
    - o Visually verify seal is not leaking before removing from the sink
- ☐ Measure the weight of the full tank using the scale in the Fluids Laboratory (CAES 113).
- ☐ Reinstall the LTT into the system by setting the LTT in position in the system, strapping the LTT in place, reconnecting the fittings that attached to the tank valves, reconnecting the tank's blanket heaters, and coiling the rope heaters.
- ☐ Wrap each joint with a colored paper towel using tape to secure it. In the event that any water leaks from a joint, the darkened spots on the colored towels will make noting them easier. Note: while paper towels are in contact with the system, the heaters will <u>NOT</u> be activated to avoid fire hazard.
- ☐ Open the LTT manual valves *sodium out*, *sodium in*, *gas out*, and *gas in*, identified in Figure 3, completely and ensure that the LTT vent is closed. Opening these valves will allow water to be sent into the entire system. Note: during water testing air is being used.

- ☐ Ensure that pressurized air is tied into the system so that it will flow through the argon lines (See Figure 1 to determine the correct inlet). The fume hood will provide the pressurized air supply.
- ☐ Open the supply line of the pressurized air source so that it is available to the system.
- ☐ Open valve G-6 and maintain the pressure of the LTT at (TBD) psi by using the G-6 line's throttle (See Figure 1).
- ☐ Open valve S-1 and the UTT vent to begin water flow (See Figure 2).
- ☐ Allow the water to flow to the UTT for about XXs (TBD) so that it may be assumed that the total volume has been transferred.

- ☐ Close valve S-1 then open the LTT vent and stop the airflow into the LTT (See Figure 2).
- ☐ Take time to inspect the LTT, UTT, and transfer line that is regulated by valve S-1 for leaks. Make appropriate adjustments if leaks found (i.e. tightening fittings using Swagelock spacer tool, replace defective fittings, re-apply Rectorseal 7).
- ☐ Open valve S-2 and allow the water to drain from the UTT into the natural convection test section (See Figure 2). This will take about XXs to complete.

- ☐ Take time to inspect the transfer line regulated by valve S-2 for leaks. Make appropriate adjustments if leaks found (i.e. tightening fittings using Swagelock spacer tool, replace defective fittings, re-apply Rectorseal).
- ☐ Open valve S-4 and allow the water to drain from the natural convection test section to the LTT (See Figure 2). This will take about XXs to complete.

- ☐ Close valves S-2, S-4, and the LTT vent (See Figure 2).
- ☐ Take time to inspect the transfer line regulated by valve S-4 for leaks. Make appropriate adjustments if leaks found (i.e. tightening fittings using Swagelock spacer tool, replace defective fittings, re-apply Rectorseal).
- ☐ Open valve S-1 and the UTT vent to begin water flow (See Figure 2). Close valve S-1 XXs after opening it, which will leave a portion of the system's water in the LTT. This will allow water to flow into the forced convection (FC) test section through both jets.
- ☐ While continuing to maintain pressure in the LTT, open valves S-6 and S-3 so that water can flow into the forced convection test section (See Figure 2)
- ☐ After the water has flowed for XXs, close valve S-6, close G-6, and open the LTT vent (See Figure 2).
    - o Water will continue to flow from the UTT for about XXs, after which valve S-3 may be closed.

- ☐ Take time to inspect the transfer lines regulated by valves S-6 and S-3 for leaks. Make appropriate adjustments if leaks found (i.e. tightening fittings using Swagelock spacer tool, replace defective fittings, re-apply Rectorseal).
- ☐ Open valves S-5 and S-6 to allow the outer and inner weirs of the test section to drain to the LTT (See Figure 2). This will take about XXs.
- ☐ Take time to inspect the transfer line regulated by valve S-5 for leaks. Make appropriate adjustments if leaks found (i.e. tightening fittings using Swagelock spacer tool, replace defective fittings, re-apply Rectorseal).
- ☐ Take time to inspect the entire system for leaks. Make appropriate adjustments if leaks found (i.e. tightening fittings using Swagelock spacer tool, replace defective fittings, re-apply Rectorseal).
- ☐ Repeat parts of the process where leaks occurred until there are no detectable leaks.

- ☐ Drain the entire system to the LTT by opening the LTT and UTT vents, valves S-1 through S-6 (See Figure 2). Allow the system to drain for at least XXs to ensure complete draining.
- ☐ Seal off the LTT completely by closing all of its manual valves (See Figure 3). Disconnect the LTT from the system by undoing the piping on the outflow side of the LTT's valves, uncoiling the rope heaters from the LTT, disconnecting the blanket heaters that are mounted on the LTT, and removing the strapping that holds the LTT in place. Remove the LTT and record its weight.
    - o Note: If the second recorded water weight is less than the first by more than one percent, the system will need to be dried following steps XXX of *Drying SOP*. Upon drying the system, refill the LTT, record its full weight, and run the water

through the entire system using the aforementioned processes (excluding the paper towels). This is crucial because a difference between the first and second weights shows that a residue of fluid is being left behind in the system. A residue of sodium greater than one percent the original amount left in the system is unacceptable on safety terms.

- Some of the loss during the first water testing may be due to drips or leaks. After the second water test, if the second recorded water weight is more than one percent different there may be another fault in the system. Inspect the FC test section and the UTT to see if there is water remaining in them.

2.2 Natural convection startup and experimentation process

- ☐ Ensure that the LTT has been installed in the system filled with 9L of water by having set the LTT in position in the system, strapped the LTT in place, reconnect the fittings that attached to the tank valves, reconnected the tank's blanket heaters, and coiled the rope heaters.
    - If the aforementioned step has not been completed, follow steps 1-7 of the *Leak and Residue Detection Process.*
    - If the readings that result from the following steps are not of the quality expected, micro-spheres (Expancel 551 DU 80) may be added to the water to enhance its readability. PH strips must be available to the researchers when disposing of the water if micro-spheres are used. The PH of the water must be neutral if it is to be dumped down a lab drain. Appropriate action (storage bucket, treatment, etc.) will be taken for disposal if the solution is not found to be neutral.
- ☐ Initialize all associated instrumentation: laptops, DAQ, LabView, DUO
- ☐ Open the LTT manual valves labeled *sodium out*, *sodium in*, *gas out*, and *gas in* completely and ensure that the LTT vent is closed (See Figure 3). This will allow water to be sent into the system.
- ☐ Ensure that pressurized air is tied into the system so that it will flow through the argon lines (See Figure 1 to determine the correct inlet).
- ☐ Open the supply line of the pressurized air source (fume hood) so that it is available to the system.
- ☐ Open valve G-6 and maintain the pressure of the LTT at (TBD) psi (See Figure 1).
- ☐ Open valves S-1 and S-2 and the UTT vent (See Figure 2).
- ☐ Allow the water to flow to the UTT for about XXs (TBD) so that it may be assumed that the total volume has been transferred to the natural convection test section.
- ☐ Close valve G-6 to stop the airflow to the LTT and open the LTT vent (See Figure 1).
- ☐ Close valve S-2.
- ☐ Take initial temperature readings of the NC test section and record them in the designated lab notebook.
- ☐ Activate the heaters and coolers of the NC test section to induce natural convection.
- ☐ Allow the heaters and coolers to operate until steady state conditions are obtained. Steady state is considered obtained when the hot side to the cold side temperature difference is maintained at 30 DGC for 30 minutes, while bulk temperature profile remains constant (fluctuations within .5 DGC)
- ☐ Make desired measurements (outlined measurements can be found in *Natural Convection Measurement Procedures*).

- Keep an eye out for off normal events (i.e. leaks, over/under heating). If an off normal event occurs make note of the occurrence and resolve it if possible. Continue taking measurements once the event has been resolved.

- ☐ Deactivate heater and coolers.
- ☐ Open valves S-2 and S-4 to allow the water to drain completely into the LTT (See Figure 2). Draining time will be about XXs.
- ☐ Power down instrumentation and unplug all system components (i.e. heaters, computers, DAQ, Duos) from their wall outlet power sources.
- ☐ Use infrared temperature gun to verify safe handling temperatures (< 30 C).
- ☐ Close all of the manual valves of the LTT
- ☐ When water testing has been concluded, disconnect the LTT from the system by undoing the piping on the outflow side of the LTT's valves, uncoiling the rope heaters from the LTT, disconnecting the blanket heaters that are mounted on the LTT, and removing the strapping that holds the LTT in place. Record the LTT weight. Note whether or not the second measured fluid weight is within one percent of the loaded weight before experimental startup.
    - If residue weight returns within 5% (as stated under RCRA regulations) of the initial loading weight then the system is considered fully drained and the residue can be neglected. Note: the residue measurements can be used as a benchmark for sodium testing.
    - If residue weight returns greater than 5%, then residue cannot be neglected, and special care must be taken after sodium testing.

2.2 Forced convection startup and experimentation process

Internal test section status can be verified visually throughout startup, experimental and shutdown processes though the use of webcams.

Startup Process:

- ☐ Ensure that the LTT has been installed in the system filled with 9L of water by having set the LTT in position in the system, strapped the LTT in place, reconnected the fittings that attached to the tank valves, reconnected the tank's blanket heaters, and coiled the rope heaters.
    - If the aforementioned step has not been completed, follow steps 1-7 of the *Leak and Residue Detection Process.*
    - If the readings that result from the following steps are not of the quality expected, micro-spheres (Expancel 551 DU 80) may be added to the water to enhance its readability. PH strips must be available to the researchers when disposing of the water if micro-spheres are used. The PH of the water must be neutral if it is to be dumped down a lab drain. Appropriate action (storage bucket, treatment, etc.) will be taken for disposal if the solution is not found to be neutral.
    -
- ☐ Initialize all associated instrumentation: laptops, DAQ, LabView, DUO
- ☐ Open the LTT manual valves labeled *sodium out*, *sodium in*, *gas out*, and *gas in* completely and ensure that the LTT vent is closed (See Figure 3). This will allow water to be sent into the system.
- ☐ Ensure that pressurized air is tied into the system so that it will flow through the argon lines (See Figure 1 to determine the correct inlet).

- ☐ Open the supply line of the pressurized air source (fume hood) so that it is available to the system.
- ☐ Open valve G-6 and maintain the pressure of the LTT at 5 psi (See Figure 1).
- ☐ Open valve S-6 to fill the forced convection test section with water for XXs.
- ☐ Close valve S-6

Experimental Process:

- ☐ Open valves S-1 and the UTT vent (See Figure 2).
- ☐ Allow water to flow to the UTT for XXs then close valve S-1.
- ☐ Open valves S-3 and S-6.
- ☐ Take desired measurements for up to XXs and then close valve S-6, open the LTT vent, and close valve G-6 (See Figures 1, 2).
- ☐ Open valve S-5 to drain the overflow area of the test section (See Figure 2). This will take XXs.
- ☐ Close valves S-3 and S-5.

If repeating experiment follow next three steps, otherwise, continue to Shutdown Process.

- ☐ Close LTT vent.
- ☐ Open G-6 and maintain LTT pressure at 5 psi.
- ☐ Repeat experimental process.

Shutdown Process:

- ☐ Open valves S-5 and S-6 to drain inside and outside weir. This will take XXs.
- ☐ Close UTT vent.
- ☐ Open G-2 and maintain UTT at 2-3 psi. Maintain for XXs. This will clear any residue in the gravity jet line.
- ☐ Close G-2 and S-3. Open UTT vent
- ☐ Close S-5 and S-6.
- ☐ Power down instrumentation and unplug all system components (i.e. heaters, computers, DAQ, Duos) from their wall outlet power sources.
- ☐ Use infrared temperature gun to verify safe handling temperatures (< 30 C).
- ☐ Close all of the manual valves of the LTT
- ☐ When water testing has been concluded, disconnect the LTT from the system by undoing the piping on the outflow side of the LTT's valves, uncoiling the rope heaters from the LTT, disconnecting the blanket heaters that are mounted on the LTT, and removing the strapping that holds the LTT in place. Record the LTT weight. Note whether or not the second measured fluid weight is within one percent of the loaded weight before experimental startup.
    - o If residue weight returns within 5% (as stated under RCRA regulations) of the initial loading weight then the system is considered fully drained and the residue can be neglected. Note: the residue measurements can be used as a benchmark for sodium testing.
    - o If residue weight returns greater than 5%, then residue cannot be neglected, and special care must be taken after sodium testing.

3. RISK AND CONTROLS

The safety related equipment and hazards are identified and listed as follows:

- Heaters (blanket, rope, strip, ring) – electrical (>50V), high temperatures
- Gas valves – failure could result in over pressurization of the system (>15psi)

Table 2.1 Risks and controls (replicate table as many times as necessary to describe the hazards of your project).

This table is for information purposes only. Delete this table prior to submitting the plan for review.		
Task: *Leak Testing*	**Hazard(s)**	Pooling water / electrical shortage
	Engineering Control(s)	Certified electrician completed wiring. Wiring is insulated and protected. Rectorseal 7 has been used on threaded fittings to help prevent leaking
	Administrative Control(s)	At least one researcher will be monitoring the testing during operation. The testing will only be operated during normal working hours (6:00am to 6:00pm). Signs indicating that the testing is underway will be posted.
	PPE	Safety glasses will be worn by all researchers in the Fluids Laboratory (CAES 113) at all times.
	Special Instruction(s)	Upon identifying a leak, shutdown and clean up should immediately occur. Fix leak before resuming testing activities.
	Task Specific Training	

Task: Experimental Water Testing	**Hazard(s)**	Hot Surfaces, Hot Water, Overheating
	Engineering Control(s)	Two researchers will be monitoring the experiment during operation. The experiment will only be operated during normal working hours (6:00am to 6:00pm). Thermocouples will monitor the system's temperature at various locations. Leak testing will have been performed previously to lower the possibility of water leaking from the system.
	Administrative Control(s)	Signs indicating that the experiment is hot and active will be posted.
	PPE	Safety glasses will be worn by all researchers in the Fluids Laboratory (CAES 113) at all times.
	Special Instruction(s)	Researchers are not to touch the system while it is heated. If the system overheats by ~15DGC it will be promptly powered down before the issue is resolved.
	Task Specific Training	

Task: Experimental Water Testing	**Hazard(s)**	Over Pressurization (>15psi)
	Engineering Control(s)	Two researchers will be monitoring the experiment during operation. The experiment will only be operated during normal working hours (6:00am to 6:00pm). Pressure indicators are installed on all appropriate lines and equipment.

		A single switch activates electronic actuated valves to release any over-pressurization. Electronic switches are plugged into the fume hood (back-up power is provided)
	Administrative Control(s)	Signs indicating that the experiment is hot and active will be posted.
	PPE	Safety glasses will be worn by all researchers in the Fluids Laboratory (CAES 113) at all times.
	Special Instruction(s)	Researchers are to depressurize the system if a pressure buildup >15psi is observed at any location in the system.
	Task Specific Training	

4. WASTE GENERATION

Type of Waste	Anticipated Volume	Container Type	Disposal Responsibility
Non rad waste, water, paper towels, etc.	~9L of water, ~1L of paper towels	Sink drain (water), waste basket (paper towels)	Researchers will dispose of the water and paper towel waste generated by the experimenting and testing.

List any special needs/requirements for storage and handling and disposal of wastes.
If a spill occurs, how will it be cleaned up? Paper towels will be used to mop up any spilt water. If the leak cannot be stopped easily (i.e. by tightening a joint) then the system will be depressurized until it is resolved.

5. DRAWINGS AND DIAGRAMS

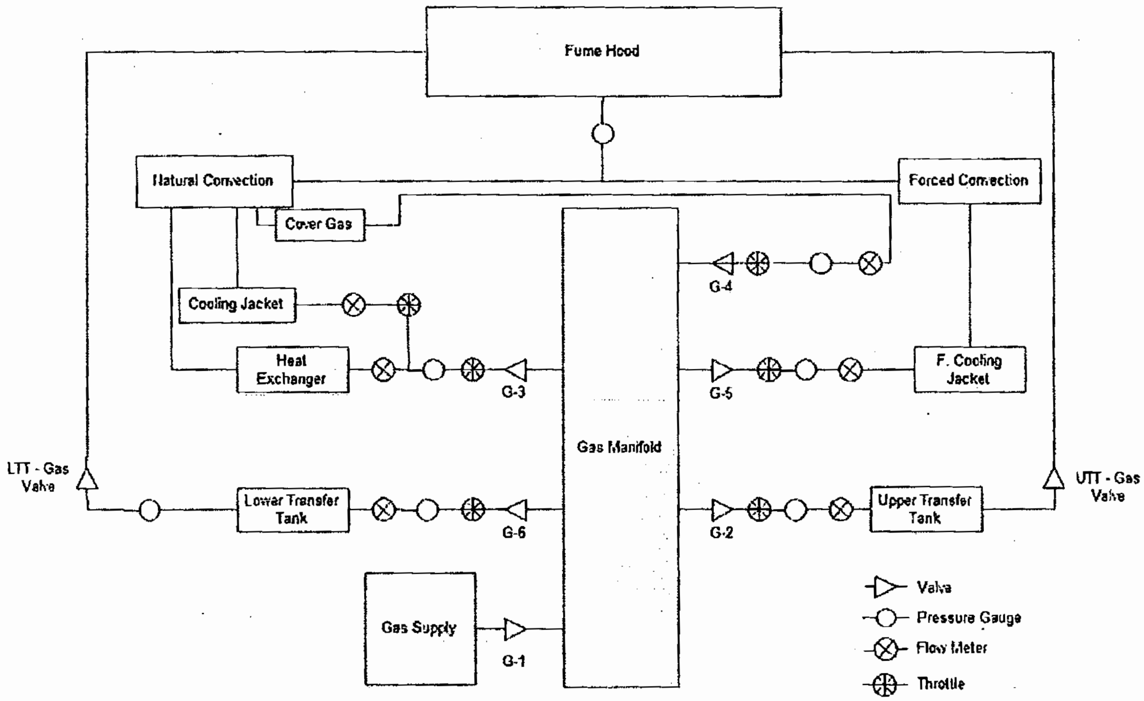


Figure 1 Gas line diagram.

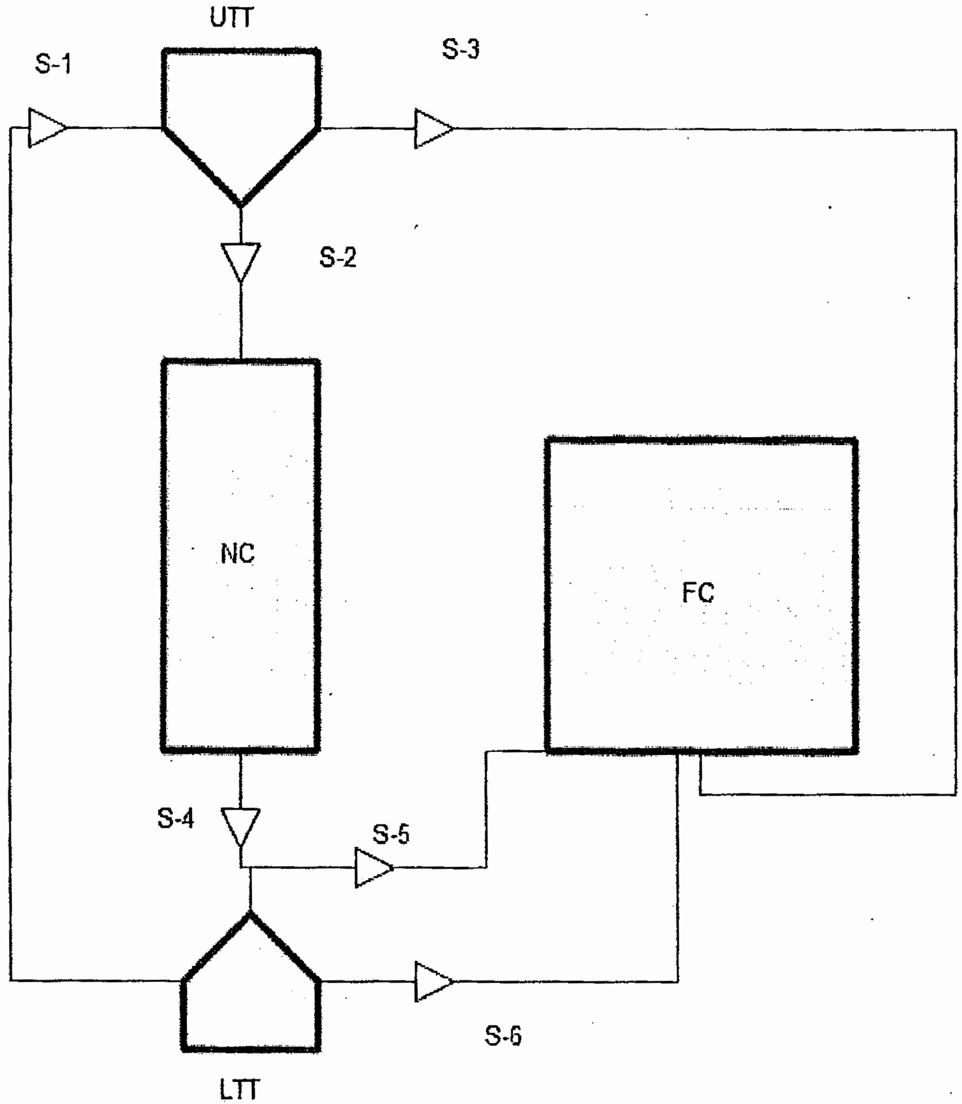


Figure 2 Sodium line diagram.

DOCUMENT COMMENTS

This document is a living document. Please provide recommendations below so that your inputs can be reviewed and incorporated into the next revision of this document.			
Contributor Name	Document Section	Comment	Date

APPENDIX A

CHEMICAL INVENTORY

(Chemical hazards are captured in the body of the Project Plan - this section only provides a list of chemicals used in execution of the plan.)

Name	CAS Number	NFPA	Maximum Storage Volume	Comments
		Health - Fire - Reactivity -		