ANL-ART-126

FY 2017 Progress Report on the Argonne Sodium Draining and Refilling Experiments

Nuclear Engineering Division

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FY 2017 Progress Report on the Argonne Sodium Draining and Refilling Experiments

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ABSTRACT

The main incentive for utilization of compact diffusion-bonded sodium-to-CO_2 heat exchangers for a Sodium-Cooled Fast Reactor (SFR) with a supercritical carbon dioxide (sCO_2) Brayton cycle power converter is the potential for reduction in heat exchanger size and cost relative to traditional shell-and-tube technology. There is an incentive for the designer to reduce the width of the sodium and CO_2 channels as much as possible to realize the greatest size and cost reductions. However, there are practical limits on minimum channel size due to fundamental phenomena particular to sodium and CO_2. One is that the channel size must be large enough to enable the rapid draining of sodium from the heat exchanger sodium channels in the event that a sodium leak is detected in an intermediate sodium heat transport system loop, in order to rapidly drain the sodium into the loop sodium storage vessel/tank and thereby limit the sodium mass released that could potentially burn if exposed to air. Information about the minimum sodium channel size can only be obtained by actually draining sodium from representative wetted stainless steel sodium channels under prototypical conditions. It is not possible to obtain such information through modeling and simulation or through simulant experiments. The ANL Sodium Draining and Refilling experiment facility has been designed and is being assembled to obtain data on the draining of sodium from compact diffusion-bonded sodium-to-carbon dioxide heat exchanger sodium channels including the mass of sodium drained versus time, the mass of sodium retained inside of the channels, and the potential for sodium to bridge the channel, freeze, and form a plug inside the channel versus the channel size. This information is needed to determine the minimum sodium channel size required to meet the requirements for sodium draining without bridges being left inside of the channels. Initial shakedown testing has been initiated using water and glass and plastic tubes before transitioning to sodium and stainless steel test sections. For the latter, the test sections will be heated to high temperature to promote rapid sodium wetting of the stainless steel prior to draining. Testing with sodium will be initiated in FY 2018.

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1 Introduction

The main incentive for utilization of compact diffusion-bonded sodium-to-CO_2 heat exchangers for a Sodium-Cooled Fast Reactor (SFR) with a supercritical carbon dioxide (sCO_2) Brayton cycle power converter is the potential for reduction in heat exchanger size and cost relative to traditional shell-and-tube technology. There is an incentive for the designer to reduce the width of the sodium and CO_2 channels as much as possible to realize the greatest size and cost reductions. However, there are practical limits on minimum channel size due to fundamental phenomena particular to sodium and CO_2.

In the event of the postulated rupture of a sodium pipe in a Sodium-Cooled Fast Reactor (SFR) Intermediate Heat Transport System (IHTS) sodium loop, it is desired to shut down the affected loop (i.e., to turn off the sodium pump in the affected loop) and to drain the sodium from the affected loop into its sodium storage vessel/dump tank. It is typically required to drain the sodium in about twenty minutes or less to limit the amount of sodium that is released and that can potentially burn if exposed to air. Utilization of the supercritical carbon dioxide (sCO_2) Brayton cycle with a SFR requires a sodium-to-CO_2 heat exchanger that meets the drainage requirement. For a traditional shell-and-tube heat exchanger, the requirement should be readily met as it is analogous to draining sodium from a sodium-heated steam generator. However, for a compact diffusion-bonded sodium-to-CO_2 heat exchanger, it is less clear whether the requirement can be met due to the typically small dimensions of the sodium channels. To promote draining of sodium, the heat exchanger would likely be oriented vertically with vertical sodium channels. The channels must be large/wide enough such that sodium can freely drain within the specified timeframe (e.g., twenty minutes). Significantly, the draining process must not give rise to sodium bridging the width of any of the channels and freezing such that the sodium might be retained inside of the channel. If that were to happen, then air subsequently entering the channel could oxidize the retained sodium. Because sodium oxide melts at a significantly higher temperature than the loop operates, it would not be practical to melt out the plug. It is possible to dissolve away a sodium oxide plug by washing it with relatively pure (of dissolved oxygen) sodium, but that could take a long time (e.g., weeks or longer). Thus, it is essential to understand sodium draining phenomena from compact diffusion-bonded heat exchanger sodium channels as well as the phenomena in refilling the sodium channels with sodium such that the heat exchanger can be designed correctly with sufficiently large sodium channels.

This document provides a status report on the design and assembly of the Argonne National Laboratory (Argonne) Sodium Draining and Refilling experiments. The objective of the experiments is to provide fundamental information on the draining and refilling of sodium from compact, diffusion-bonded, sodium-to-CO_2 heat exchanger sodium channels such that the sodium channels can be designed to be large enough to enable efficient draining of sodium from the heat exchanger. Information about the minimum sodium channel size can only be obtained by actually draining sodium from representative wetted stainless steel sodium channels under prototypical conditions. It is not possible to obtain such information through modeling and simulation or through simulant experiments. During FY 2017, significant progress was made on assembling, operating, and troubleshooting the test facility. Assembly of the modified design was completed, and shakedown water tests were performed. Unfortunately, it was not possible to generate sodium data before the end of FY 2017 due to the water testing that revealed minor operational issues that took longer than expected to resolve.

2 Sodium Draining and Refilling Experiment Facility Design

The Sodium Draining and Refilling experiment was designed to be a small-scale pressure driven experiment utilizing a minimum amount of sodium to fill and drain test sections of different cross section geometries to study the behavior or sodium draining in these channels. It was built as an experiment where test sections are installed, wetted with sodium, and drained into a vessel that measures the sodium volume over time. The design of the experiment to accomplish all of these functions is complicated, and takes considerable time to learn how to operate. For that reason, a preliminary testing phase was added where water is used in place of sodium for shakedown testing of the experiment. The properties of water are roughly similar to sodium with the exception of surface tension and allow for safe testing of experiment systems. This allowed the testing of the pressure control system, checking the operation of the valves, testing the load cell output, data acquisition, and sensors and controls. A glass test section was used to enable viewing of the water in the test section. This viewing ability is quite valuable since in the actual sodium tests the operator cannot see the level of the fluid in the test section. Many water tests need to be performed and documented to understand the proper operational procedures and best practices of the system. This is what has been done if FY2017, and is still underway.

2.1 Major Component Design Descriptions and Status

2.1.1 Sodium Draining and Refilling Assembly

The current design of the Sodium Draining and Refilling test assembly is shown in the schematic in Figure 1. In FY 2016, it was decided to revisit the original design of building a test system that is capable of real time measurements of draining sodium from test sections into a vessel. During the FY 2017, the system was completed and became operational.

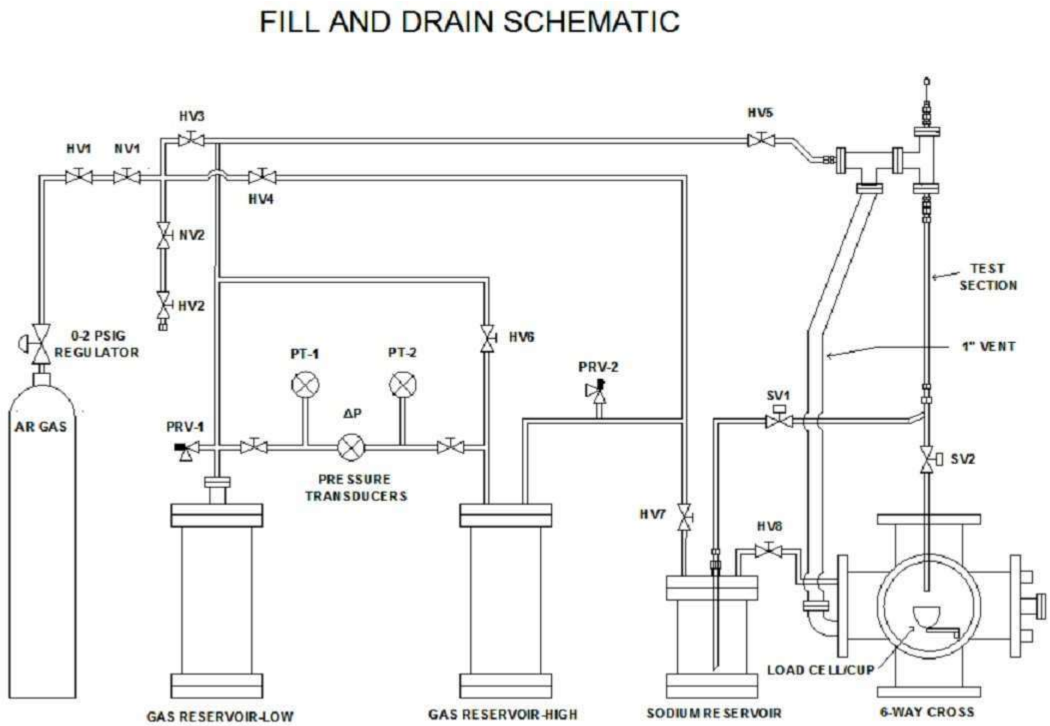

Figure 1: Latest sodium filling and wetting test assembly schematic.

As indicated in the schematic, the system is designed with one fluid reservoir (containing water or sodium), and two gas reservoirs. The "Sodium Reservoir" contains the sodium or water, with the test section mounted vertically above. Reservoir P1 is the gas reservoir that operates at a lower pressure and is connected to the space at the top of the test section. Reservoir P2 operates at a higher pressure and is connected to the gas space in the sodium reservoir. Pressurizing this gas space forces liquid up the dip tube and up into the test section. By holding this pressure steady, the sodium or water can be precisely held at any level in the test section. The differential pressure between P1 and P2 determines the height of the column of liquid in the test section. A photo of the completed system is shown in Figure 2.

Figure 2: The current improved configuration of the Sodium Draining and Refilling experiment, showing the stainless steel test section in place during water testing.

The key to the new system is the addition of a real-time sodium draining data capability. The measurement of small quantities of molten sodium requires a precise measuring system that can tolerate elevated temperatures and exposure to sodium, as well as capacity to collect high speed data in a fraction of a second. This was accomplished with the use of a custom made beam-type high speed load cell for measuring loads up to 500 grams capable of temperatures up to 230 °C, with an appropriate amplifier. The load cell is mounted inside an 8" 6-way conflat vacuum cross, where the sodium is drained into a cup, which is mounted to the load cell. The use of a vacuum vessel is necessary due to the sodium draining into an open top cup, and being exposed to the environment inside the vessel.

The operation of the system is dependent on the type of fluid being tested. Sodium testing requires evacuation with a vacuum pump followed by backfilling with Argon gas. This step is not required when water testing, and the 6-way cross can have the viewing port open for ease of cleanup after a draining event. The system is designed with one fluid reservoir (containing water or sodium), and two gas reservoirs, and a 6-way cross. Increasing the pressure in the gas space above the liquid forces liquid up into the dip tube and up into the test section. By holding this pressure steady, the sodium or water can be precisely held at any level in the test section. The differential pressure between Reservoir No. 1 and Reservoir No. 2 determines the height of the column of liquid in the test section. After the sodium is pushed to the desired elevation, valve SV-10 is closed, and the sodium is held in the test section long enough to accomplish wetting of the inside surface at the temperature to which the test section is heated. When it is time to drain the sodium into the cup, valve SV-9 is opened and the sodium drains into the cup contained inside the 6-way cross.

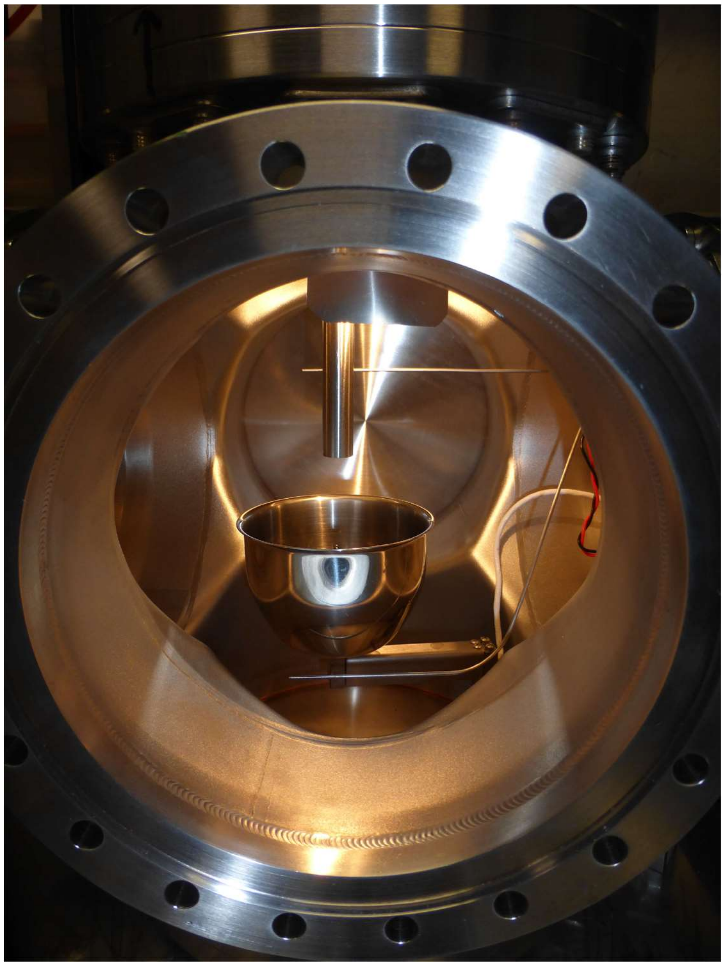

Figure 3: View inside the 6-way cross showing the sodium catch cup and thermocouples, as well as the internal illumination system.

Inside the 6-way cross, shown in Figure 3, the load cell is mounted on a short stand bolted to the bottom flange. On the opposite end of the load cell is a stainless steel 6 ounce cup with a stud welded to the bottom, threaded into the load cell. This cup is easily replaceable which will aid in cleanup after sodium draining experiments.

The design of the transfer tubing was done to minimize the amount of test fluid (other than what is in the test section) that would be drained into the catch cup. Figure 4 shows the transfer line installed with the two electro pneumatic sodium valves. Note the short incline on the end of the horizontal run (circled in red), this feature keeps the fluid that is in the horizontal tube from draining into the vertical tube and into the catch cup.

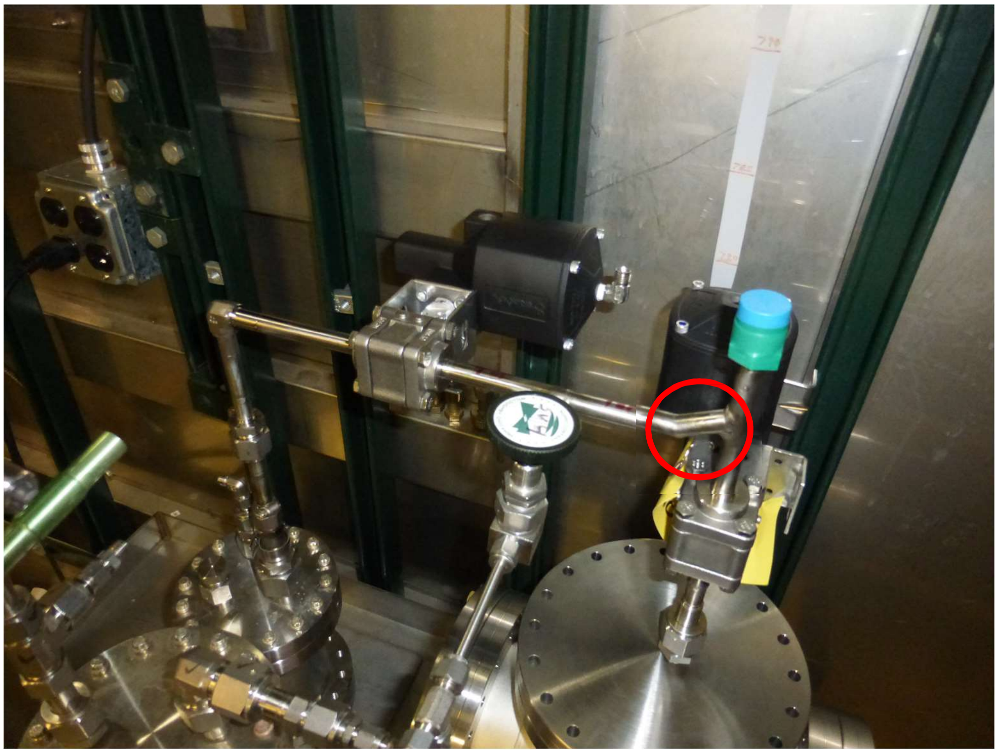

Figure 4: Transfer tube with valves, showing incline feature to minimize excess fluid drained into cup.

2.1.2 Heaters, Controls, and Data Acquisition

In the Draining and Refilling test apparatus, only the sodium reservoir, test section, and 6-way cross need to be heated. Therefore, minimal heaters and zones are needed for the experiment. All necessary heaters have been received and await installation. Figure 5 shows the heaters that are planned for the sodium transfer line. These heaters were custom ordered and are shown during a fit up to check installation. The 6-way cross will be heated over a portion of its surface with custom mica band heaters to ensure that the sodium that drains into the cup stays molten. The test section will be heated with radiant band heaters.

Figure 5: Sodium Draining and Refilling transfer line heater placement.

The heaters are powered and controlled by an industrial control chassis. The control chassis for this experiment utilizes PID process controllers with the ability to monitor two thermocouples per control zone, one for control and one for overtemperature. This is done to make sure we avoid a situation where we have a false temperature signal and overheat the experiment. The overtemperature controller is a serarate controller that independently monitors the zone temperature and can cut heater power, if necessary. This control chassis was sourced from our inventory; it was previously used for another experiment. The control chassis required additional infrastructure power wiring to be installed to provide the necessary power for the unit. Once this was complete, the control chassis was connected and tested to ensure proper operation.

The experiment system uses high-speed, full port, high temperature sodum compatible ball valves. These were custom made by Swagelok, Inc. to our specifications. Once delivered, the valves were modified inhouse by installing feedback microswitches to monitor valve position. This was done to make sure the actual position of the valves was known at all times. Since it is not obvious by looking at the valves whether or not they are open or closed, during the operation of the experiment an unsafe situation could occur since we are working with molten sodium. Whenever an actuated valve is used in a potentially dangerous application, independent feedback is highly recommended. One of the sodium valves with actuator is shown in Figure 6.

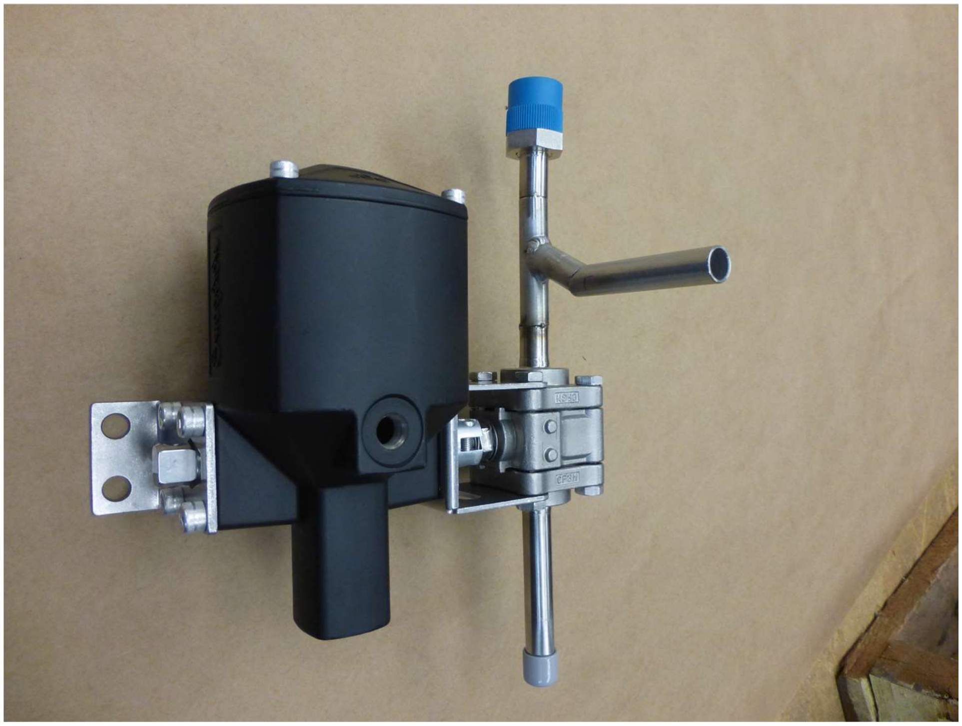

Figure 6: Electro-pneumatic sodium valve during tube weld procedure.

In order to control and monitor valve position, a power supply and control box was designed and built in-house. This box supplies 24 VDC to the valves, pressure transducers and the 6-way cross illumination system. The control box is shown below in Figure 7 and Figure 8.

Figure 7: 24 VDC power supply and electropneumatic valve control box.

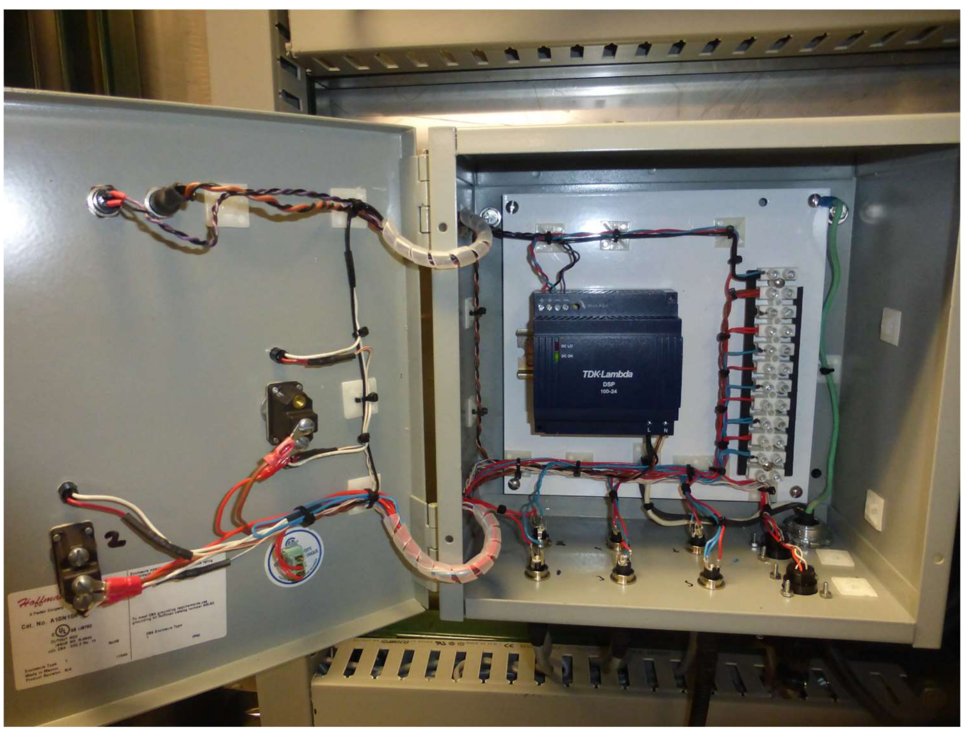

Figure 8: Internal components of 24 VDC control box.

Data acquisition for the experiment utilizes a standalone data logging recorder made by Hioki, shown in Figure 9. This recorder records the thermocouple temperatures on the test section, reservoir, and the thermocouple in the tee at the top of the test section. The recorder can operate with or without a PC and has a display to plot trends over time. This data recorded was purchased and initial testing of the recorded functions was performed.

Figure 9: Hioki data logger used to record thermocouple temperatures.

The most challenging experiment data to monitor and record is the load cell output data. The load cell is capable of measuring high speed events up to 6 kHz. The load cell conditioner contains many features to filter out unwanted data and noise from the input signal. In order to record and plot the high speed data, a Yokogawa scopecorder (Dl850E) was acquired and is used for this purpose. This device combines a mixed signal oscilloscope and portable data acquisition recorder into a modular device to capture both high speed transients and low speed trends. This device is shown below in Figure 10.

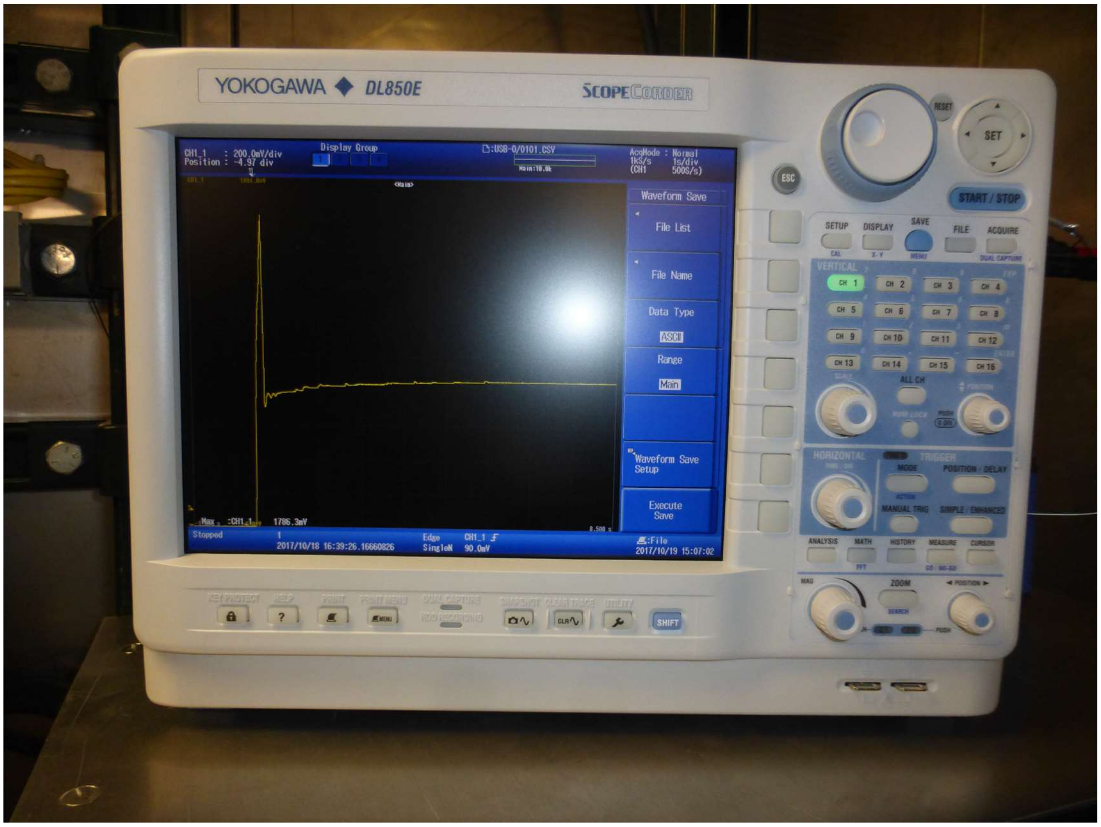

Figure 10: Yokogawa Scopecorder used to capture high speed data from the load cell.

2.1.3 Initial Test Sections

Three sets of test sections have been used for the shakedown testing activities. One set is made from glass, with a round cross section, and the other is made from stainless steel, also with a round cross section, in ¼", 3/8" and ½" diameters, with inside diameters of 0.175" 0.3", and 0.4" respectively. Plastic tubes were also used for testing. The glass and plastic test sections were only used for the water testing, and the stainless steel will be used for both the sodium testing and water testing. The inside dimensions for each type of test section used is shown below in Table 1.0.

Table 1. Comparison of test section tube sizes

TEST SECTION ROUND TUBE SIZE							
Nominal tube size (O.D.)		Stainless Steel (I.D.)		Glass (I.D.)		Plastic (I.D.)	
inches	mm	inches	mm	inches	mm	inches	mm
0.25	6.35	0.175	4.445	0.155	3.937	0.117	2.9718
0.375	9.525	0.3	7.62	0.2175	5.5245	0.26	6.604
0.5	12.7	0.4	10.16	0.375	9.525	0.375	9.525

Below in Figure 11 is a photo of the three different size stainless steel test sections.

Figure 11: Stainless steel round test sections.

During the wetting phase, the actual level of wetting on the inside of the test section will be unknown. This represents a potential problem, since the draining tests are to be performed with fully wetted test sections. In order to solve that issue, we have installed “resistivity probes” on the test section at three different locations. These probes allow us to measure the electrical resistance through the test section at those particular locations. The resistance is measured by applying a current across the probes, and measuring the voltage difference. It has been shown on other experiments that a noticeable change in measured resistance will occur during the wetting process. This is due to the change in path the electrical current takes. When the tube is not wetted, the current flows through the stainless steel tube material around the sodium. When the tube is wetted, the current flows straight through the sodium and to the other side, showing a decreased resistance. The modified probes with the probes attached are shown below in Figure 12.

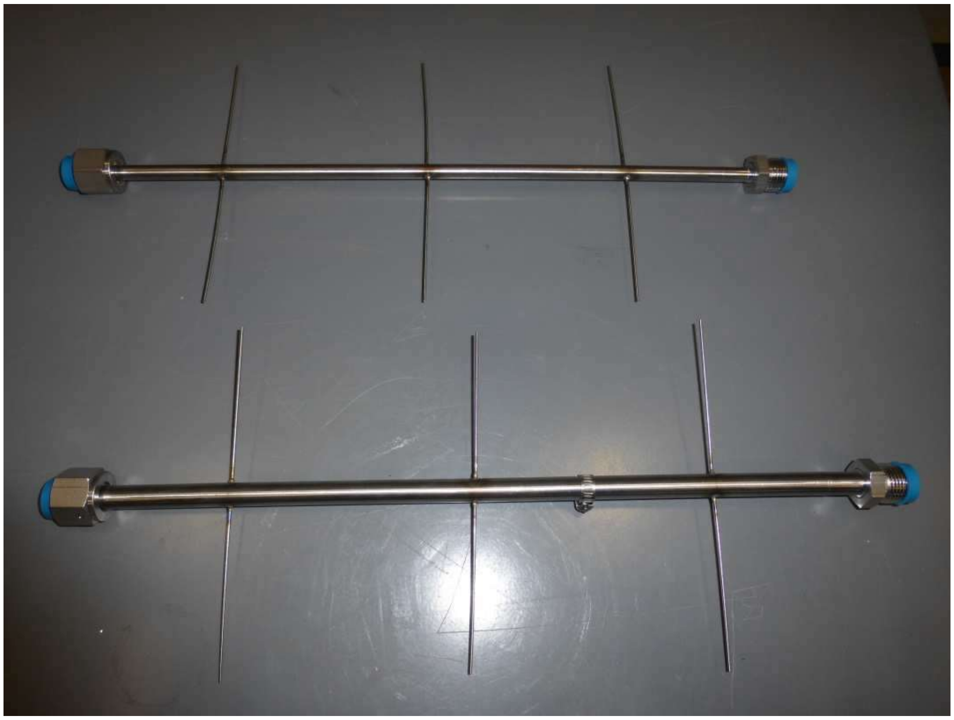

Figure 12: Test sections with probes attached.

2.1.4 Water Testing

After completion of the final design, water was used in place of sodium to test the operation of the system. For this testing, glass test sections were used instead of the stainless steel, so that the level of water would be visible in the test section. The sodium reservoir was filled with water, and Argon gas was used in the pressure system for testing. The sodium reservoir gas space was pressurized with Argon, and water was pushed up the test section while carefully controlling the pressure of the gas.

This water testing allowed testing of the overall experiment system, including the load cell and data acquisition system. Any problems that were found were easier to identify and correct due to the use of transparent test sections and water instead of sodium as a fluid.

During this testing, the use of glass test sections was found to be difficult due to the fragile nature of the material. Clear plastic tubes of the same O.D. were ordered and used in conjunction with the glass. Initial comparison tests investigating the difference in draining properties between glass and plastic test sections were performed, and are discussed below.

2.1.4.1 Repeatability Studies

Several drain tests were performed to investigate if the system was repeatable when doing multiple drains under the same conditions. Tests were done with the ¼”, 3/8” and ½” tubes in glass and plastic. In these tests, the test section was filled with water to the same elevation of the test section, and the cup was emptied after each run to see if the draining event was repeatable.

Below, a ¼" O.D. glass test section was used to test the repeatability of the results.

All of the load cell data plots exhibit a rapid rise to a peak, a rapid decrease, and a following gradual rise. This is because the load cell measures both the impact force of the impinging liquid plus the weight of liquid collected inside of the cup.

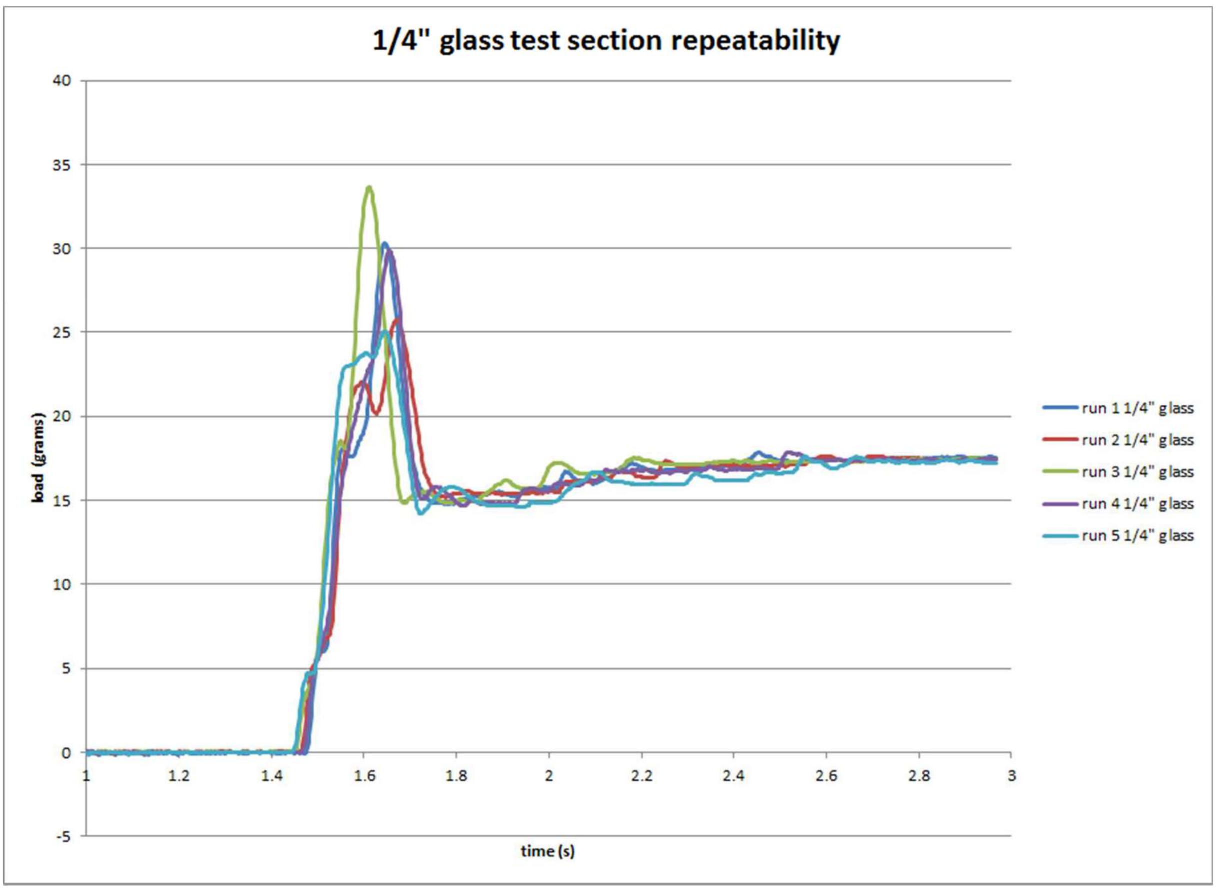

Figure 13: Repeatability test with water tested in a 1/4" glass test section.

Next, a 3/8" glass test section was used, and the results are shown in Figure 14. Comparing the four draining events, there is not much difference between the runs and therefore good repeatability for this size and material.

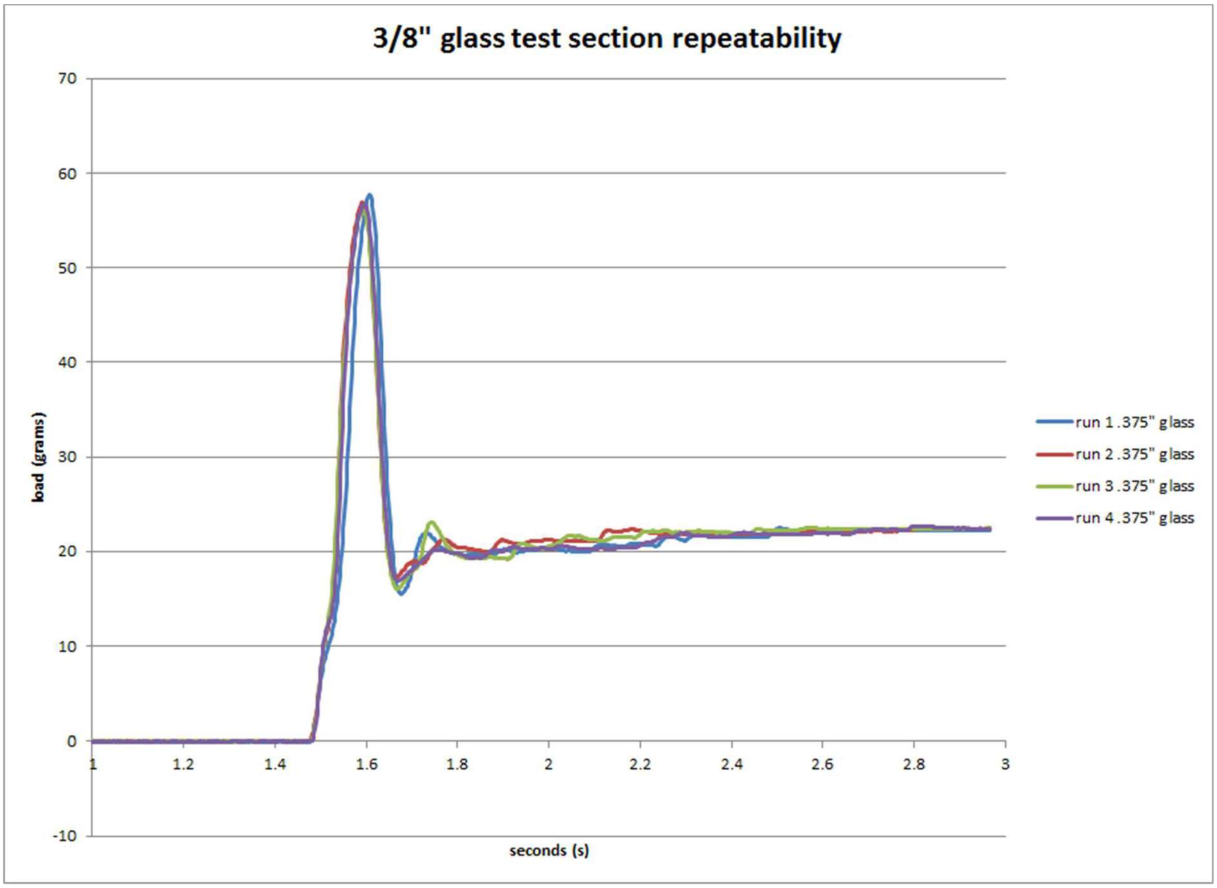

Figure 14: Repeatability test with water tested in a 3/8" glass test section.

Plastic tubing was also tested, with a ¼" test section tested first. This data is shown below in Figure 15. Although only 3 draining events were performed, it is obvious that the repeatability of the tube size and material is quite poor. This is likely due to the unpredictable wetting effects of the plastic material or the surface characteristics of the inside of the tube.

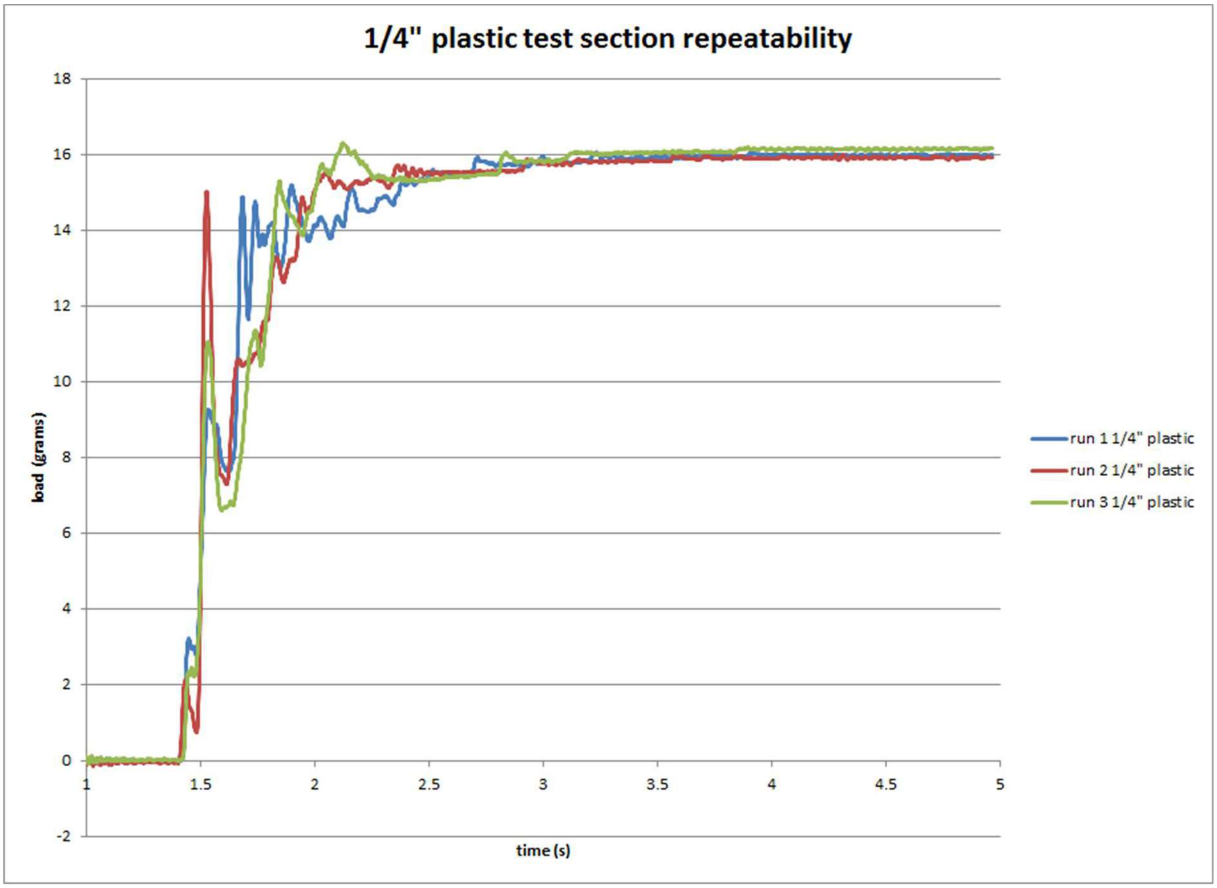

Figure 15: Repeatability test with water tested in a 1/4" plastic test section.

Next, the tube size was increased to 3/8", and a set of four draining events were recorded. This data is shown below in Figure 16. The data shows quite good repeatability for the four tests.

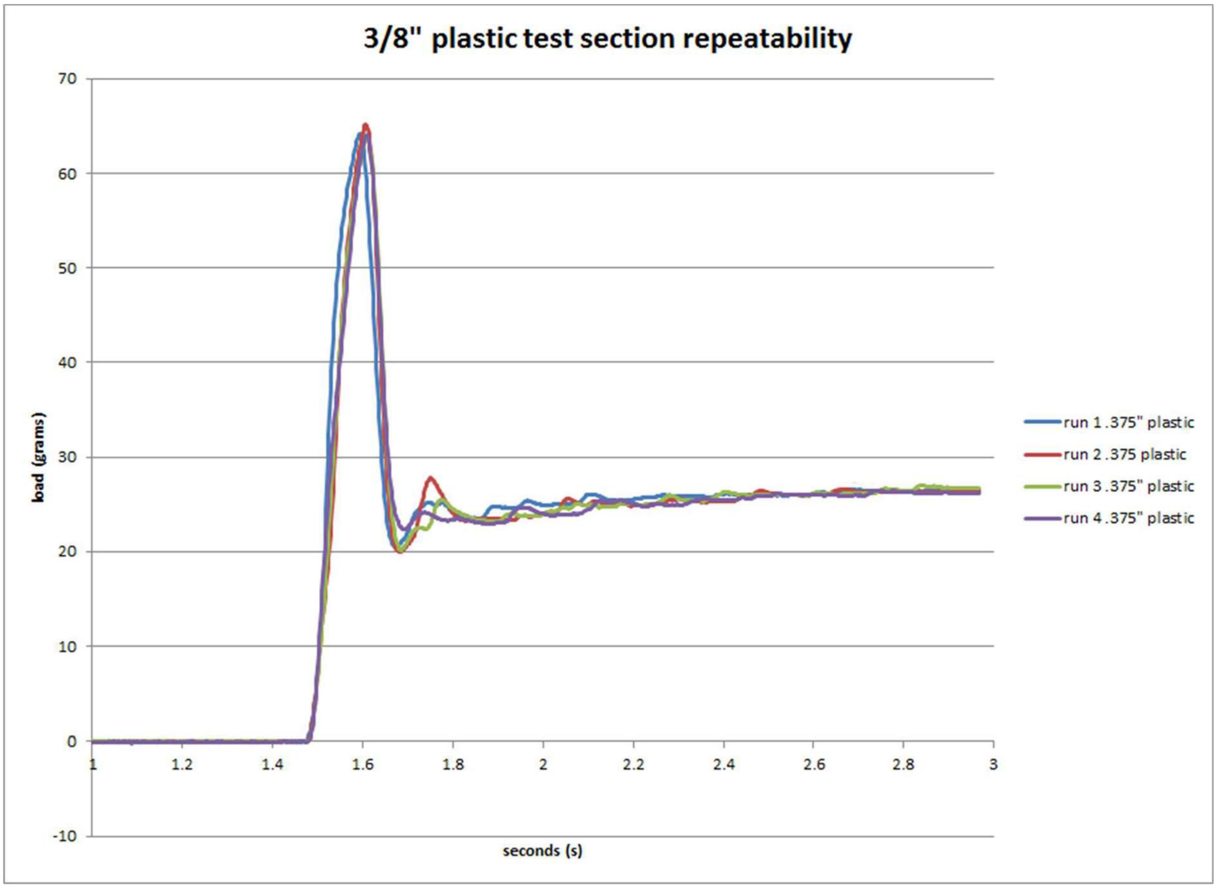

Figure 16: Repeatability test with water tested in a 3/8" plastic test section.

Next a ½" plastic test section was used, and four draining events were performed. This data is plotted below in Figure 17. The data looks very consistent and very repeatable.

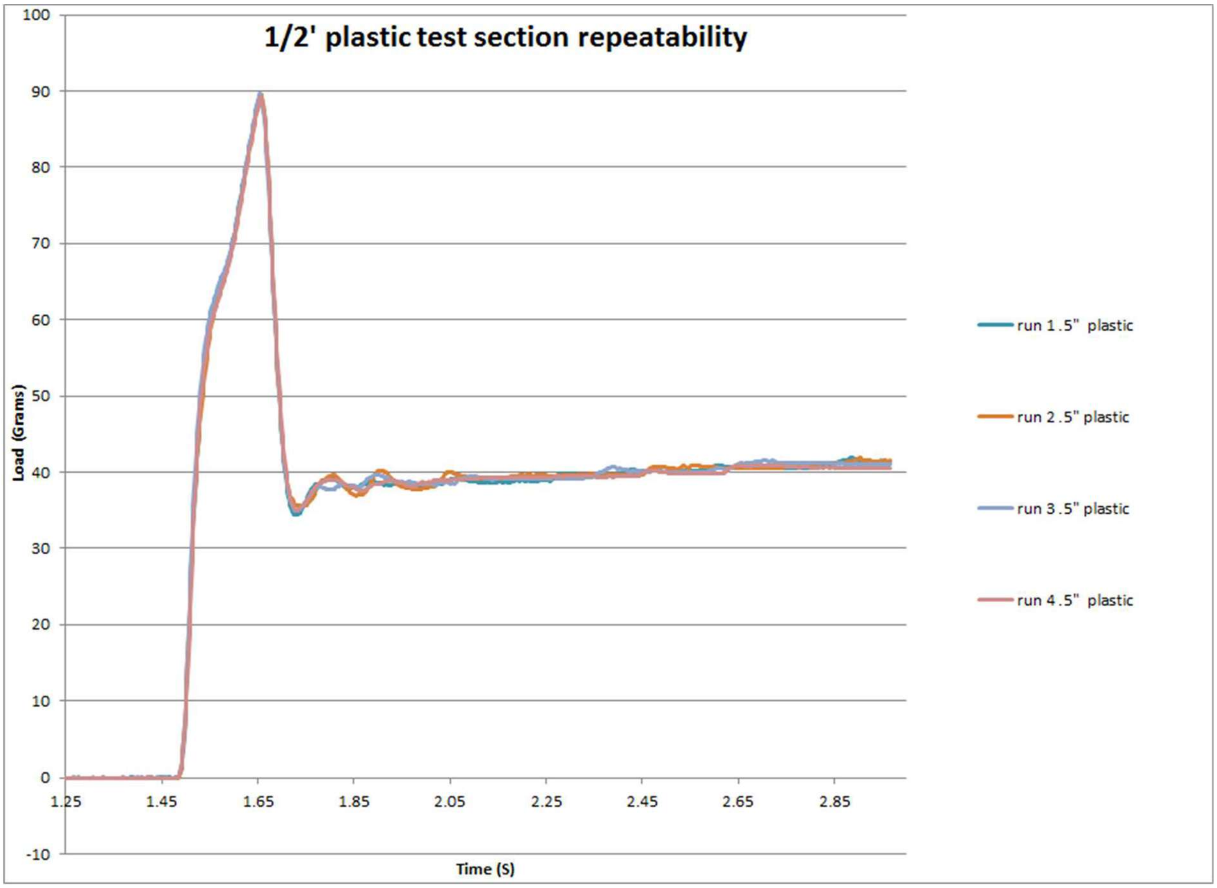

Figure 17: Repeatability test with water tested in a 1/2" plastic test section.

2.1.4.2 Glass vs. Plastic Test Sections

Since both glass and plastic test section tubes were used, draining tests were done to see if the material and slight ID change made a difference in the results. Note that glass and plastic tubes with both the same size I.D. and O.D. were not available.

Below in Figure 18 a comparison is made between 3/8" glass and plastic test sections.

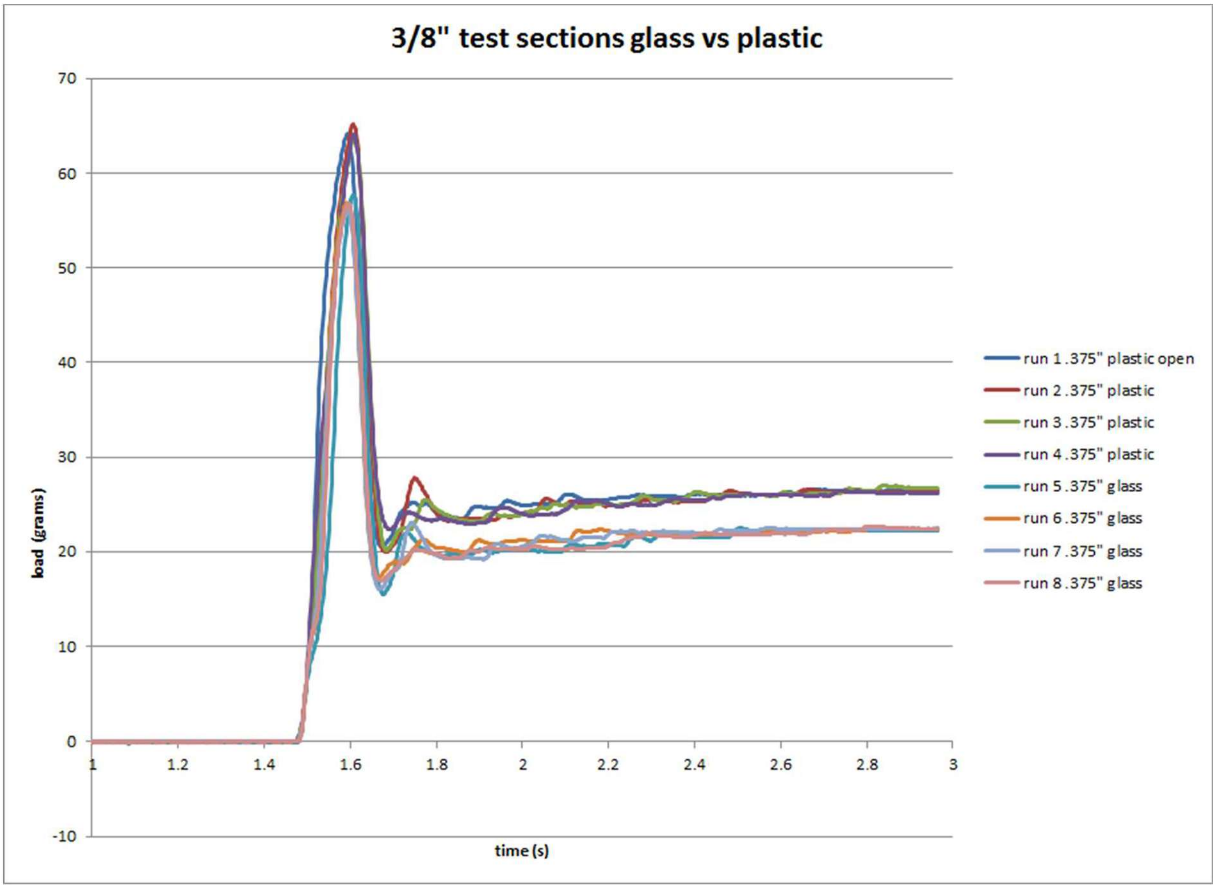

Figure 18: Water draining test comparing 3/8" plastic to 3/8" glass test sections.

As the above plot shows, the slight difference in ID (0.2175" for glass vs. 0.26" for plastic) makes a difference in maximum overshoot, as well as load gain in the cup due to the increased amount of water contained in the plastic tube compared to the glass. Other than these differences, the data looks very similar and quite repeatable.

2.1.4.3 Venting Effects

When the initial draining tests were performed, it was observed that the water drained slower than expected. After further investigation, it was determined that the vent line was restricted, resulting in reduced gas flow to the top of the test section, slowing down the natural draining of water. The design was revised to incorporate a much larger vent line connected directly to the 6-way cross, new parts were ordered, and the system was reassembled. The new design is shown in the Figure 19 below.

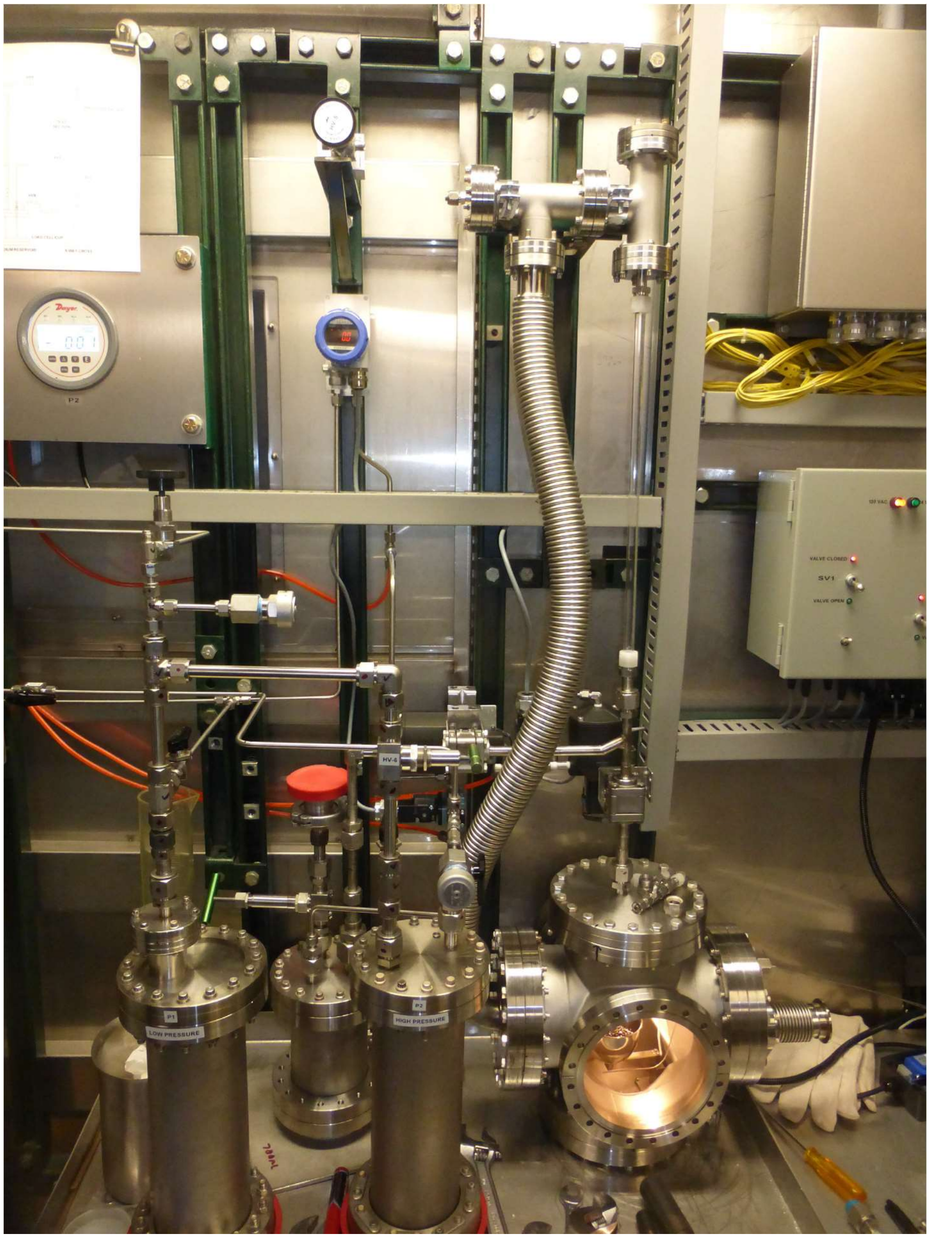

Figure 19: Experiment system with improved larger test section venting system.

2.1.4.4 Sequential Drains

When operating with sodium instead of water, performing a drain test is a multi-step process. The system must first be heated up to operating temperature, followed by filling the transfer line and test section with sodium. Next the sodium is held in the test section until wetting occurs, which could take days. Then, when wetting has occurred As evidenced by resistance measurements using the attached probes, the sodium can be drained into the catch cup. If the test is considered complete at this time, the system has to be allowed to cool, and then the system can be serviced (test section changed, cup cleaned, etc), which involves using a glove bag and argon gas.

If only one sodium drain occurs, there is very little data captured for the amount of time involved in testing. Therefore it is desirable to be able to perform multiple sodium drains during the same wetting test with the same test section. In order to test whether this is possible, multiple water drain tests were performed with all test section sizes. The only change in the system that occurs during these tests is that the mass of the catch cup increases due to the cup filling with water. In order to account for this added mass, the load cell was zeroed before each water drain. It was hypothesized that the increase in mass of the system would cause the reaction time of the system to increase, and also an increase in overshoot could occur due to inertial effects.

Presented below are plots of water tests performed without draining the catch cup for each tube size. Figure 20 shows nine tests performed with a ¼" glass test section.

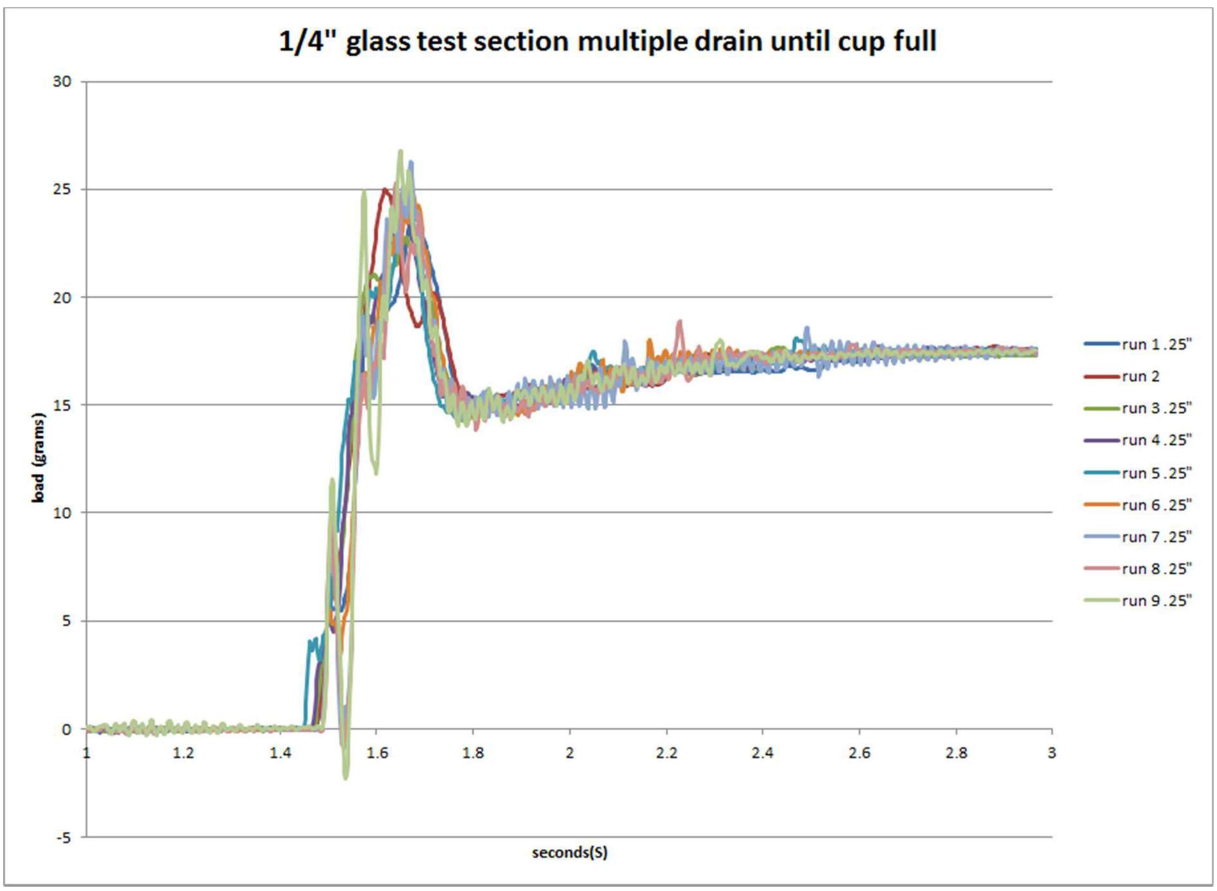

Figure 20: Multiple drain test with ¼" glass test section.

The data plotted in Figure 20 shows a somewhat consistent trend in most of the curves, other than the last run (run 9). This apparent excessive fluctuation is due to the catch cup being full and the water sloshing around, causing the instability in load reading.

The next set of runs were performed with a ¼" plastic test section. The data shown below in Figure 21 shows significantly more variability between runs compared to the data in Figure 20. Again the load instability is visible in the last run (run 9) due to the cup being near capacity. Overall, the change to plastic material seems to result in much more variation between each draining event.

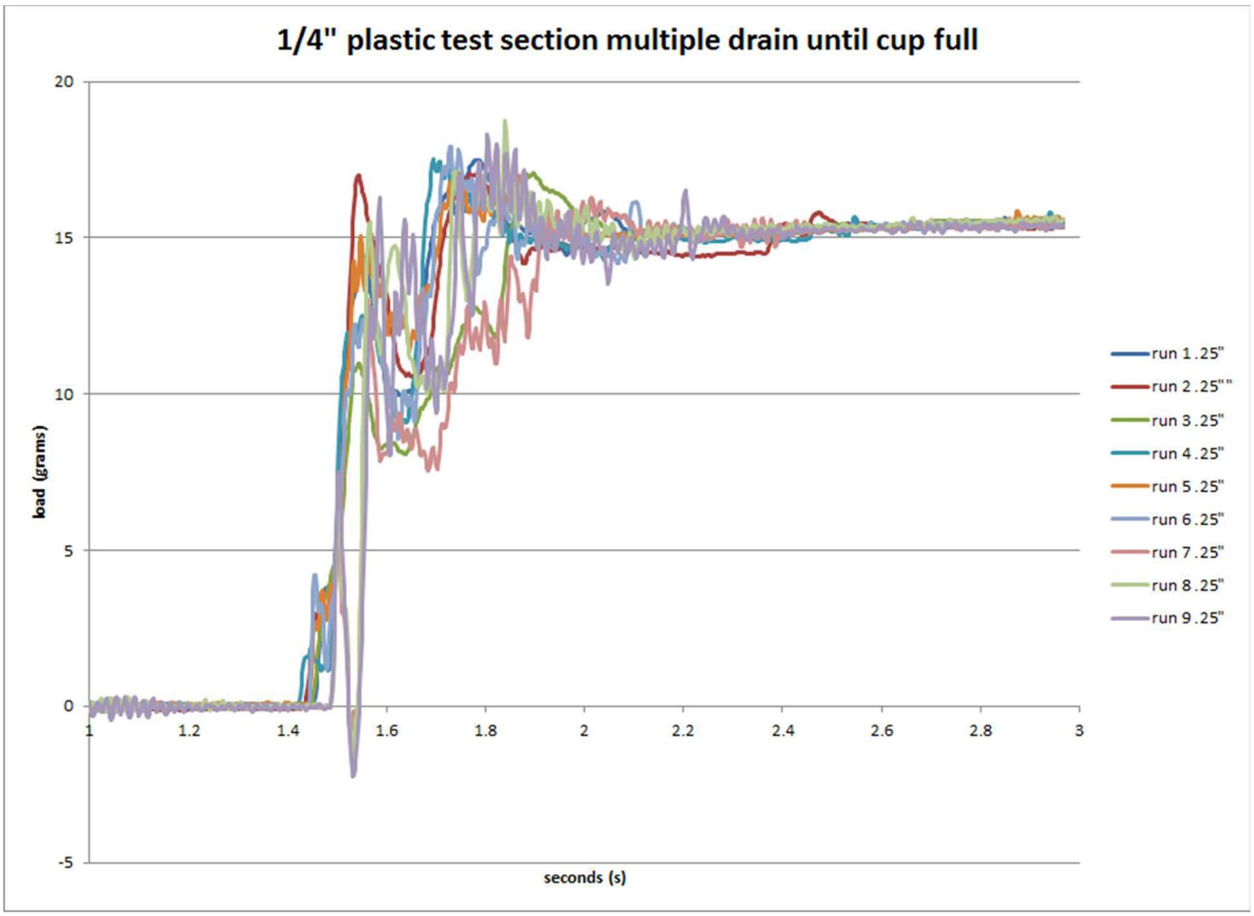

Figure 21: Multiple drain test with ¼" plastic test section.

Next, the test section material was changed to 3/8" plastic. Only five drain tests were performed, since the larger diameter tube contains more volume, and the catch cup was nearly full at that time. The data plotted in Figure 22 shows much better repeatability between runs, although the last run (run 5) again shows the sinusoidal effect of the catch cup being full of water. Overall the 3/8" plastic tube is much more repeatable compared to the ¼" plastic.

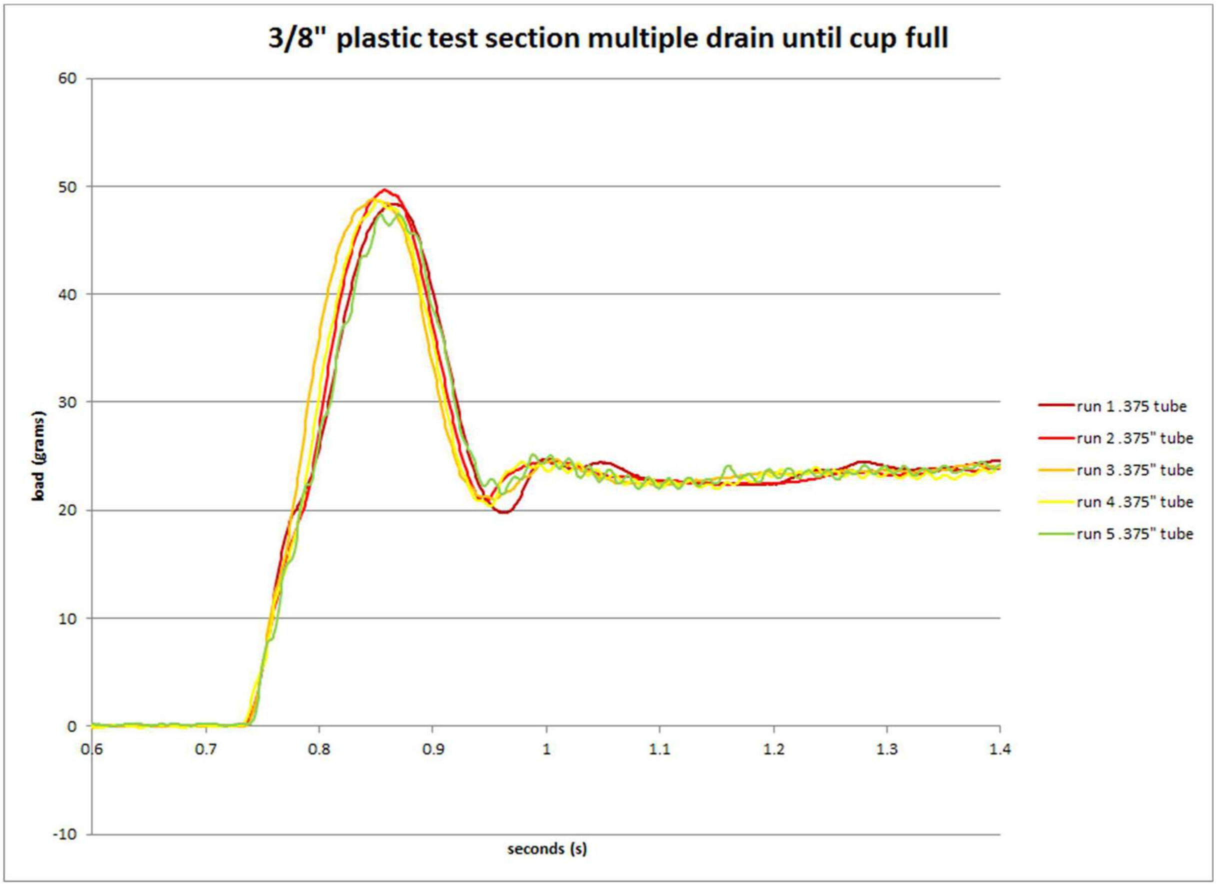

Figure 22: Multiple drain test with 3/8” plastic test section.

The next test was done with a ½” plastic test section. Only three draining events were performed since the cup was nearly full after only three drains. The data is plotted in Figure 23 below. The overall data looks very consistent and repeatable. The effect of the full catch cup can be seen in run 3, but is less pronounced compared to the previous runs, at least partially due to the change in y-axis scale.

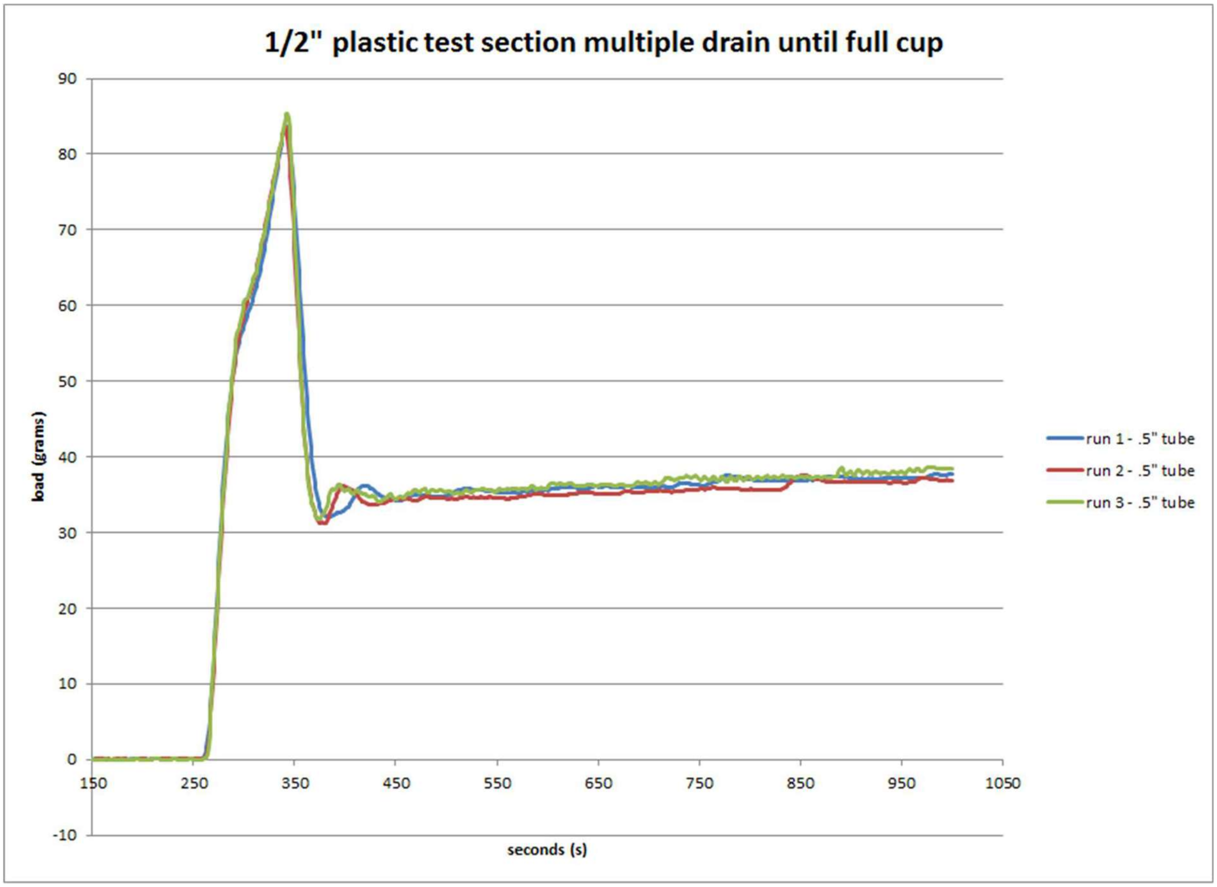

Figure 23: Multiple drain test with 1/2" plastic test section.

2.1.4.5 Testing of Updated Venting System

Once the venting system was redesigned and reassembled, draining tests were performed to check if the improvements were sufficient to solve the draining issues. Below in Figure 24 is a data plot of a ½" test section run multiple times with the new venting system installed compared to multiple tests performed with the top of the test section open to the atmosphere (no restriction). The plots shows no apparent difference between these four draining events in each configuration. This proves that our updated venting system is sufficient and is no more restrictive than having the top of the tube open to the air.

2.1.4.6 List of Drain Tests Performed

Shown below in Table 2 is a complete list of draining tests performed with water using various test sections. Draining tests are still underway so this list is not all inclusive.

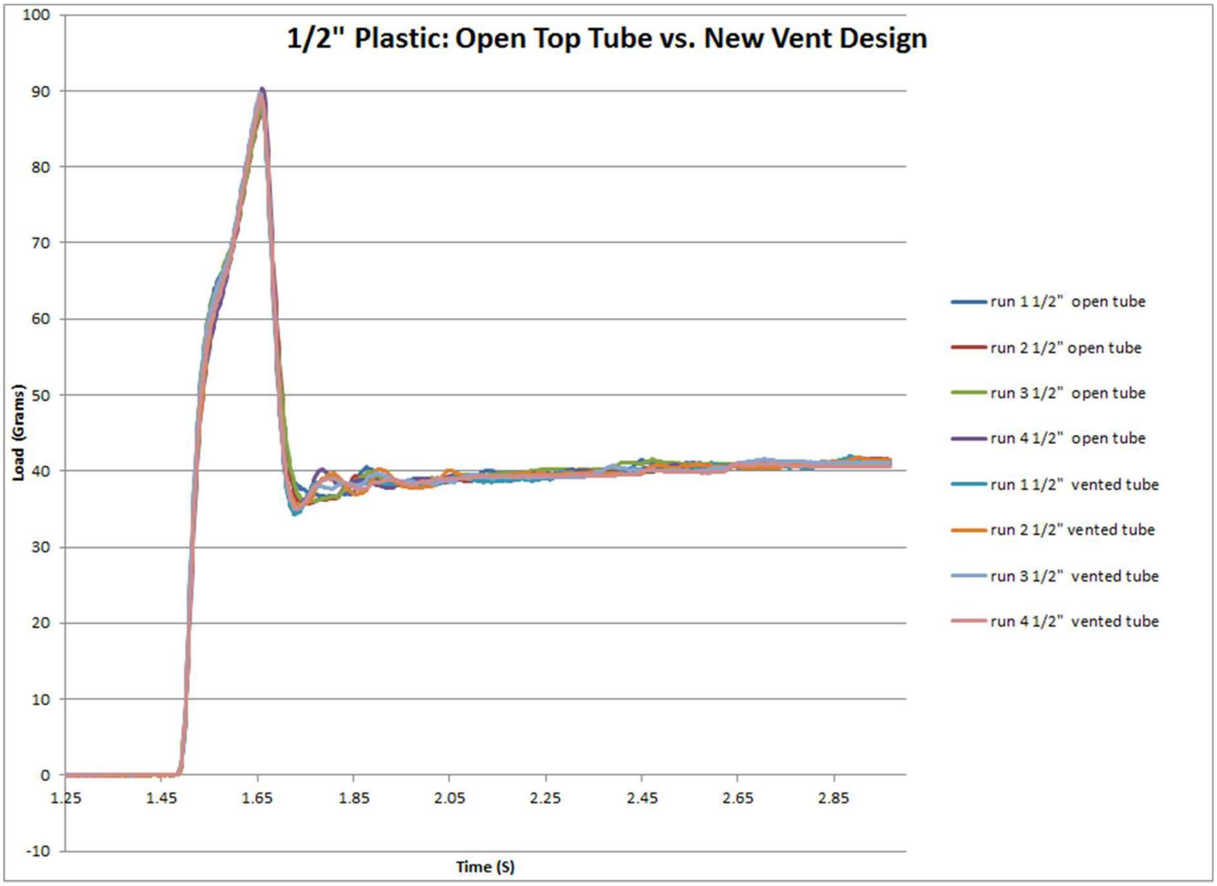

Figure 24: Comparison between new vent system and open top test section.

Table 2. List of water drain tests performed as of September 2017

RUN NUMBER	TUBE SIZE (OUTER DIAMETER)	TUBE MATERIAL	TEST CONDITIONS	NOTES
7	.25"	glass	vent line connected, t/c removed from tee	drains faster than with t/c installed
8	.25"	glass	vent line connected, t/c removed from tee	repeat of previous test
9	.25"	glass	removed tee to vent line, open test section top	drain time appears faster
10	.25"	glass	removed tee to vent line, open test section top	scope set up incorrect
11	.25"	glass	removed tee to vent line, open test section top	repeatability compared to run 9
12	.25"	glass	removed tee to vent line, open test section top	repeatability compared to run 9
13	.25"	plastic	removed tee to vent line, open test section top	compare plastic tube to previous glass tube tests
14	.25"	plastic	removed tee to vent line, open test section top	repeatability compared to run 13 draining characteristics

				different than previous
15	.25"	plastic	removed tee to vent line, open test section top	repeatability compared to run 13
16	.5"	plastic	removed tee to vent line, open test section top	higher overshoot than 1/2" tube
17	.5"	plastic	removed tee to vent line, open test section top	repeatability compared to run 16
18	.25"	plastic	top of tube closed-no venting	water level drops about 1.25"
19	.25"	plastic	top of tube closed-no venting	repeat of previous run
20	.375"	plastic	top of tube closed-no venting	repeat of previous test water level drops about .125"
21	.375"	plastic	top of tube closed-no venting	water level drops about .125"
22	.5"	plastic	top of tube closed-no venting	initial level drop about 1/8" then slow drain to empty
23	.5"	plastic	top of tube closed-no venting	repeat of previous test- identical results

24	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	First test with ¼" plastic tube
25	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 24
26	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 24
27	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 24
28	.5"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	
29	.5"	plastic	top of tube open to atmosphere, no empty of load cell cup	repeatability compared to run 28

			but zero after each run	
30	.5"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 28
31	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	
32	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 31
33	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 31
34	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 31

35	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 31
36	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 31
37	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 31
38	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 31
39	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 31
40	.25"	plastic	top of tube open to atmosphere, no empty of load cell cup	repeatability compared to run 31

			but zero after each run	
41	.375"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	
42	.375"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 41
43	.375"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 41
44	.375"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 41
45	.375"	plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 41
46	.25"	Plastic	top of tube open to atmosphere,	

			no empty of load cell cup but zero after each run	
47	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46
48	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46
49	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46
50	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46
51	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46

52	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46
53	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46
54	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46
55	.25"	Plastic	top of tube open to atmosphere, no empty of load cell cup but zero after each run	repeatability compared to run 46
56	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	

57	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 56
58	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 56
59	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 56
60	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed	repeatability compared to run 56

			flat and even, no empty of load cell cup but zero after each run	
61	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 56
62	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 56
63	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 56

64	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 56
65	.25"	Plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 56
66	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	
67	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed	repeatability compared to run 66

			flat and even, no empty of load cell cup but zero after each run	
68	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 66
69	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 66
70	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 66

71	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 66
72	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 66
73	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 66
74	.25"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed	repeatability compared to run 66

			flat and even, no empty of load cell cup but zero after each run	
75	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	
76	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 75
77	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 75

78	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 75
79	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 75
80	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 75
81	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed	repeatability compared to run 75

			flat and even, no empty of load cell cup but zero after each run	
82	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, no empty of load cell cup but zero after each run	repeatability compared to run 75
83	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, zoom scope from 50mv/div to 60	
84	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, zoom scope from 50mv/div to 60	repeatability compared to run 83

85	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, zoom scope from 50mv/div to 60	repeatability compared to run 83
86	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, zoom scope from 50mv/div to 60	repeatability compared to run 83
87	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, zoom scope from 50mv/div to 60	repeatability compared to run 83
88	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed	repeatability compared to run 83

			flat and even, zoom scope from 50mv/div to 60	
89	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, zoom scope from 50mv/div to 60	repeatability compared to run 83
90	.25"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even, zoom scope from 50mv/div to 60	repeatability compared to run 83
91	.5"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	
92	.5"	plastic	top of tube open to atmosphere, all fittings removed from	repeatability compared to run 91

			top of tube, mesh placed flat and even	
93	.5"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 91
94	.5"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 91
95	.5"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even large vent system connected	compare large vent to open tube tests run 91-94
96	.5"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even large vent system connected	repeatability compared to run 95

97	.5"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even large vent system connected	repeatability compared to run 95
98	.5"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even large vent system connected	repeatability compared to run 95
99	.375"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	3/8" tube data to compare to glass and stainless tube
100	.375"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 99
101	.375"	plastic	top of tube open to atmosphere, all fittings	repeatability compared to run 99

			removed from top of tube, mesh placed flat and even	
102	.375"	plastic	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 99
103	.375"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	3/8" tube data to compare to plastic and stainless tube
104	.375"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 103
105	.375"	glass	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 103
106	.375"	glass	top of tube open to atmosphere, all fittings removed from	repeatability compared to run 103

			top of tube, mesh placed flat and even	
107	.375"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	3/8" tube data to compare to plastic and glass
108	.375"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 107
109	.375"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 107
110	.375"	stainless steel	top of tube open to atmosphere, all fittings removed from top of tube, mesh placed flat and even	repeatability compared to run 107

3 Summary and Future Plans

Much time and effort was spent during FY 2017 building an updated system for the Sodium Draining and Refilling experiments. The new experiment design that measures in real time the cumulative drained sodium impact force and collected weight data has been completed and has been operational with water as a test fluid. Shakedown tests draining water in round tubes were initiated. Testing with sodium will be initiated during FY 2018.

The initial experiment configuration will examine sodium draining and refilling for vertical stainless steel tube with different inner diameters. Initial tests will be conducted with the existing three test sections incorporating instrumented stainless steel tubes having three different diameters. It is expected that the inner diameters of all three tubes are sufficiently large for efficient sodium draining. Two stainless steel tubes having smaller inner diameters will be ordered and instrumented with resistance probes.

Following testing with vertical circular tubes of different inner diameters, testing will proceed to instrumented stainless steel test sections with semicircular and/or rectilinear sodium channels representative of compact diffusion-bonded sodium-to-CO_2 heat exchanger designs. This is necessary to understand if there are differences in the phenomena between circular, semicircular, and rectilinear channels, and how those differences affect the minimum sodium channel size for draining.

The Sodium Draining and Refilling facility might then be modified to also investigate sodium draining from stainless steel test sections in different orientations at angles between vertical and horizontal. For example, in developing the layout for a sCO_2 power converter, it is also possible to orient the heat exchanger such that the sodium channels are at a 45 degree angle from the vertical (or some other angle), provided that the sodium draining requirements are still met. The authors are not aware of any previous data on the effect of angle for intermediate angles between vertical and horizontal with sodium. When a fundamental understanding of sodium draining and refilling phenomena has been obtained, then the Project can be completed.

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