

Report on Level Sensor Development

Nuclear Science and Engineering Division

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March 2019

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1 Executive Summary

This report details the development of sensors capable of measuring the level of liquid sodium at the Mechanisms Engineering Test Loop (METL) of Argonne National Laboratory. A differential pressure level sensor and variations of a mutually inductive level sensor have been designed, built, and tested in sodium at METL. A differential pressure level sensor was successfully calibrated during the initial dump tank sodium fill and continues to operate effectively. A differential pressure level sensor has been procured for use in the expansion tank. Three variations of mutually inductive level sensors have been designed, built, and tested in an out-of-sodium testing station in Building 308. The most advanced variation consists of a coil wound mineral insulated cable capable of continuous level measurement of liquid sodium up to 538°C over a range of 70". Successful in-sodium testing occurred in late 2018.

2 Background

2.1 Mechanisms Engineering Test Loop

The Mechanisms Engineering Test Loop (METL) is a liquid metal research facility located in Building 308 at Argonne National Laboratory. The U.S. DOE-NE Advanced Reactor Technology program built this test loop at Argonne to support intermediate scale testing of liquid metal components. METL is capable of testing small to intermediate-scale components and systems in order to develop advanced liquid metal technologies. Testing different components in METL is essential for the future of advanced fast reactors as it should provide invaluable performance data and reduce the risk of failures during plant operation. METL also provides development opportunities for younger scientists, engineers, and designers who will ultimately lead the advancement of U.S. liquid metal technologies. In 2018, METL completed Phase I construction, performed an initial heat-up of all sodium seeing components, baked out the facility under vacuum, transferred roughly 750 gallons of sodium from 15 55-gallon drums to the dump tank, and filled the first test vessel with sodium. The first experiment was installed in METL in early FY2019 and began operation [1]. As shown in Figure 1 and Figure 2, the design of the METL facility consists of a number of test vessels connected in parallel to a main sodium loop. The different vessels share an expansion tank, purification system, and several electromagnetic (EM) pumps and flowmeters.

Some examples of technologies that can be tested in METL include:

- 1. Components of an advanced fuel handling system Fuel handling systems are used for the insertion and removal of core assemblies located within the reactor vessel. These components are essential to the successful operation of fast reactors. For liquid metal applications, fuel handling systems need to work inside the primary vessel and typically penetrate through the cover gas of the primary system. As a result, fuel handling systems must address issues associated with 'sodium-frost' buildup.
- 2. Mechanisms for self-actuated control and shutdown systems These components have been conceived by various designers to provide added defense-in-depth for reducing the consequences of beyond-design-basis accidents. These self-actuated control and shutdown mechanisms include devices such as Curie-point magnets and fusible linkages.
- 3. In-service inspection and repair technologies These systems include visualization sensors for immersed coolant applications and technologies for the welding and repair of structures in contact with the primary coolant.
- 4. Advanced sensors and instrumentation Advanced fast reactors contain sensors and instrumentation for monitoring the condition of the plant. Sometimes these components are required to work while immersed in the primary coolant. This category includes but is not limited to, sensors for the rapid detection of hydrogen presence in sodium (which is indicative of a leak), the detection of impurities in the coolant (i.e., improvement of plugging meters or oxygen sensors), alternative methods of leak detection, and improved sensors for the measurement of liquid level.



Figure 1: 3D Model of METL during Phase 1 [1].



Figure 2: Image of METL during Phase 1 [1].

2.2 Level Detection in Liquid Sodium Systems

This report focuses on the technology development efforts at the METL facility to develop liquid metal level measurement sensors. Monitoring the level of liquid sodium in advanced fast reactors is of paramount importance. The safe and efficient performance of the reactor's heat removal systems depend on the presence of the appropriate level of liquid sodium. Due to the higher temperatures, chemically active nature of the liquid sodium, and the "sodium-frost" buildup phenomena, traditional level detection methods cannot typically be employed [2]. While most traditional level detection methods have been tested in liquid sodium system, a select few have been determined to be viable. This report presents the development and testing results of two such systems: the differential pressure level sensor and the inductive level sensor deployed at the METL facility.

3 Differential Pressure Level Sensor

3.1 Background

The differential pressure method (bubbler method) to determine liquid level has been employed with moderate success in liquid metal applications. The method utilizes two pressure transducers; one to measure the cover gas pressure near the top of the vessel volume, the other to measure the hydrostatic pressure of the liquid at the bottom of the vessel volume (Figure 3) [3].



Figure 3: Simplified Differential Pressure Level Sensor [3].

The observed difference in pressure is equal to the height of the sodium in the vessel multiplied by the specific gravity of sodium (Equation 1).

$\Delta Pressure = height_{Na} * specific gravity_{Na} \qquad Equation 1$

The submerged pressure measurement can be simplified by the use of a bubbler. A bubbler consists of a vertically oriented tube with a pressure transducer and gas feed at the top end and an opening at the bottom end. The bubbler is submerged in the sodium such that the open bottom end of the tube is located near the bottom of the vessel. The instrumented top end can then be located outside the vessel above the fluid and gas space to protect the sensitive components and allow for easier access. The gas feed is adjusted such that an inert gas fills the tube, forcing the fluid inside the tube out the open bottom, and bubbles are produced at the bottom of the tube. The pressure required to force all the fluid from the tube is then equal to the hydrostatic head of the liquid at the bottom end of the tube.

Differential pressure level sensors are typically used due to their simplicity in design and operation. They are often easy to install, operate, and maintain. A major drawback of using this design in a liquid sodium system is the tendency for the bubbler tube to become plugged. This can occur if the system experiences rapid pressure changes and sodium is forced into a cold spot in the bubbler or due to the buildup of sodium frost. Once this happens, the bubbler tube must be cleaned or replaced and the system recalibrated.

3.2 Design

Differential pressure level sensors that utilize bubblers are currently installed on METL in the dump tank and the expansion tank. Each system consists of two 316 stainless steel welded bellows pressure transducers, two NaK filled diaphragm lines 10 feet in length, a differential pressure transmitter, and an argon gas feed system consisting of a regulator and a mass flow controller. Each individual pressure transducer is fitted with a 1" male VCR fitting that is used to mate the transducer to the bubbler. Figure 4 shows a cross-section view of the diaphragm line connection, the diaphragm, and the VCR process connection of an individual pressure transducer. The VCR process connection is rated to 537 °C and has a relatively small form factor. All remaining connections on the system are fully welded.



Figure 4: Cross-Section View of NaK filled Diaphragm Pressure Transducer.

Sodium-Potassium alloy (NaK) was selected as the diaphragm line's process fluid because of its high operating temperature, material compatibility, and low melting temperature. The process material needs to be compatible with sodium because the process fluid could leak into the sodium if the bellows fails. The NaK filled diaphragm line connects each process connection to the transmitter. The transmitter can be located in an area away from the test vessel to ensure the maximum operating temperature is not exceeded. The 10-foot diaphragm line also allows for flexibility in routing the necessary data communication cables from the transmitter to the METL Control System. Figure 5 shows the transmitter with a simplified depiction of the diaphragm line routing.



Figure 5: Front View of Transmitter Unit (left). Side View of Transmitter Unit (center) Side View of Diaphragm Pressure Transducer (right).

The bubbler designed for METL was fabricated fully out of 316 stainless steel to ensure material compatibility with the sodium. At the top of the bubbler are two 1" female VCR connections used to mate the pressure transducers to the bubbler. These VCR connections are welded to a tube assembly that allows for one transducer to measure the overhead gas pressure, while connecting the other transducer to a dip tube that extends to the maximum allowable depth in the vessel of interest. The side with the dip tube is fitted with a custom VCR tee that plumbs in the argon gas line. The bubbler itself is fitted to the vessel lid using a 1.5" Grayloc connection. Figure 6 shows an engineering drawing of the bubbler manufactured for the dump tank. The dump tank was manufactured with several Grayloc ports of various sizes, including 1.5", to allow for instrumentation of the vessel. The expansion tank required a custom flange made to accept the differential pressure level system, which is shown in Figure 7.



Figure 6: Engineering Drawing of Differential Pressure Bubbler Tube.



Figure 7: Expansion Tank Lid with 1.5" Grayloc Ports

3.3 Results

Both differential pressure level sensors were calibrated prior to installation by CML Enterprises in early 2018. Each transmitter was setup such that the 4-20mA output was calibrated to 0-100 inH₂O. This decision was made due to the similarities in density between water and liquid sodium. The inH₂O pressure measurement is displayed on a small digital readout on the face of the transmitter. While this number can give a rough estimate of the sodium level in the vessel, a more precise calibration was desired.

The calibration of the dump tank differential pressure level sensor was completed during the initial fill of the dump tank in April 2018. A correlation between sodium volume in the dump tank and sodium level in the dump tank was supplied by the vessel manufacturer, Northland Stainless. Therefore, when a known volume of sodium was transferred to the dump tank, a correlated height of sodium could be determined. Sodium was transferred to the dump tank in 15 increments of roughly 50 gallons each. The volume of each transfer was determined by placing the 55-gallon drum of sodium on a drum scale and recording the mass before and after each transfer. The transferred sodium mass could be converted to transferred volume of sodium by dividing the mass by the density of sodium. The temperature dependence of density was taken into account by recording the temperature of the drum and the dump tank during each transfer. The results of the dump tank differential pressure sensor calibration are presented in Figure 8. The error bars shown in Figure 8 represent the uncertainty in the mass and temperature measurements.



Figure 8: Differential Pressure Level Sensor Calibration for Dump Tank.

The results follow a trend with acceptable linearity. The equation presented in Figure 8 can be used to take the raw signal from the differential pressure transmitter and output the METL dump tank's actual sodium level in inches on the METL Control System.

As previously mentioned, a second differential pressure level sensor was installed in the METL expansion tank. This system was also calibrated independently such that the 4-20mA output was correlated to 0-100 inH₂O. Unfortunately, this system was plugged during the initial METL loop fill. During this operation, the main loop plumbing, the cold trap, the plugging meter, and the expansion tank were filled with liquid sodium from the dump tank. To ensure that there was no entrapped argon gas in the system, a partial vacuum was pulled on the loop side while the dump tank was under a slightly positive argon gas pressure. The pressure difference between the loop and the dump tank forced the sodium through a dip tube in the dump tank into the loop. Once the sodium filled the loop and flowed into the expansion tank, the process was stopped. Plugging to the differential pressure level sensor occurred when the overhead argon gas pressure was increased in the expansion tank. The expansion tank, including the bubbler's dip tube, started at a partial vacuum. Then the tank was partially filled with liquid sodium, covering the opening of the bubbler's dip tube. When a positive argon gas pressure was reintroduced to the overhead gas space in the expansion tank, the partial vacuum in the bubbler's dip tube forced the sodium to the top of the bubbler causing a sodium freeze plug. Attempts at clearing this plug without removing the bubbler were unsuccessful. A new differential pressure level sensor has been ordered and is expected mid-2019.

4 Inductive Level Sensor

4.1 Background

An inductive level sensor operates on the principal of mutual inductance between two or more coil wound conductors in the proximity of an electrically conductive fluid. This work focuses on a sensor consisting of two equal length coils wrapped around a common axial core. When one of the conductor coils is supplied with an alternating current (primary coil), a magnetic field is generated that flows through the center of the primary coil and out into the surrounding area. This magnetic field also flows through the center of the non-energized coil (secondary coil) and generates an induced current in the secondary coil [4]. The current induced in the secondary coil can be accurately measured with laboratory electronics, and is reported in either volts or millivolts. Figure 9 shows a simplified representation of a two coil mutual inductive level sensor located in a thimble.



Figure 9: Simplified Bifilar Inductive Level Sensor [3].

When the mutually inductive coil is located near an electrically conductive material, such as liquid metal, the magnetic field lines generated in the primary coil travel through the conductive fluid. These magnetic field lines then generate current loops in the conductive fluid that act to oppose the original magnetic field, essentially short circuiting the mutual inductance circuit. This short circuiting is observed as a decrease in the induced current generated in the secondary coil. The result is that the measured secondary coil voltage is an inverse linear function of the liquid metal's height. Figure 10 and Figure 11 show representations of the magnetic field lines generated in an inductive level sensor at varying levels of surrounding liquid metal.



Figure 10: EMF of an Inductive Level Sensor with Increasing Sodium Level.

A consequence of the electromagnetic characteristics of the inductive level sensor is that the sensor does not need to be in direct contact with the liquid metal. The inductive level sensor can be located in a closed off thimble that is submerged in the liquid metal of interest. As long as the thimble material is non-magnetic, such as 300 series stainless steel, the magnetic field lines can penetrate well beyond the wall thickness of the thimble and into the liquid metal. Figure 12 displays data relating the frequency and depth of penetration of an electromagnetic field. Multiple plots are displayed representing materials of different electrical resistivity. For reference, 304 stainless steel has an electrical resistivity of 72 $\mu\Omega$ -cm.



Figure 11: Depth of Penetration of AC field as a Function of Frequency of Oscillator and Resistivity of Penetrated Material [4].

4.2 Design

During FY2017, the METL Program Manager attempted to find a U.S. domestic source of inductive level sensors. These sensors had been developed by U.S. companies and installed in operating sodium-cooled fast reactors in the past. In fact, the lead nuclear engineering company for the Fast Flux Test Facility (FFTF) had designed and deployed these types of sensors during the design and operations of FFTF. Argonne reached out to the vendor, but they had no record of developing these level sensors. The METL program team also reached out to another vendor (located in Colorado) who was working on an advanced inductive level sensor for the past liquid metal technology development program. This company had designed and tested their inductive level sensors at the Energy Technology Engineering Center. This company stated that they had no record of working on this technology and declined to discuss further. Therefore, a decision was made to resurrect the inductive level probe technology as a robust alternative means for measuring level for liquid metal applications.

The inductive level sensor offers a level detection solution that has a continuous measurement range and can be isolated from the liquid metal and handled more easily. This drove the development of a series of inductive level sensors at Argonne National Laboratory intended for use in METL. The scope of this work was to develop an inductive level sensor for each the dump tank and the expansion tank that allows for continuous level measurement at the full temperature range of each vessel. Literature suggests the use of coil wound mineral insulated cables to ensure the durability and uniformity of the sensors. The lack of a willing vendor of such a sensor led to the fabrication of hand wound coils with different conducting materials and insulation.

The first of these sensors was a hand wound sensor with a nickel coated copper (NCC) conductor and mica insulation. The NCC sensor was designed to operate in the dump tank, and therefore had a measurement range of 0"-40" and a max operating temperature of 1000°F. Two NCC conductors were wound around a 304ss tube to ensure the coils were on the same axis. A programmable signal generator was used to power the primary coil with an alternating current, and an oscilloscope was used to measure the induced current on the secondary coil. A testing station was constructed in Building 308 to perform out of sodium testing. The stand consisted of a 304 stainless steel thimble prototypic of what would be used in METL. The thimble was surrounded by a 6061 aluminum cylinder that acted as an analog to sodium as the aluminum has similar electromagnetic properties to sodium. The aluminum was then instrumented with mineral insulated heaters and thermocouples as well as insulation to allow for testing at various temperatures. A winch system was installed at the top of the thimble to adjust the axial position of the sensor, simulating a change in sodium height. Results of the testing performed with the NCC sensor are presented in the next section. Figure 13 shows the testing station with a crosssection view of the setup.



Figure 12: Testing Station for Out Of Sodium Measurements.

The next sensor in the series was a hand wound sensor made with a constantan conductor and fiber glass insulation. Constantan was selected as the conducting material due to its low temperature coefficient of resistivity. The effects of temperature on the performance of these sensors is well documented, and the use of constantan aims to reduce the temperature dependence. The fiber glass insulation was rated to 1200°F to allow for the possibility of fabricating a sensor for the 28" METL Test Vessels. The conductor was wound on the same diameter 304 stainless steel core as the NCC sensor, and the length of the coil was 40" to meet the requirements of the dump tank. This sensor was operated in the testing station, and later was installed in the dump tank to record the initial dump tank fill. The results of this testing are presented in the next section.

Following the operation of the constantan dump tank (CDT) sensor, a vendor was found that could manufacture custom wound mineral insulated cable to the specifications needed for this work. The first mineral insulated inductive level sensor (MI-ILS) developed for this work was fabricated and delivered in August 2018. Two variations of this sensor were purchased; one with a 40" measurement range for use in the dump tank, and a second with a 70" measurement range for use in the expansion tank. Testing is currently underway with this sensor variation, and

results are presented in the next section. Figure 14 shows the three variations of sensors developed in this work. Figure 15 shows the design of the thimbles used in both the dump tank and expansion tank to house these sensors. The thimble seals to the flange using a 1.5" Graylock connection, and the feedthrough wires are sealed using a grafoil packed Conax connection. The only difference between the thimble designs is the overall thimble length.



Figure 13: Nickel Clad Copper Sensor (left). Constantan Sensor (middle). Mineral Insulated Sensor (right).



Figure 14: Inductive Level Sensor Thimble Design.

4.3 Testing Results

Testing of the NCC sensor occurred out of sodium in the station described in the previous section. The scope of the NCC testing was to determine the necessary configuration of the electrical hardware as well as the optimal settings for each electrical component. The first

configuration consisted of a programmable signal generator used to power the primary coil of the sensor with a high frequency AC signal, and an oscilloscope to measure the output of the secondary coil. The first test with this setup aimed to determine the optimal output frequency of the signal generator. The sensor was positioned such that it was fully surrounded by the sodium analog and the output of the secondary coil was observed for various frequencies. The sensor was adjusted using the winch such that it was fully uncovered by the sodium analog and the output of the secondary coil was again observed for various frequencies. The difference in output signal was calculated, and the results were plotted as a function of frequency to generate a Bode plot. An example Bode plot for the NCC sensor is displayed in Figure 16.





These results suggested operating the NCC sensor at a frequency near 4kHz to maximize the output signal. Using this information, a mock calibration was performed. This was accomplished by powering the primary coil with the signal generator set at 4kHz and recording the output of the secondary coil at regular increments of simulated sodium level. The mock calibration follows the RDT standard (C 5-1T) that presents the requirements for the design, fabrication and examination of inductive level sensors [5]. The calibration requirements are that such sensors shall be calibrated in increments equal to 10% of full scale over the total measurement range of the sensor and that the calibration shall be performed with the sensor in a fixture with a thimble the same size as the in-vessel thimble. The results from this testing are presented in Figure 17



Figure 16: Nickel Clad Copper Mock Calibration.

The results of this testing showed acceptable linearity. It was desirable to increase the output signal to improve the accuracy and performance of these sensors. This was accomplished through two modifications to the system made when developing the CDT sensor. The first was to increase the wrapping density of both the primary and secondary coil. This increased the mutual inductance of the coils, and increased the output of the secondary coil. The second modification was to add a DC powered constant current amplifier to the circuit. This increased the signal strength in the primary coil, while also allowing for more control of the signal. Again a Bode plot was generated with the CDT sensor to determine the optimal signal generator frequency. Figure 18 displays the results of this test. Note that the amplifier was not added to the electrical setup until the dump tank sodium fill.



Figure 17: Constantan Dump Tank Sensor Bode Plot.

The results suggested a signal generator frequency of 4.4kHz. With this information a mock calibration was conducted with the CDT sensor in the testing station, again following the RDT standard. Figure 19 displays the results of this testing, where each plot point represents the average value of 300 data points taken at one second intervals over five minutes. The error bars represent the standard deviation from this average.



Figure 18: Constantan Dump Tank Sensor Mock Calibration.

The results again showed an acceptable linearity. This testing was repeated at different temperatures to observe the temperature dependence of the sensor. Testing was repeated at 150°C and 250°C. Results from this testing are presented in Figure 20. The results of the temperature study show there is a measureable temperature dependence for these sensors. Even with the use of constantan, additional measures must be made to accurately operate these CDT sensors over a wide temperature range.



Figure 19: Constantan Dump Tank Sensor Temperature Study.

The CDT was then installed in the dump tank of METL to calibrate the sensor during the initial sodium fill. As with the calibration of the differential pressure level sensor, the "Actual Sodium Level" was determined by the mass transfer of sodium from each individual barrel. This allowed for extended data collection at each level increment, helping to increase the accuracy of the data. The dump tank fill calibration data is presented in Figure 21. Note that the "Sensor Signal" in Figure 21 is on the order of a few volts, where the "Sensor Signal" in Figure 20 is on the order of hundreds of millivolts. This is due to the addition of the DC powered constant current amplifier. The error bars represent the measurement uncertainty associated with the mass and temperature measurements.



Figure 20: Constantan Dump Tank Sensor Fill Calibration.

After receiving the MI-ILS, benchtop tests similar to the ones conducted on the NCC and CDT sensors were performed in the testing station. First a Bode plot was generated to find the optimal frequency for this sensor. The optimal frequency was found to be between 3-3.5kHz which was slightly lower than the previous tests, possibly due to the added sheath metal through which the magnetic field needed to propagate. This added sheath metal is likely the cause of a significantly reduced signal when comparing the results to the CDT sensor dump tank fill. Using a frequency of 3.5kHz a mock calibration was performed in the testing station that again followed the RDT standard. The calibration produced acceptably linear results. Figure 22 displays the results of the Bode plot testing. Figure 23 displays the results of the mock calibration in the testing stand where each plot point represents the average value of 300 data points taken at one second intervals over five minutes. The error bars represent the standard deviation from this average.



Figure 22: MI-ILS Mock Calibration.

An opportunity to test the MI-ILS in liquid sodium occurred during the filling of METL Test Vessel 1. During this fill, thermocouple data in Vessel 1 was used to monitor the rise of the sodium level. The data resulted in multiple discrete level measurements, and when plotted against time a fill rate could be determined. Figure 24 displays the results of monitoring the TC data during the Vessel 1 fill.





During this procedure, the gas space of Vessel 1 and the expansion tank were tied together using the METL Valve Manifold. This forced the level rise in both vessels to be equal during the fill. Therefore, this sodium level vs. time data collected in Vessel 1 can be assumed to be equal in the expansion tank (where the MI-ILS was installed). A 70" MI-ILS was installed in the expansion tank and instrumented with the appropriate electrical hardware. By monitoring the MI-ILS signal vs. time in the expansion tank, a sodium level vs. MI-ILS signal chart can be generated. Note that this shouldn't be considered a true calibration, as the data should be collected over a period of time at each of the 10% increments of full scale. A proper calibration will be completed during an upcoming sodium fill operation. Figure 25 displays the data collected during the Vessel 1 fill.



Figure 24: MI-ILS Data During Vessel 1 Fill.

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