ANL-NRIC-002
ANL-METL-45

Report of METL Mutual Inductance Level Sensor Development for Use in Liquid Metals – FY2023

Nuclear Science & Engineering

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Executive Summary

A robust mutual inductance level sensor (MILS) for use in high temperature liquid metals has been developed at Argonne National Laboratory (ANL). The current design utilizes mineral insulated cables with a 300-series stainless steel sheath, magnesium oxide insulation, and a single copper conductor. Two coils are wrapped on a common core made of a 300-series stainless steel tube. One coil is energized with an alternating current (AC) source, and this electromagnetically couples with the second coil to generate an induced voltage. The voltage is measured to determine the mutual induction between the coils, and the mutual inductance measurement can be used to determine the level of a nearby liquid metal volume. The MILS can be located in an isolating thimble that is fully sealed to a vessel containing liquid metal for ease of maintenance and replacement. When the primary coil is energized with the AC source, the coil not only electromagnetic (EM) couples with the second coil, but also the surrounding liquid metal. The EM coupling with the surrounding liquid metal reduces the EM coupling with the second coil, producing an inverse-linear relationship between liquid metal level and secondary coil voltage. This has all been demonstrated at the Mechanisms Engineering Test Loop (METL) liquid sodium facility at ANL.

The most current iteration of the MILS system is the MILS-MK-II. This sensor system has been commissioned in a non-sodium test stand where calibrations were performed using a sodium analog. The calibrations proved to be highly linear and repeatable. The MILS-MK-II has been installed in the METL expansion tank where high temperature sodium tests have been performed. The MILS-MK-II has been calibrated against a known standard at temperature of 300°C, and the calibrations have proved to be highly linear and repeatable. The calibrated MILS-MK-II has been in operation in the METL facility for several thousands of hours at temperatures around 300°C. The experimental data has been used to develop and validate electromagnetic finite element models in COMSOL Multiphysics, and now these models can be used to advance the development of the sensor system.

Next steps will include temperature compensation to allow for operation at various temperatures. Additionally, efforts to incorporate a self-calibration methodology are underway.

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1. Introduction

The Mechanisms Engineering Test Loop (METL) was built at Argonne National Laboratory (ANL) to provide a testing environment for liquid sodium component and instrument technology in support of advanced sodium fast reactor (SFR) development. 2,840 liters of reactor-grade sodium is contained in four test vessels, a dump tank, an expansion tank, a purification system, and the process piping that connects these components. All sodium-wetted components are fabricated from 300-series stainless steel, or other materials that are compatible with the high-temperature liquid sodium. The importance of material compatibility complicates the design and operation of all liquid sodium technology. This report will discuss the development of liquid level sensors that utilize the high electrical conductivity of the liquid sodium. Figure 1 is a 3D representation of the METL facility after Phase I of construction was completed.

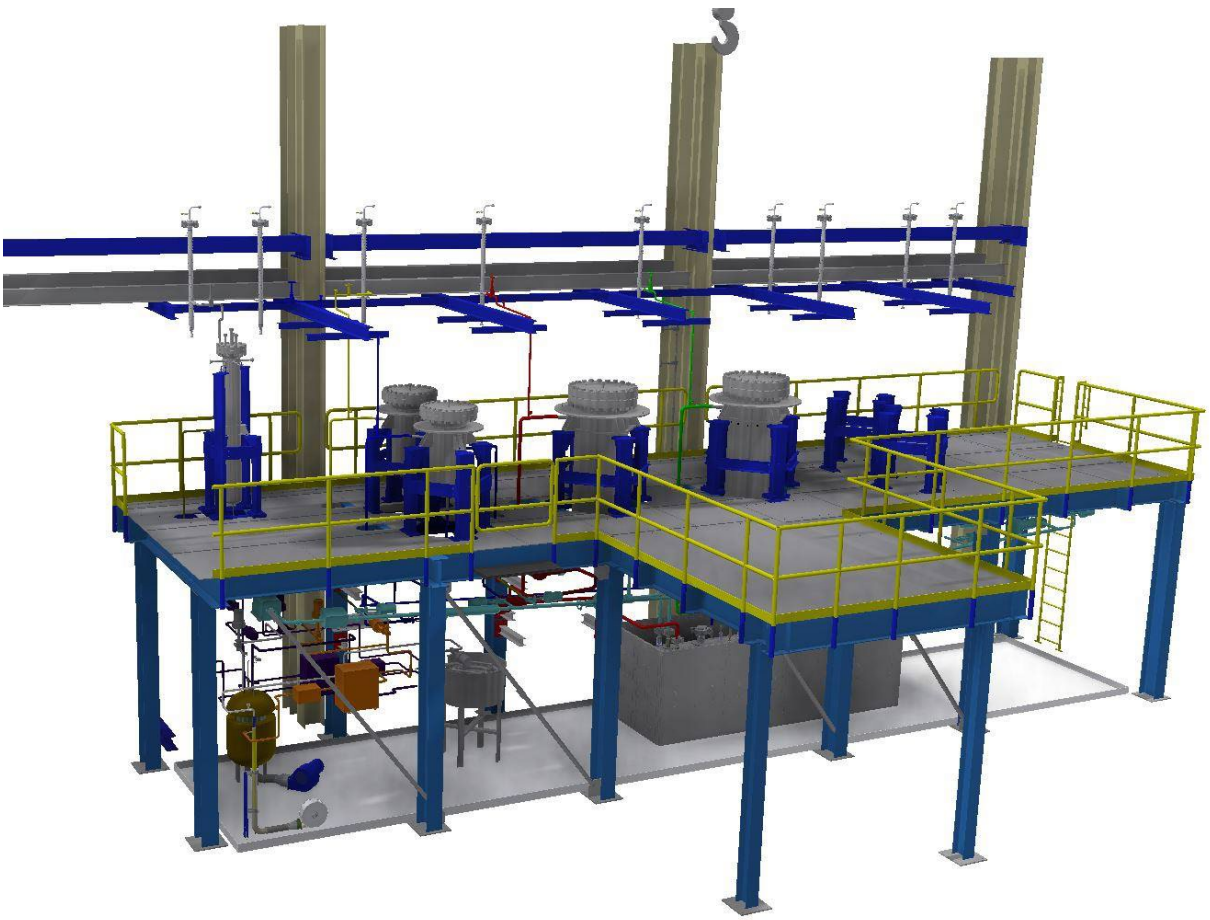

Figure 1: A 3D model of the METL facility after Phase I was completed [1].

1.1. Purpose & Background

Accurate liquid level measurement is a key safety parameter used in SFR operation. For instance, the level of the primary coolant must be maintained above a certain level to provide adequate cooling to the reactor core. Accurate liquid level measurement is also important in the operation of non-nuclear facilities, such as METL, as the experiments require a certain amount of contact with the liquid sodium to generate the desired results. Traditional level measurement methods do not perform reliably in the unique environment present in liquid sodium systems. While there are countless liquid level measurement systems for all types of process fluids, a few used in liquid sodium systems will be discussed next.

Displacement, or float, level sensors operate on the principal of liquid buoyancy. A float made of a compatible material forms a geometry with an overall density lower than the liquid sodium. The float is positioned to contact the liquid sodium at the liquid surface, or is partially/fully submerged. Level changes can be determined by using a displacement transducer or force transducer that is connected to the float. While the operation of these sensors is fairly simple, there are several disadvantageous factors. First, the connection between the float and transducer must penetrate the vessel wall. Second, sodium frost or oxide can adhere to the float or connector arm that will cause inaccuracies or fully impede the system performance. Finally, any swirling currents generated inside the vessel will lead to irregular measurements.

Differential pressure level sensors are another method used to measure the level of liquid sodium. Two pressure transducers are used to measure the hydrostatic head of the liquid sodium over a selected range. This is typically accomplished by installing a dip tube in the sodium vessel to a depth that represents the lower range of level measurement. One pressure transducer is tied to the dip tube, and inert gas is bubbled through the dip tube such that all the sodium is displaced from the tube. The second pressure transducer is located in the cover gas space of the sodium vessel. The hydrostatic head (or level) is determined from the pressure difference between the dip tube pressure and cover gas pressure. While this is a well-established liquid level measurement technique for most fluids, there are a few complication when applied to liquid sodium systems. One is the tendency for the dip tube to become plugged, with either frozen sodium or sodium oxide buildup. The whole assembly typically needs to be removed and cleaned to remedy the plug. Another issue is the addition of impurities from the inert gas bubbles to the liquid sodium inventory. Even the purest inert gas will have trace impurities, and the sodium will dissolve.

While liquid sodium systems complicate most traditional level sensing methods, the electrically conductive nature of sodium allows for unique electrical methods to detect level. The simplest is the electrical continuity probe. A continuity probe uses two leads that are electrically isolated from each other, as well as isolated from the sodium vessel wall. When the sodium level in the vessel rises to meet the two

leads, an electrical circuit is completed and the resistance between the leads drops to near zero. While this method is simple to implement, there are a number of drawbacks. Continuity probes are point level measurements, and do not give a more desirable continuous level measurement. The leads are also affected by sodium frost buildup that shorts the leads, creating a false positive reading. This requires removal from the sodium vessel and cleaning to bring back into operation. Nonetheless, these are commonly used as high and low level indicators in many sodium systems. More sophisticated electrical level measurement methods have been developed, and this report focuses on one of the electromagnetic methods.

1.2. Inductive Level Sensor Theory of Operation

The electrically conductive nature of liquid sodium allows for the use of unique electromagnetic methods to detect level. The simplest form of this type of level measurement is the single coil inductive level sensor. A solenoid coil is located near to the liquid sodium volume with the coil length set to the desired measurement range. The coil is energized using an alternating current (AC) source, and this generates a magnetic field coaxial to the coil axis. As the generated magnetic field travels through the surrounding liquid metal, eddy currents are generated that consume power from the energized coil. As the liquid metal rises, more power is consumed and a relationship between power consumption and liquid level can be determined. Because this method does not required the coil to be in contact with the liquid metal, the sensor can be placed in an isolating thimble made of 300-series stainless steel that has a relatively low electrical conductivity. Figure 2 (left) shows a simple schematic of the single coil inductive level sensor. A disadvantage of the single coil setup is the system has a significant sensitivity to changes in temperature. As the temperature of the system rises, the resistance of the coil rises leading to increased power consumption in the coil. Additionally, the change in resistance (inverse conductivity) of the surrounding metal thimble and liquid sodium reduce the power consumption in the coil. Therefore, the sensor system must be compensated for changes in temperature.

One method to accomplish temperature compensation uses a second reference coil that is either never surrounded by liquid metal, or always surrounded by liquid metal. The active coil and reference coil are setup in a bridge circuit with an adjustable balance resistor. Figure 2 (right) shows a simple schematic with the reference coil positioned in the vessels cover gas space. As the reference coil is also inside the vessel, any impedance change associated with temperature changes in the coil and thimble are included in the bridge circuit. In the configuration shown in Figure 2 (right), a balance (null) reading at the indicator would occur at zero level. While this method offers temperature compensation, measuring systems with a long active length would require an equally long reference length. Therefore, this leads to considerable size constraints.

An inductive method that includes temperature compensation while considering undesirable size constraints is the mutual inductance level sensor (MILS). This method also uses a second identical coil, but here the coil is wrapped on the same axis/bobbin. The primary coil is energized using an AC source with a constant current. The secondary coil is on an independent circuit with a digital multimeter measuring the voltage across the coil. The primary coil again generates a magnetic field along the coil's axis, and this magnetic field couples with the reference coil and generates an induced voltage. This coupling is affected by the surrounding liquid metal by reducing the mutual inductance with an increase in liquid sodium level. As the liquid sodium level increases the voltage measured across the secondary coil decreases, developing an inverse-linear relationship. This measurement method does not consider the resistance of either coil, as mutual inductance of coaxial solenoids only depends on coil geometry and the exciting current. Temperature sensitivity related to the changes in the thimble and sodium conductivity must still be considered. Figure 2 (bottom) shows a simple schematic of the MILS setup.

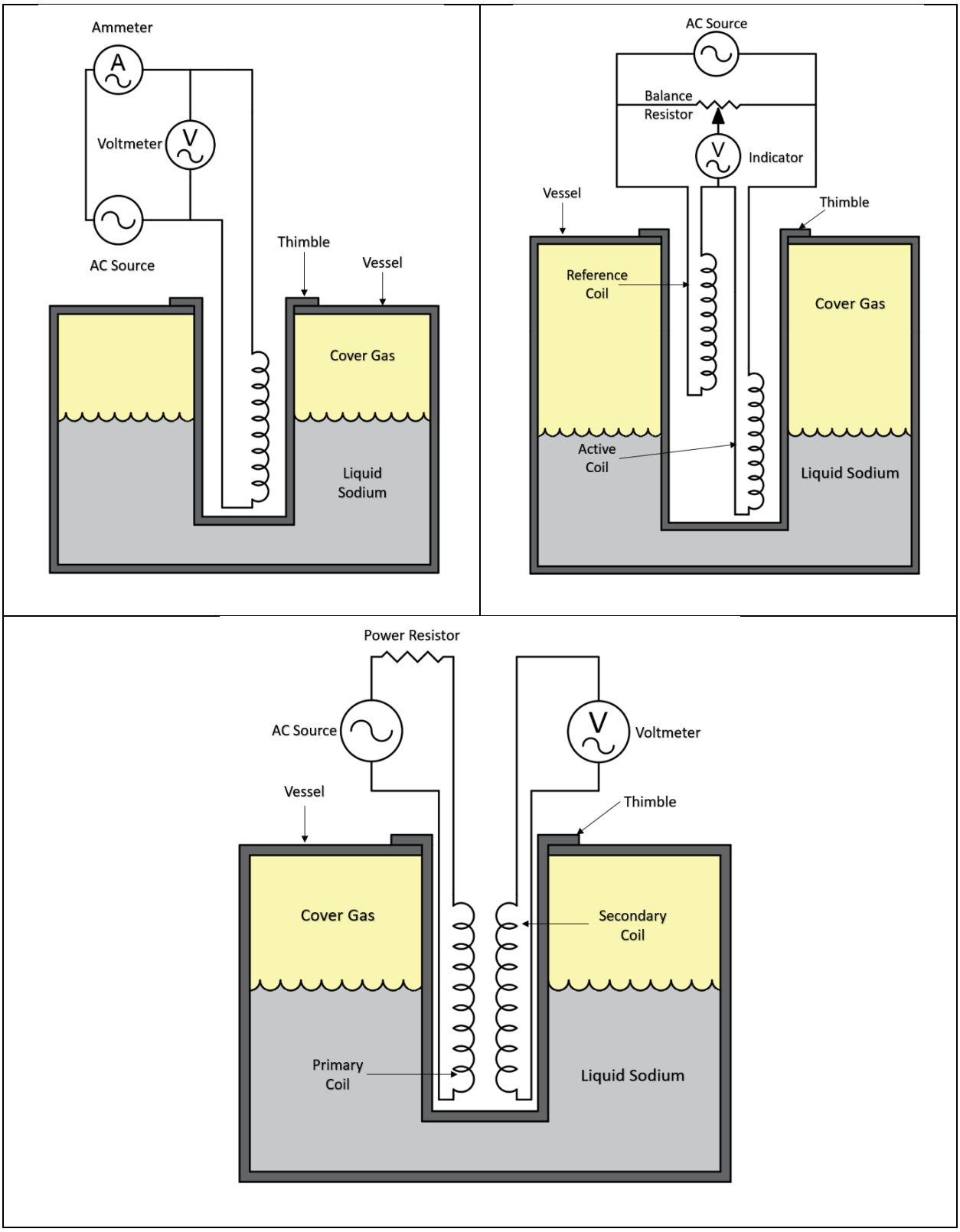

Figure 2: Simple diagram of the single coil setup (left). Simple diagram of the two-coil bridge setup (right). Simple Diagram of bifilar mutual inductance setup (bottom)

2. Design of the Mutual Inductance Level Sensor

MILS systems have previously been used in SFR applications, and they were supplied from several industrial companies [2]. Unsuccessful efforts were made to purchase similar systems from these companies, as they had apparently lost this expertise. Therefore, efforts focused on developing these sensors in-house. A series of prototype sensors were hand-wound and tested at METL, and this work is described in more detail in previous reports [3]. Robust sensors using machine wound mineral insulated cable have since been procured and tested at METL. The first iteration of these (MILS-MK-I) is described in more detail in a previous report [4], along with the design of the second iteration (MILS-MK-II).

2.1. Prototypes

Prototype sensor were hand-wound at ANL to gain experience in the operation of the MILS system. The first prototype used ceramic-coated nickel wires wound on an alumina core. The ceramic-coated nickel had an upper temperature limit of 538°C and had a very small diameter, allowing for a high wrapping density. The alumina core was selected as it was uncertain if using an electrically conductive metal core would adversely affect the sensor performance. Benchtop calibrations of this sensor failed repeatability tests as the fragile ceramic coating failed, allowing coils to short to one another.

The second prototype used mica-insulated nickel-clad copper wires wrapped on a 300-series stainless steel core. The alumina core was replaced after preliminary electromagnetic modeling suggested a metal core would not dramatically affect the sensor output, and the alumina was fragile. The new wires also demonstrated an upper temperature limit of 538°C, but they had a significantly larger outer diameter. This sensor produced highly linear benchtop calibrations that were repeatable, but the signal strength was lower than desired.

The third prototype used fiberglass-insulted constantan wires wrapped on a 300-series stainless steel core. The new wires have a reduced diameter when compared to the nickel-clad copper wires, while maintaining the same upper temperature limit. This sensor also produced highly linear benchtop calibrations that were repeatable, and an increased signal when compared to the second prototype. A high temperature sodium calibration was performed using this prototype in the METL dump tank during the initial sodium fill. The sensor performed well for several month, until the fiberglass insulation failed and the sensor shorted out. Images of a section of each sensor is shown in Figure 3.

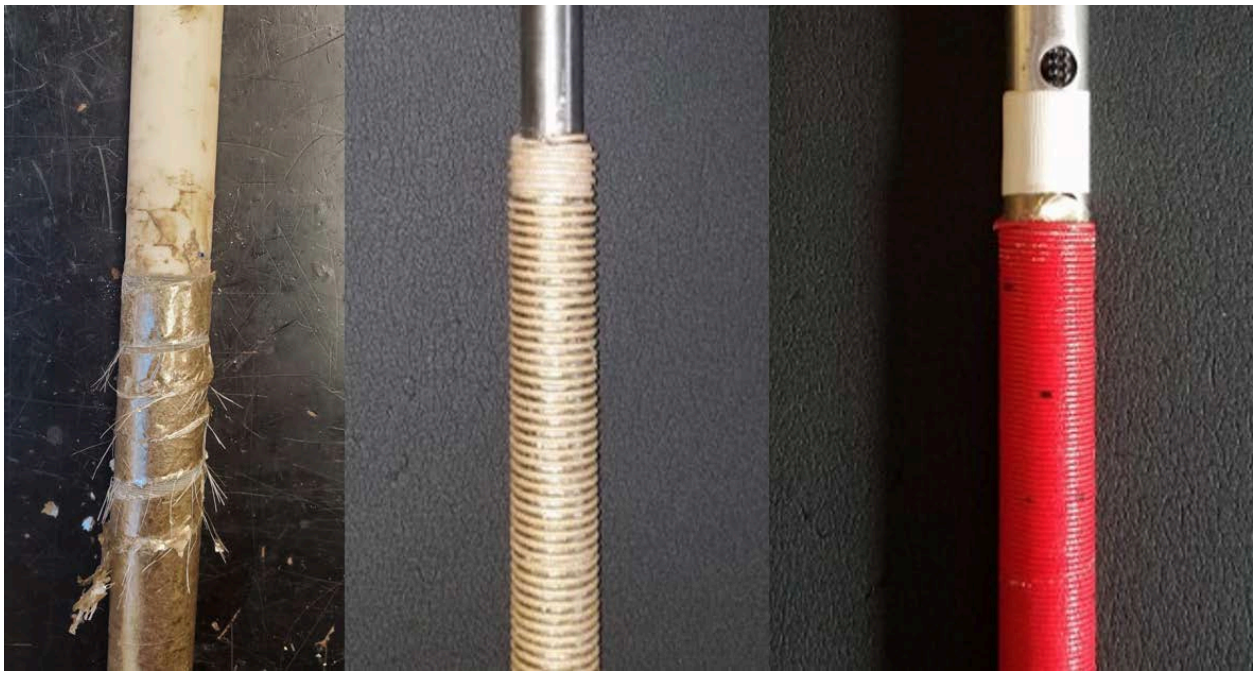

Figure 3: An image of the three prototype sensors developed during this project. The first was the ceramic-coated nickel wire sensor (left). The next was the mica insulated nickel clad copper sensor (middle). The last prototype sensor was the fiberglass insulated constantan wire sensor (right).

2.2. MILS-MK-I

Lessons learned from the prototype sensor work informed the design of the MILS-MK-I. The main issue with the prototype sensor was loss of insulation integrity. To address this, mineral insulated (MI) cables were used to form the coils. The MILS-MK-I used MI cable that was readily available at a domestic wire company. The cable has a 300-series stainless steel sheath, magnesium oxide (MgO) insulation, and two identical copper conductors. The two-conductor cable was selected to simplify construction, allowing one cable wrap to form both primary and secondary coils. Two variations of the MILS-MK-I were fabricated, one with a 40-inch active length for the METL dump tank, one with a 70-inch active length for the METL expansion tank. Both variations underwent non-sodium calibration in a testing stand (to be described in Section 3.2) and demonstrated highly linear and repeatable performance. The 70-inch variation was installed in the METL expansion tank where it produced useful level measurements for well over a year at temperature of 300°C. The measurements were of a relative nature (fill or drain observations) as there was no means to calibrate the sensor in-situ. Electromagnetic finite element analysis (EM FEA) was performed using the calibrated test stand data to develop a validated model. Analysis performed using this model, along with the METL expansion tank testing, informed the design of the MILS-MK-II. Figure 4 shows the 40-inch MILS-MK-I sensor, will a close up of the top end of the active length.

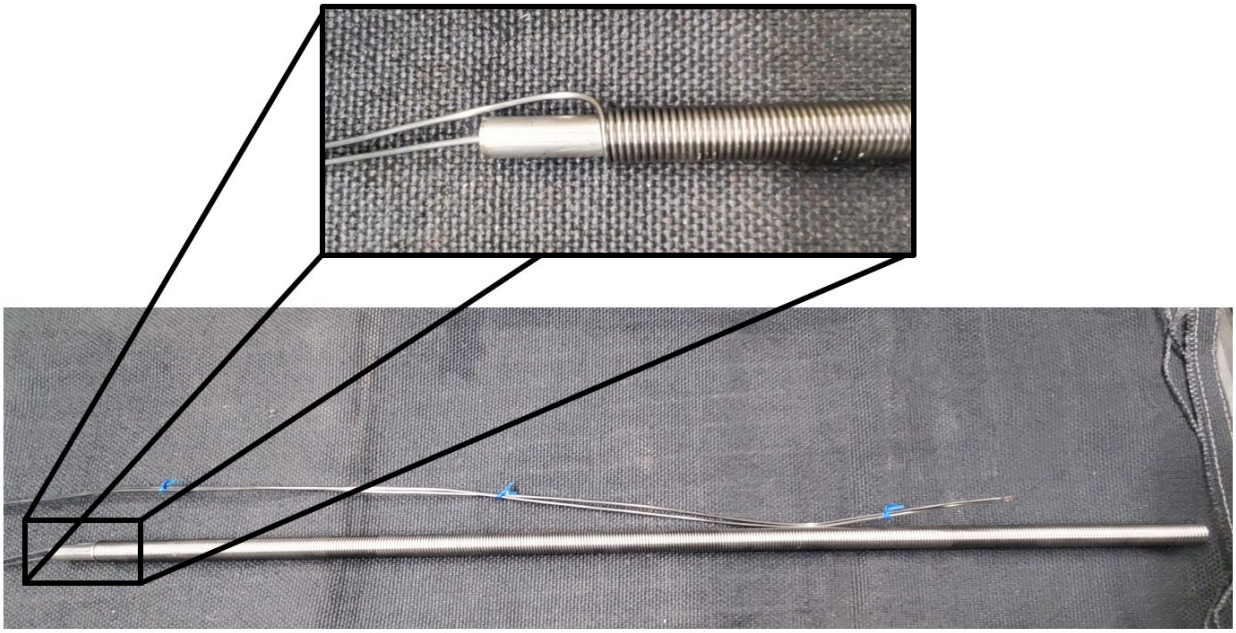

Figure 4: Image of the MILS-MK-I with a close up of the top end of the active length.

2.3. MILS-MK-II

EM FEA performed using data from the MILS-MK-I suggested that the selection of a two-conductor cable would lead to suboptimal performance of the sensor. The orientation of the conductors in the cable would essentially be arbitrary, when they would ideally be stacked vertically on top of each other. This is because mutual inductance of coaxial solenoids is maximized when the cross-section of the coils are identical. Therefore, the MILS-MK-II was fabricated using single conductor MI cable. The MI cable again was a 300-series stainless steel sheathed, MgO insulated, copper conductor cable. The diameter of the cable and conductor were reduced so that more wraps of each coil could be formed when compared to the MILS-MK-I. Additionally, 300-series stainless steel guides were added to the top and bottom of the sensor to ensure its location would be on the same axis of the thimble, maintaining a uniform distance from the liquid sodium. Again, 40-inch and 70-inch variations of the MILS-MK-II were fabricated. Figure 5 shows the MILS-MK-II with a close up of the top of the active length. Figure 6 shows a comparison of the MILS-MK-I and MILS-MK-II.

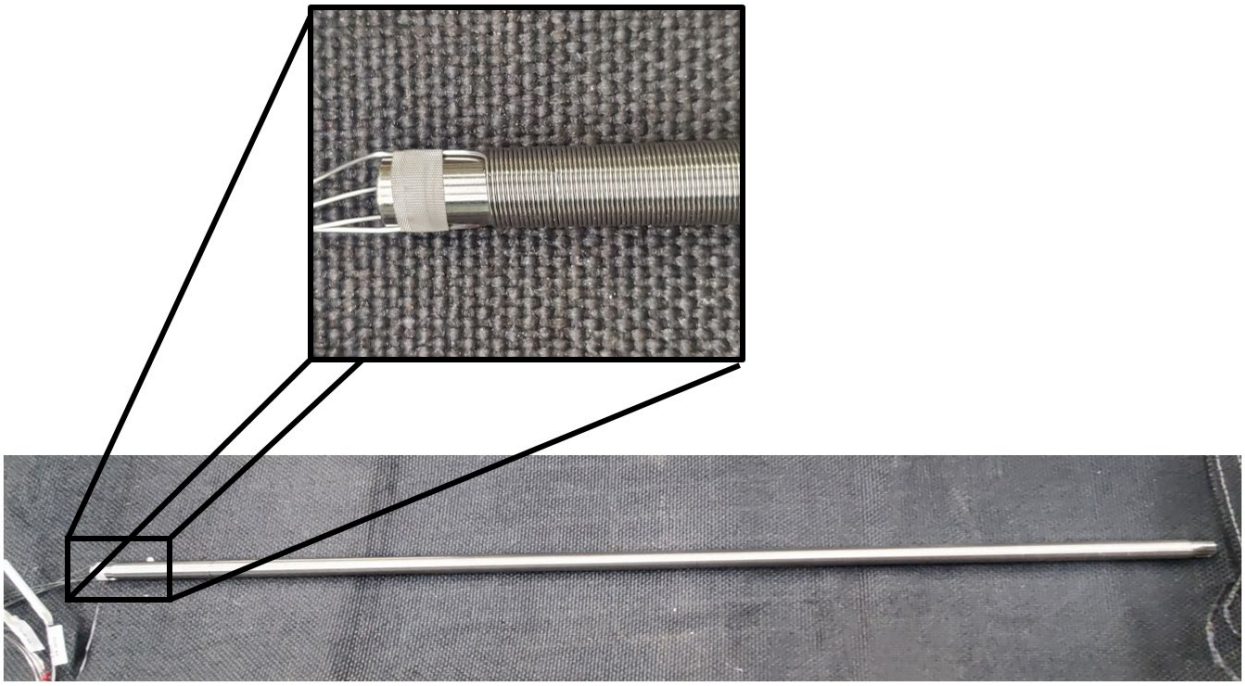

Figure 5: Image of the MILS-MK-I with a close up of the top end of the active length.

Figure 6: Bottom end of active section of the MILS-MK-II (left) and the MILS-MK-I (right) for comparison. Note the stainless steel guide on the MILS-MK-II.

3. Experimental Equipment & Testing Procedure

This section will describe the testing environment and equipment used for the MLS-MK-II operation. Much of the prototype and MILS-MK-I work focused on selection of proper electrical equipment. The electrical setup is in more finalized state now, and this has dramatically improved the sensor performance, most notably the repeatability of testing. All sensors are first characterized in a non-sodium testing stand located next to the METL facility to commission the sensor before installation into METL. Finally, all sodium testing to-date has been completed in the METL expansion tank as this is the best location to perform sodium level changes.

3.1. Electrical Equipment

In general, when two identical, coaxial solenoids are far from other electrically conductive material, their mutual inductance (M) can be defined by Equation 1:

$$M = \mu * 2 * N * {}^{A}/_{L} \tag{1}$$

Where μ is the magnetic permeability of the medium through which the magnetic field travels, N is the number of coil turns, A is the cross-sectional area of the coils, and L is the length of the solenoid. This can be measured as a voltage across the secondary coil when the primary coil is excited with an AC source. This voltage is defined by Equation 2:

$$V = {}^{d\varphi}/_{dt} = M * {}^{di}/_{dt} \tag{2}$$

Where ${}^{d\varphi}/_{dt}$ is the time-varying magnetic flux through the secondary coil cross-section, and ${}^{di}/_{dt}$ is the time-varying current (AC source) through the primary coil. When these solenoids come near other electrically conductive material, their mutual inductance is affected by the generation of eddy currents in the surrounding material. As we only wish to measure the change in mutual inductance, we must keep the AC source as constant as possible. Therefore, a custom constant current amplifier was procured for this work. A Keithley 3390 arbitrary signal generator is used to generate a sine wave that is amplified by the constant current amplifier. A power resistor is placed in series with the primary coil to provide a sufficient impedance to allow for low voltage operation. The induced voltage generated in the secondary coil is measured with a Keysight 34465A digital multimeter. During all testing operations, the primary coil was excited using a 100 mA_{rms} constant current signal with a frequency of 1000 Hz. The induced voltage in the secondary was on the order of 10-100 mV_{rms}.

3.2. Non-Sodium Test Stand

A non-sodium test stand was constructed in the same building at the METL facility to allow for pre-sodium commissioning of the sensors. This included a 300-series stainless steel thimble identical to the ones in the expansion tank and dump tank. Aluminum cylinders were used as a sodium analog as they have similar electrical conductivity. A cable and winch system was used to change the relative position of sensor to aluminum by moving the sensor vertically inside the thimble. Finally, a 72-inch scale with an accuracy of 0.0625-inch was oriented in line with the cable and a marker was affixed to the cable to measure the level changes. All components were checked to ensure they were level and plumb before any measurements were taken. Figure 7 shows a 2D representation of the non-sodium testing stand, with simplified electrical hardware representations.

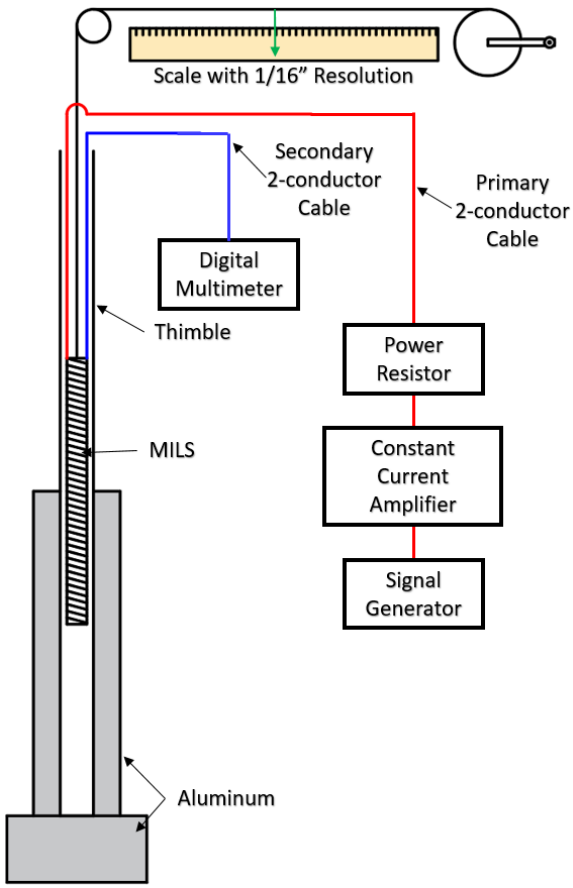

Figure 7: A 2D representation of the non-sodium test stand with electrical equipment layout.

3.3. Sodium Testing Environment at METL

All sodium testing conducted with the MILS-MK-II have been completed in the METL expansion tank. The METL expansion tank performs the important function of providing an expansion volume for the sodium inside of the METL facility. When the temperature of the sodium changes, the density and total

volume of sodium present also change. The expansion tank is therefore always online to provide the extra volume needed to accommodate this volume change. The expansion tank is also the tallest tank in the METL facility, and is an excellent testing ground for level sensor systems. A 300-series stainless steel isolating thimble was installed in the expansion tank before METL underwent the initial sodium fill. This allows for easy maintenance and swapping of sensors. The expansion tank can remain online, at temperature, with sodium inventory while sensors are swapped in and out. A thermocouple rake has also been installed in the expansion tank to provide a calibration standard against which the MILS systems are calibrated. The resolution of the thermocouple rake is 2.5-inch. Sodium level changes are made in the expansion tank by pushing sodium through a dip tube in the METL dump tank using differential pressure. All sodium testing has been performed with the expansion tank at 300°C. Figure 8 shows a half-section view of the METL expansion tank with the MILS-MK-II installed, as well as the thermocouple rake.

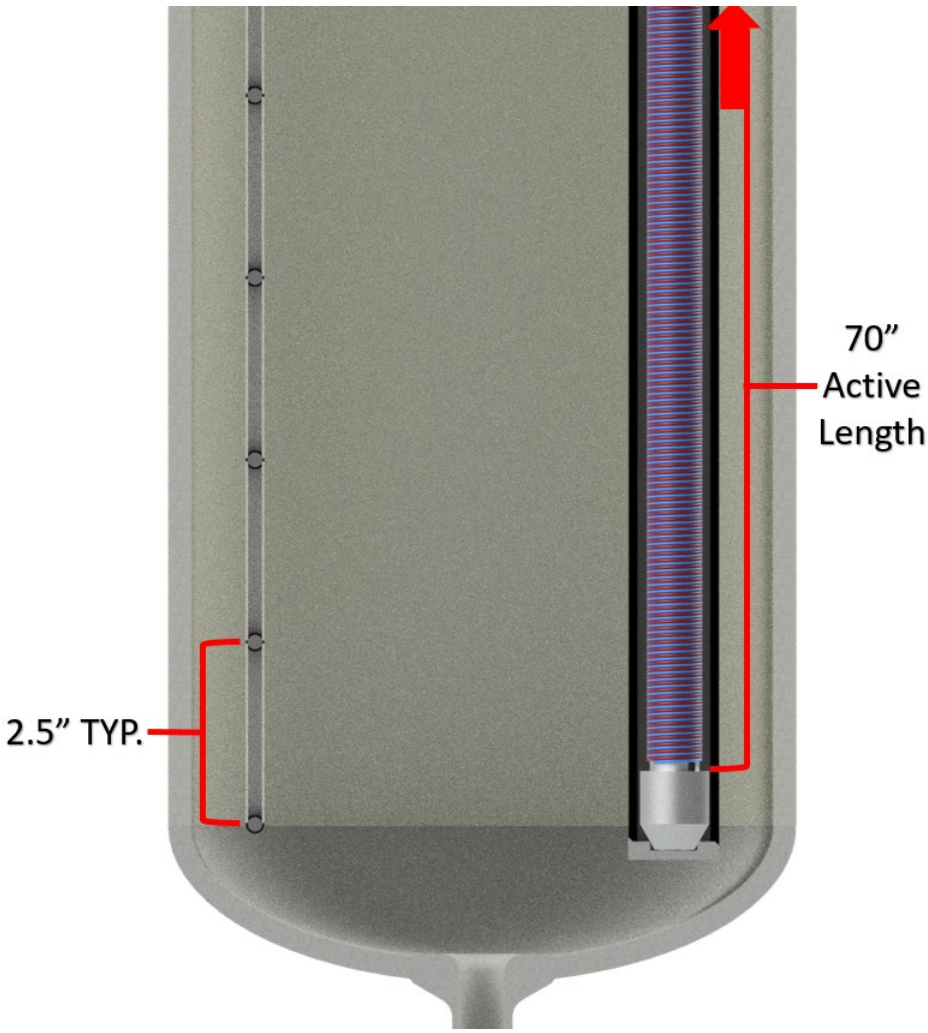

Figure 8: A 3D model of the METL Expansion Tank with the MILS-MK-II and the thermocouple probe used as a calibration standard.

4. Experimental Results

4.1. Non-Sodium Test Stand Results

Experimental data was collected using the 40-inch version of the MILS-MK-II in the non-sodium test stand. The test stand has 40-inches of aluminum that acts as a sodium analog, as they have very similar electrical conductivities and solid sodium would oxidize in ambient atmosphere. Data was collected using a purpose built LabVIEW VI that reads and records the measurements from the Keysight 34465A digital multimeter. The first data point was collected with the sensor fully inserted in the testing stand, where the sensor was surrounded by 40-inches of aluminum. Once a stable reading was taken, the cable and winch system was used to raise the sensor 10% of the full range, or 4-inches. Then a new data point was taken once a stable reading is made. This is repeated for the full range of the surrounding aluminum, until the sensor is no longer surrounded by aluminum. The thimble extends well beyond the aluminum and sensor to ensure the effects of the metal thimble are included. Figure 9 presents the calibration data taken using the 40-in MILS-MK-II in the non-sodium test stand, with a linear regression included. Error bars are included that represent ±1σ uncertainty. The uncertainty associated with the scale is the largest contributor.

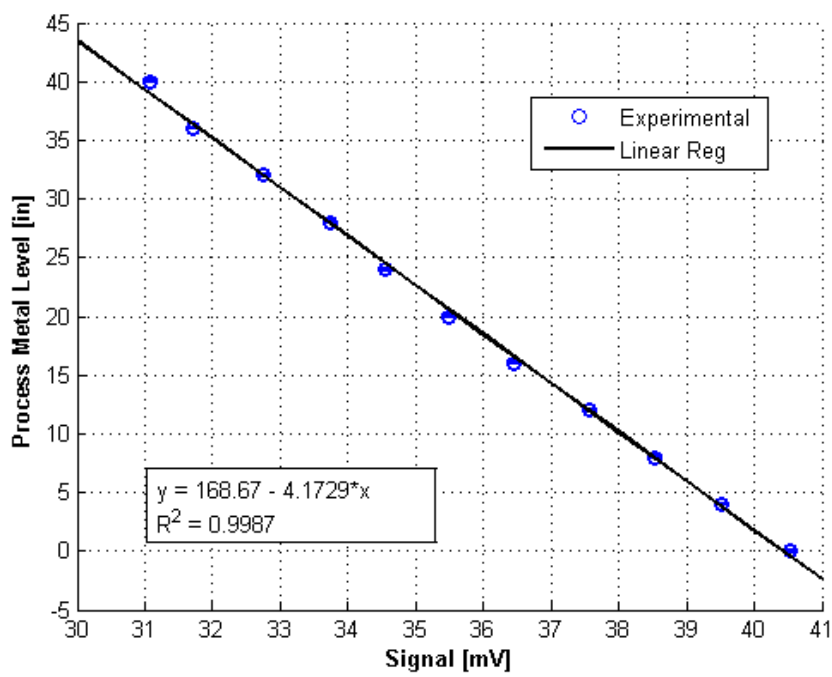

Figure 9: Calibration data collected in the non-sodium test stand with the 40" MILS-MK-II.

When one of the ends of the active length of the MILS is near the edge of the process metal, there are edge effects that skew the data. Figure 10 presents the same data shows in Figure 9, but with the end points

discarded. The linear regression is shown to change, with the R^2 value moving from 0.9987 to 0.9993. This method helps to improve the accuracy of the calibration fit for level readings between the ends of the active coil (middle 90%), but obviously does not improve the level readings at the ends of the active coil. It is therefore best practice to make the sensor slightly longer than the anticipated level measurement range, if possible. Electrical parameters have been collected for each sensor in ambient air, and the data is presented in Table 1. A Keysight U1732C LCR meter was used to collect these parameters. Error bars are included that represent ±1σ uncertainty. The uncertainty associated with the scale is the largest contributor.

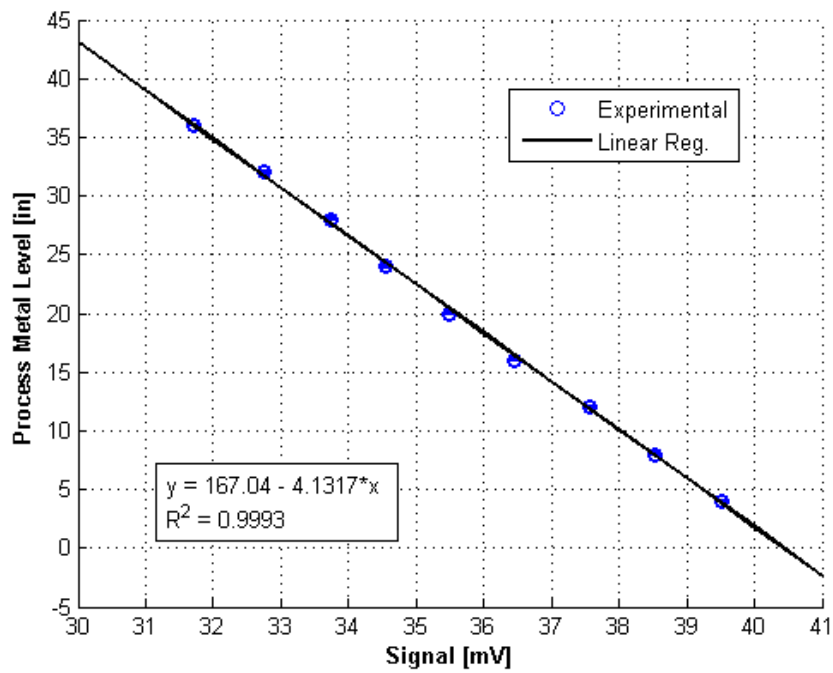

Figure 10: Calibration data collected in the non-sodium test stand with the 40" MILS-MK-II. Two data points are removed where the end of the active length is near the end of the process metal.

Table 1: Electrical Parameters of the four MILS-MK-II sensors.

Class	40 inch				70 inch			
Sensor	40-4849		40-5051		70-5253		70-5455	
Coil S/N	202348	202349	202350	202351	202352	202353	202354	202355
R @ 20°C [Ω]	7.398	7.401	7.363	7.379	12.735	12.643	12.605	12.377
L @ 20°C [μH]	79.60	79.83	79.44	79.46	137.78	136.97	136.09	136.43
R @ 300°C [Ω]	-	-	-	-	-	-	24.94	24.57
L @ 300°C [μH]	-	-	-	-	-	-	119	118.5
Turns per coil	497	497	498	498	860	860	862	862

4.2. Results of Sodium Testing in the METL Expansion Tank

The high temperature sodium testing was performed in the METL expansion tank using one of the 70-inch MILS-MK-II systems. The sensor was installed in the expansion tank thimble while the vessel was hot and full of sodium. Time was allowed for the sensor to equalize at temperature with the expansion tank, and the electrical parameters were collected again. Note that the sensor was now surrounded by the thimble, some sodium, and was at 300°C. This data is presented in Table 1.

Sodium level changes were performed from an initial low level reading of 17.5-inches, to a high level of 47.5-inches. It is not good practice to fully dump the expansion tank as argon gas could become entrained in the sodium piping and possibly travel further downstream. This lead to the conservative low reading of 17.5-inches. The high level was also conservatively selected as the expansion tank does not have an overflow line like the test vessels, and therefore could potentially be filled to the lid. Measurements were taken at 5-inch intervals instead of the 2.5-inch resolution of the thermocouple rake due to heat conducting up the thermocouple rake and obscuring the level change measurement. By bypassing the closest TC point and going 5-inches, the results were much clearer. As this test did not have the ends of the active coil come near the sodium/argon interface, no edge effects were observed. Figure 11 presents the sodium calibration data, with a linear regression. Error bars are included that represent ±1σ uncertainty. The uncertainty associated with the thermocouple rake is the largest contributor.

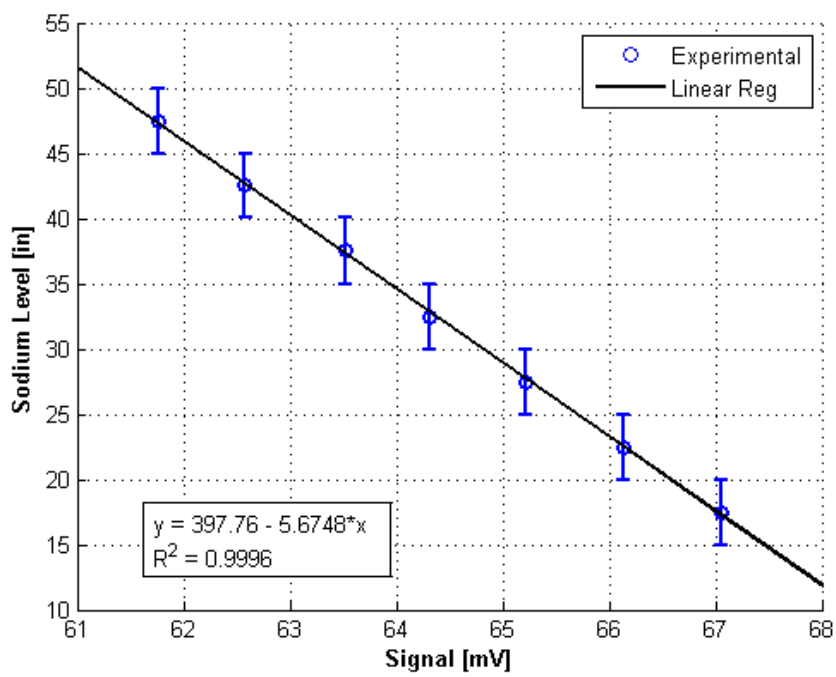

Figure 11: Calibration data collected in the METL Expansion Tank with the 70" MILS-MK-II.

5. Electromagnetic Finite Element Modeling – COMSOL

Electromagnetic finite element modeling was performed using the data collected with the new MILS-MK-II systems. A 2D-axissymmetric model of the entire non-sodium test stand geometry, as well as a 2D-axissymmetric model of the METL expansion tank were generated in COMSOL Multiphysics. These models were then validated using the experimental data available for each case. All material data was temperature corrected for the sodium case. These models will be invaluable in the design progression of the MILS technology. Figure 12 shows the experimental data collected in the non-sodium test stand and compares it to the validated model data. Figure 13 shows the experimental data collected in the METL expansion tank and compares is to the validated model data. The models can be improved if measurements of the material properties used in the analysis are taken, but this is an ongoing effort.

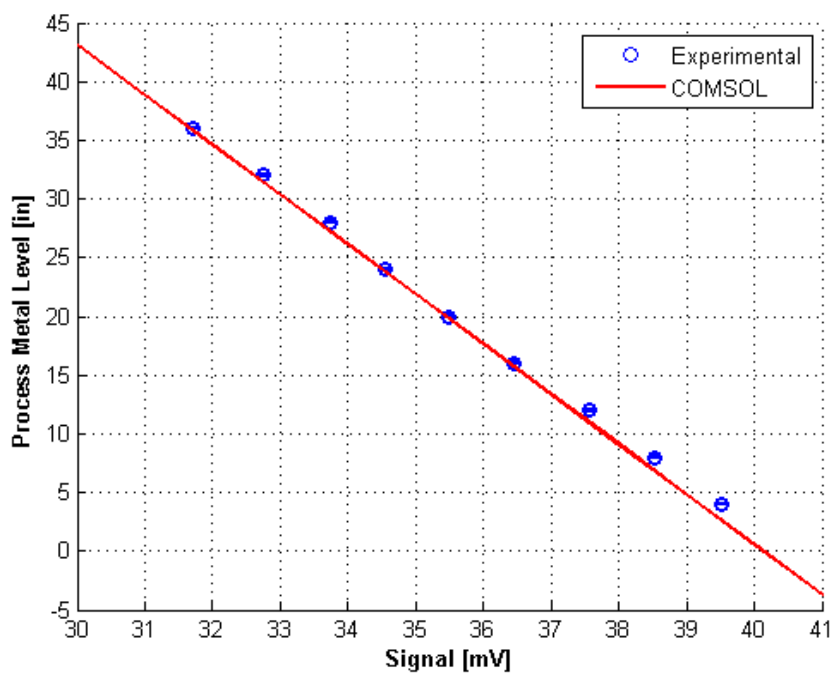

Figure 12: COMSOL analysis data compared to experimental test stand data.

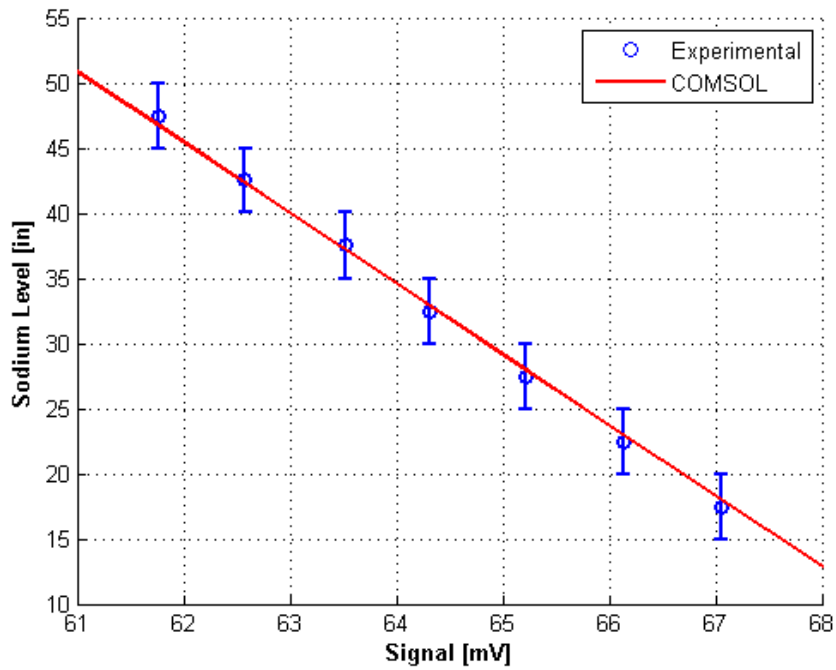

Figure 13: COMSOL analysis data compared to experimental sodium data.

6. Conclusion & Path Forward

The mutual inductance level sensor work has progressed from early concept prototypes to fully functional, calibrated sensors with hundreds of hours of sodium operation. This report covers the design, experimental testing, calibration, and modeling of the most up to date model, the MILS-MK-II. This sensor is extremely robust due to its full metal fabrication and has demonstrated highly linear and repeatable performance in both air and high temperature liquid sodium. While this system is performing well for the needs of the METL facility, there are several improvements that should be made.

The most important development will be a full temperature compensation methodology. While the use of the mutual inductance measurement eliminates the largest temperature sensitivity (the resistance change of the coils), there are still the temperature sensitivities associated with the change in conductivities of the surrounding stainless steel and the sodium itself. Figure 14 presents some example data collected using the constantan prototype sensor in the non-sodium test stand. The test stand was instrumented with heaters, insulation, and thermocouple to allow for elevated temperature testing. The resulting data demonstrated that the change in conductivity of the stainless steel thimble and the aluminum analog significantly effect the calibration. It is therefore important to resolve this to provide a more useful sensor system. Additionally,

the need for an in-situ calibration can be impractical, so the development of a self-calibration method or model calibration would be desired.

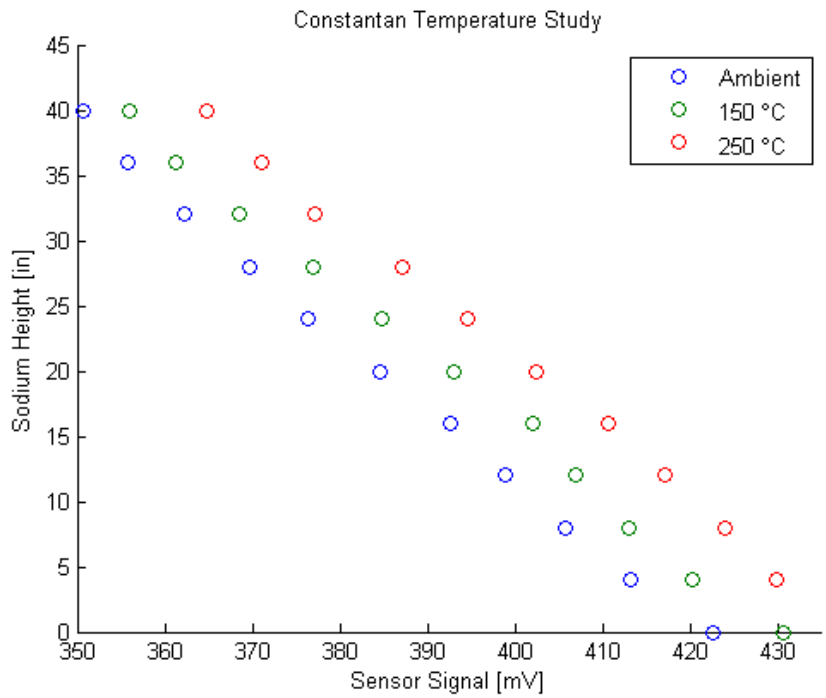

Figure 14: Example temperature change data collected with the constantan prototype in the non-sodium test stand.

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