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# An Evaluation of Pressure and Flow Measurement in the Molten Salt Test Loop (MSTL) System

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# An Evaluation of Pressure and Flow Measurement in the Molten Salt Test Loop (MSTL) System

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**Abstract**

The National Solar Thermal Test Facility at Sandia National Laboratories has a unique test capability called the Molten Salt Test Loop (MSTL) system. MSTL allows customers and researchers to test components in flowing, molten nitrate salt at plant-like conditions for pressure, flow, and temperature. An important need in thermal storage systems that utilize molten salts is for accurate flow and pressure measurement at temperatures above 535°C. Currently available flow and pressure instrumentation for molten salt is limited to 535°C and even at this temperature the pressure measurement appears to have significant variability. It is the design practice in current Concentrating Solar Power plants to measure flow and pressure on the cold side of the process or in dead-legs where the salt can cool, but this practice won't be possible for high temperature salt systems. For this effort, a set of tests was conducted to evaluate the use of the pressure sensors for flow measurement across a device of known flow coefficient Cv. To perform this task, the pressure sensors performance was evaluated and was found to be lacking. The pressure indicators are severely affected by ambient conditions and were indicating pressure changes of nearly 200psi when there was no flow or pressure in the system. Several iterations of performance improvement were undertaken and the pressure changes were reduced to less than 15psi. The results of these pressure improvements were then tested for use as flow measurement. It was found that even with improved pressure sensors, this is not a reliable method of flow measurement. The need for improved flow and pressure measurement at high temperatures remains and will need to be solved before it will be possible to move to high temperature thermal storage systems with molten salts.

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# 1. INTRODUCTION

Thermal energy storage (TES) is the key differentiating technology between Concentrating Solar Power (CSP) and the other renewable energy sources. Thermal storage is a very efficient way to store energy for time periods up to several days and decouples the power production from the solar resource. This technology has been successfully applied to enable solar power plants to generate electricity around the clock or to shift the electricity generation several hours from the solar flux.

To date, the gold-standard of TES systems is nitrate molten salt storage. Nitrate salt for solar applications is either a sodium nitrate / potassium nitrate mixture (near but not at the eutectic point) or a sodium/potassium/calcium nitrate eutectic. These salts have excellent properties in the temperature range of interest, are relatively inexpensive at approximately $1/kg, and have performed for extended time periods with no significant degradation of the heat transfer/storage fluid. These salts are typically used to a maximum temperature of 585°C because of a nitrate/nitrite disassociation that occurs more rapidly above this temperature. Though this reaction is reversible, often the oxygen from the dissociation creates metal-oxides with the fluid handling piping/tankage/pumps/valves and thus corroding the equipment.

In order to create more cost effective solutions for CSP, the US DOE has created the SunShot Initiative which seeks to reduce the cost of CSP generated electricity to 6¢/kWhr. This aggressive goal requires improvements in the entire CSP system, but is likely to require a higher efficiency power cycle which requires a higher operating temperature. The SunShot goal is above 650°C. This will require different heat transfer fluids and different thermal storage fluids. There are numerous possibilities for meeting these requirements, but each one has significant challenges that must be overcome. Two possible solutions for this are the carbonate and chloride salts both of which can be made to have good temperature ranges of operation and are relatively inexpensive when compared to some of the other heat transfer options. The salts are best used for sensible heating which is advantageous for its close match to Rankine and Brayton power cycles for thermal input profile. Also, by utilizing all of the research and development that has gone into salt storage systems, high temperature salts face many fewer technical challenges than other heat transfer/storage options.

However, there are still challenges that must be solved before either chloride or carbonate salts are economical to use in thermal energy storage systems. In either the 585°C nitrate salt case or the >650°C carbonate or chloride case, there is a significant challenge regarding pressure and flow instrumentation. There are currently no measurement options for either pressure or flow above 535°C. This work seeks to determine the ability of current pressure and flow instrumentation to meet the challenges of high temperature measurement in mildly or highly corrosive environments. The evaluation is done with current generation technology in the Molten Salt Test Loop (MSTL) at Sandia National Laboratories.

# 2. CURRENT TECHNOLOGY FOR FLOW AND PRESSURE MEASUREMENT IN MSTL

The Molten Salt Test Loop (MSTL) at Sandia National Laboratories is a newly completed test facility for the testing and evaluation of components in flowing molten salt in plant-like conditions. The system is nominally capable of flow to 600gpm, 600psi, and 585°C though these values are increased or decreased depending on the pump curve at the desired operating point. The system has 3 parallel test loops that provide locations where a customer's experiment can be attached for testing in flowing salt in plant-like conditions. Figure 1 shows a schematic of the MSTL flow path and highlights the pressure transducers (indicated as PI_...) and the flow meters.

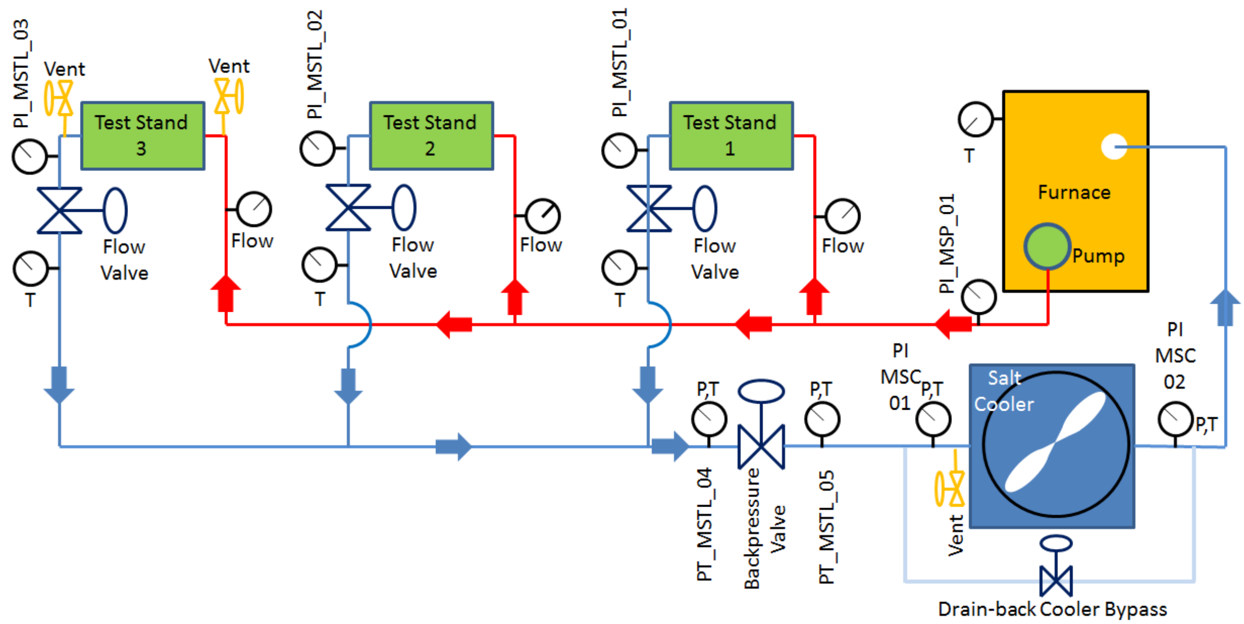


**Figure 1. Flow Schematic for the Molten Salt Test Loop Showing Flow and Pressure Meters.**

## 2.1 Flow Measurement in MSTL

The flowmeters utilized in MSTL are double-pass, ultrasonic flow meters manufactured by Krohne. These flowmeters are installed on each of the 3 test loops in the MSTL system. The performance of these flowmeters has been tested by using the pump speed to determine the expected flow from the pump curve. The pump curve is derived from measured data in a water test at ambient conditions and then scaled for molten nitrate salt's specific gravity and for temperature. Also, a test was performed in which the pump was run at a constant speed, the backpressure control valve put at a specific position, and 400gpm flow run through each test leg individually. Though imperfect in testing due to differences in pipe length, this test showed the flowmeters to agree under flow control with pump speed matching within 6%. Some mismatch in pump speed is expected because the flow paths to test loops 1 and 3 differ by approximately 80ft. An additional potential error source in this test is the valves which could have slightly different limits positions and a 0.5% measurement resolution in the valve position. Throughout the operation of MSTL, the flow meters have not appeared to exhibit noticeable drift, their output appears to be very consistent meter to meter and, so far as can be determined, the flow measurement appears to be accurate. However, these flowmeters have a temperature limit in the technical specifications of 535°C. For the operation of MSTL, Sandia was given a special guarantee that the meters would perform accurately and safely up to the maximum design temperature of MSTL of 585°C. So, while these meters were acceptable for this application, they likely would not be acceptable for a CSP plant that had to meet production guarantees. These flowmeters are not capable of meeting the >650°C goals of the SunShot program. The reason for this temperature limitation is not completely clear. It is likely at least partly due to the material challenges at temperatures above 600°C where stainless steel loses much of its strength and the materials of choice are high temperature nickel superalloys. It may be difficult, or at the very least expensive, to provide flowmeters in these materials. For some applications, the desired material properties seem to be difficult to achieve with nickel superalloys and some of their work-hardening tendencies. Additionally, few electronics devices will operate at these temperatures, requiring remote mounting. This requires the use of temperature controlled dead-legs or intermediate fluids in the transducer to remove the electronics to a cooler area. In fact, the MSTL flow meters require that the flow meter not be insulated. So in contrast to the rest of the piping, valves, furnace, and MSTL equipment which is heavily insulated, the flow meters are open to atmosphere. The meters must still be heat traced to prevent salt freezing in the main flow path and therefore the flow meters consume considerable amounts of energy when the system is not flowing salt. This point is illustrated by Figure 2, taken during construction, which shows the piping with only half of its insulation thickness installed.

**Figure 2. A Flowmeter in MSTL, Shown During Construction, Remains Uninsulated and Is Contrasted with the Highly-Insulated Piping.**

## 2.2 Pressure Measurement in MSTL – First Attempt

In contrast to the flow meters which have been fairly successful in MSTL, the pressure sensors have given significant challenges. The transducers used are technology originally developed for the injection molding industry and utilize a diaphragm that is in contact with the heat transfer/storage fluid on one side. Because of the contact with salt, the materials that can be used for this diaphragm are limited. Behind this diaphragm is a very small capillary filled with sodium-potassium (NaK) fluid. Pressure waves in the salt impinge on the diaphragm which transmits the wave to the capillary fluid. After traveling the length of the capillary in the capillary fluid, the pressure wave impinges on diaphragm that is located with the sensing technology for the sensor, very often a capacitance measurement, or less often, a laser measurement of diaphragm movement. The advantage of these sensors is that they remove the sensitive electronics package from direct contact with the high heat and potential corrosion experienced at the HTF end of the transducer. Figure 3 shows one of the first pressure transducers installed at MSTL. The sensing diaphragm is at the lower left of the Figure. The capillary is in the straight tube and the instrumentation electronics are in the larger unit at the upper left of the Figure.

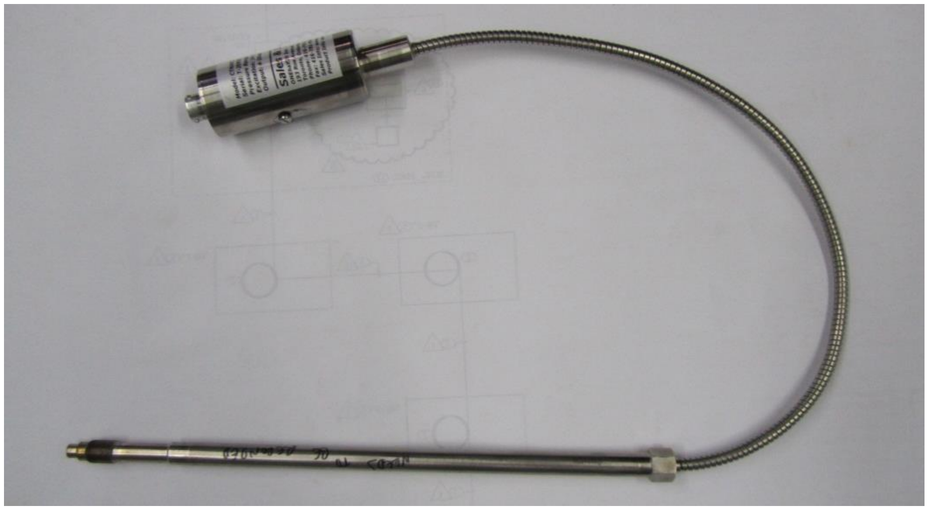

**Figure 3. This One-Half 20 Pressure Transducer Was Initially Installed at MSTL But Proved to be Unreliable**

The first pressure transducers provided for MSTL, shown in Figure 3, were manufactured by One-half 20. These pressure transducers had some manufacturing defects as they stopped measuring reasonable pressure values after only being exposed to 300°C heat and no pressure. The company fixed 3 of the 8 transducers and returned them to Sandia where they await testing at some point in the future. Some of the other pressure transducers were damaged upon removal from MSTL and were thus deemed to be structurally suspect and not worthy of repairing.

## 2.3 Pressure Measurement in MSTL – New Transducers

Because of the problems with the original transducers, an emergency purchase of Gefran pressure transducers was made. One of these transducers is shown in Figure 4. Similar in design to the One-half 20 transducers, the HTF diaphragm is at the end of the rigid stainless tubing at the bottom left of the Figure. The capillary transmits the pressure wave through the length of the stainless tubing and the electronics unit is shown at the upper left of the Figure. The Gefran transducers are temperature compensated and the thermocouple connection at the lower right of the Figure is for this purpose. It is important to note, however, that the temperature measured is at the tip of the transducer and the remainder of the transducer, including the capillary, is not temperature compensated or temperature controlled. The Gefran transducers have an upper temperature limit of 535°C which is due to the strength reduction of the PH15-5 stainless steel used in the threaded portion of the transducer end as well as temperature limitations of the diaphragm. Because this is a potential safety and performance issue, there has been no approval to take these sensors above 535°C. Gefran has developed a pressure transducer that may be an improvement over this type by changing the thread to a larger thread size and by changing a few of the materials of construction. However, none of the current options are rated for measuring chloride or carbonate salt at 650°C or above. Gefran is contemplating changing the materials for their sensor, but have not done so yet.

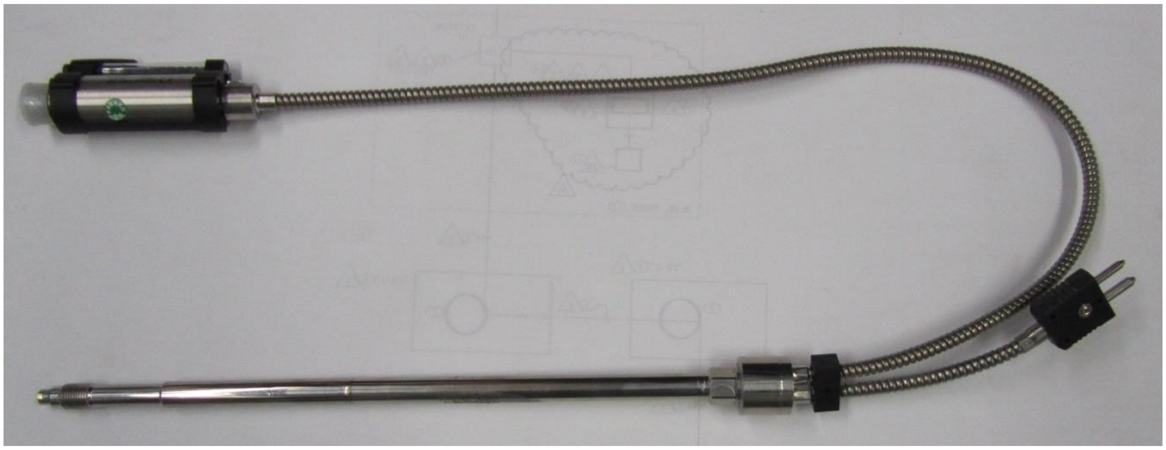

**Figure 4. Gefran Pressure Transducer Like Those Installed in MSTL.**

As of the 3rd month of operation, the Gefran transducers have shown good reliability as far as returning signals of somewhat reasonable magnitude. However, upon first using the transducers, it quickly became apparent that they were significantly affected by ambient temperature conditions and with no salt in the line the pressure readings would change by several hundred psi day to night.

## 2.4 Pressure Measurement with Insulated Capillaries

The first attempt to counteract this temperature sensitivity was to place insulating sun covers over the transducers to eliminate the solar input from directly affecting the transducer. Though this may have helped some, the change was relatively ineffective. The second attempt was to wrap insulation around the capillary and the J-box holding the electronics unit.

**Figure 5.  A Test Was Performed by Wrapping the Box Containing the Electronics with Insulation**

Figure 6 shows pressure data measured during testing of MSTL.  The red, blue, yellow, and green lines in the Figure are pressure measurements throughout the night of September 20, 2012 and values for these measurements are in psig on the right scale of the graph.  It can be seen that after stopping salt flow just before 2pm, every pressure transducer indicates a pressure drop and the pump outlet indicates a pressure drop of 190psi.  It is important to remember that through night represented by this graph, the pipes were actually at 0psig and the temperature of the pipe was maintained at 300°C throughout the night by the heat trace system.  Obviously, pressure indicators that show 190psig pressure change that doesn't exist are not performing satisfactorily.

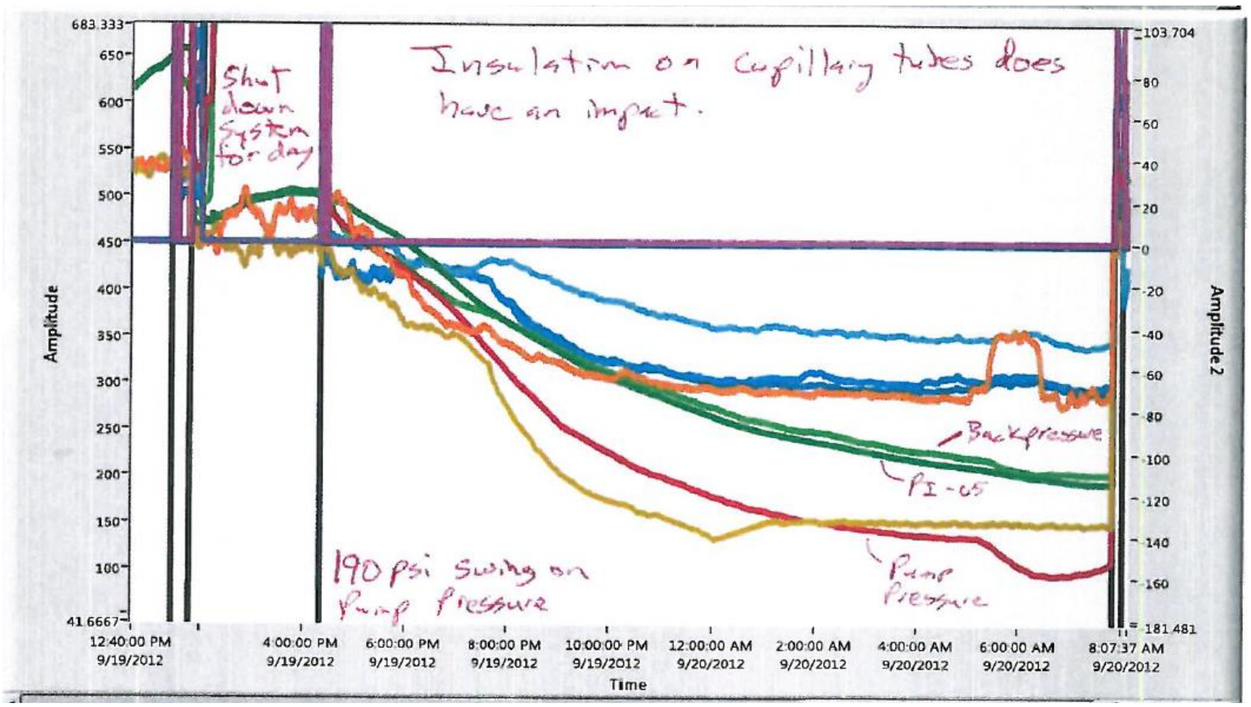


**Figure 6. MSTL Commissioning Data Showing the Effects of Temperature on Measured Pressure. The Lines Show Pressure Measurement and the Scale is psi on the Right Side of the Graph.**

## 2.5 Pressure Measurement with Heated Electronics

Testing with the insulated capillary showed that the heat from the pipe and salt system had a significant effect on the measured pressure values. The salt flowing in the pipe heated the capillary and caused a large increase in the reported pressure. Additionally, even with the capillary insulated, the diurnal temperature swing caused a matching pressure change. This result indicated that insulating the capillary was not sufficient and that the electronics package would have to be fully insulated as well. In addition, it was apparent that the capillary and electronics package would have to be heated to such an extent that the pressure transducer would maintain a constant a constant temperature whether salt was flowing or not. To test this theory, an electronic junction box was attached to the end of the pressure transducer protection pipe and the entire capillary and electronics package were placed in the box as shown in Figure 7. A heater was placed in the bottom of the box as can be seen as a flat metal strip with terminal posts shown in the Figure. For the test, the box was then insulated externally. The results of this test were positive, so a more permanent solution was developed.

**Figure 7. The Capillary and Electronics Package Were Placed in a Box with a Heater (seen at the bottom of the box)**

## 2.6 Pressure Measurement With Heated and Insulated Transducers and Electronics

Based on the success of the above test, a box-in-a-box concept was developed as shown in Figure 8. The inner electrical box is connected to the pipe that protects the pressure transducer. This inner box contains the capillary, electronics package, and a PID controlled heater. This inner box in surrounded by a larger outer box which has a 2 inch spacing for insulation all around the inner box. In the Figure, the insulation can be seen behind the inner box, but the insulation has not yet been added to the sides and in-front of the inner box. A completed box is shown in Figure 9, though the Figure shows Temporary lagging on the insulation surrounding the transducer protection pipe. This configuration has significantly improved the pressure transducer performance over previous configurations. Figure 10 and Figure 11 show a 22 hour stability test. The salt stops flowing at about noon on the left hand side of the graph and then the pressure transducers (red, green, and blue lines) are monitored for 24 hours. Most importantly, the 190psig pressure swing of previous tests has now been reduced to 20 psi or less. Secondly, the pressure transducers do not experience a large dropoff in reading after the heat of the flowing salt stops at noon. This performance improvement is marked, but one would hope for single digit variation or better. Therefore, a test was performed to see if the pressure transducers in this state were sufficient to use as another flow meter.


**Figure 8. The Box in a Box Shows the Capillary, Electronics Package, and Heater in the Inner Box**

**Figure 9. The Completed Box-In-A-Box Concept with Temporary Lagging on the Pipe**

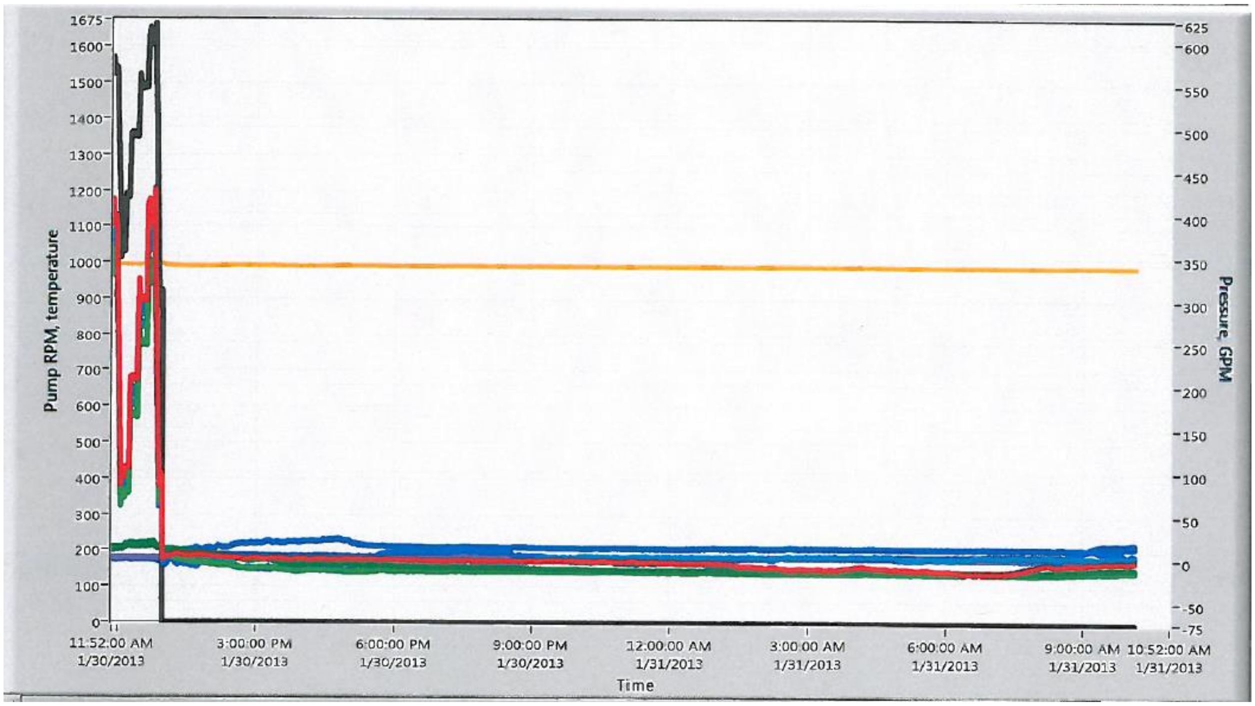


**Figure 10. A 22 Hour Test Shows Good Stability in the Pressure Transducers (red, blue, green lines)**

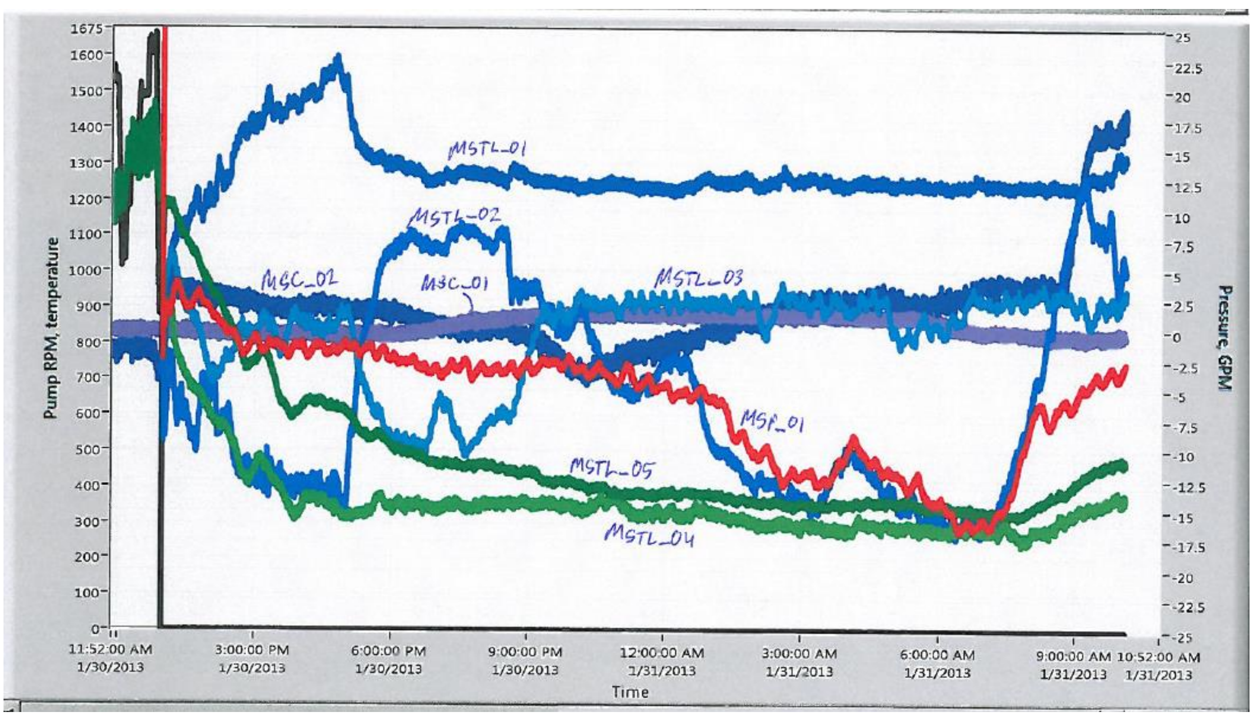


**Figure 11. An Expanded View of the Pressure Stability Test Shows Approximately 20psig Variation of 22 Hours**

# 3. AN EVALUATION OF USING PRESSURE TO MEASURE FLOW IN MSTL

When the initial Failure Mode and Effects Analysis (FMEA) was performed for MSTL, the loss of flow measurement was determined to be a severe failure mode because of the need to determine quickly and accurately if there is a breach in a customer's test. With the improved performance of the pressure transducers, a test was performed to determine if the pressure transducers could measure the flow on both sides of a valve to accurately determine flowrate. The use of a pressure drop to measure flow is a very common practice, though it is usually done with a device having a single flow coefficient, Cv, such as a knife-edge orifice plate or a Venturi. Because these devices have not been successful in salt applications (due primarily to poor pressure measurement) there is not an orifice or Venturi flow meter installed in the MSTL system. Without this fixed-Cv component, a characterized variable Cv device is the next best choice and the valves were provided with Cv curves at different valve positions. A test was run in which a broad set of flow and pressure conditions were evaluated with the pressure drop measured across Flow Control Valves 1 and 4 (FCV-1 and FCV-4). FCV-1 is used to set flow and an initial pressure drop within test loop 1. FCV-4 is used to set the back pressure of the entire system. Both of these valves have pressure transducers on both the upstream and downstream sides of the valve. The transducers are not optimally positioned, however, as they are not designed as a flow meter. The nominal test conditions are shown in Table 1. The results of the test are shown in Figure 12. The Figure shows that the valve 4 gives reasonable results around 100psi operating pressure (tests 4 and 8) but the flow values get worse with increasing system pressure. The tests indicate that it will not be possible to rely on the valves and pressure transducers as a corroborating flow measurement, and so another method is required, especially above 535°C where the pressure transducers are not rated for operation.

**Table 1. Test Conditions for the Pressure Sensor / Flow Meter Evaluation**

| Test Number | Pressure (psig) | Flow (gpm) | Pump Speed (RPM) |
|---|---|---|---|
| 1 | 200 | 400 | 1130 |
| 2 | 300 | 400 | 1321 |
| 3 | 400 | 400 | 1489 |
| 4 | 100 | 500 | 1065 |
| 5 | 200 | 500 | 1237 |
| 6 | 300 | 500 | 1401 |
| 7 | 400 | 500 | 1536 |
| 8 | 100 | 500 | 1037 |
| 9 | 100 | 600 | 1187 |
| 10 | 200 | 600 | 1355 |
| 11 | 300 | 600 | 1488 |
| 12 | 400 | 600 | 1604 |

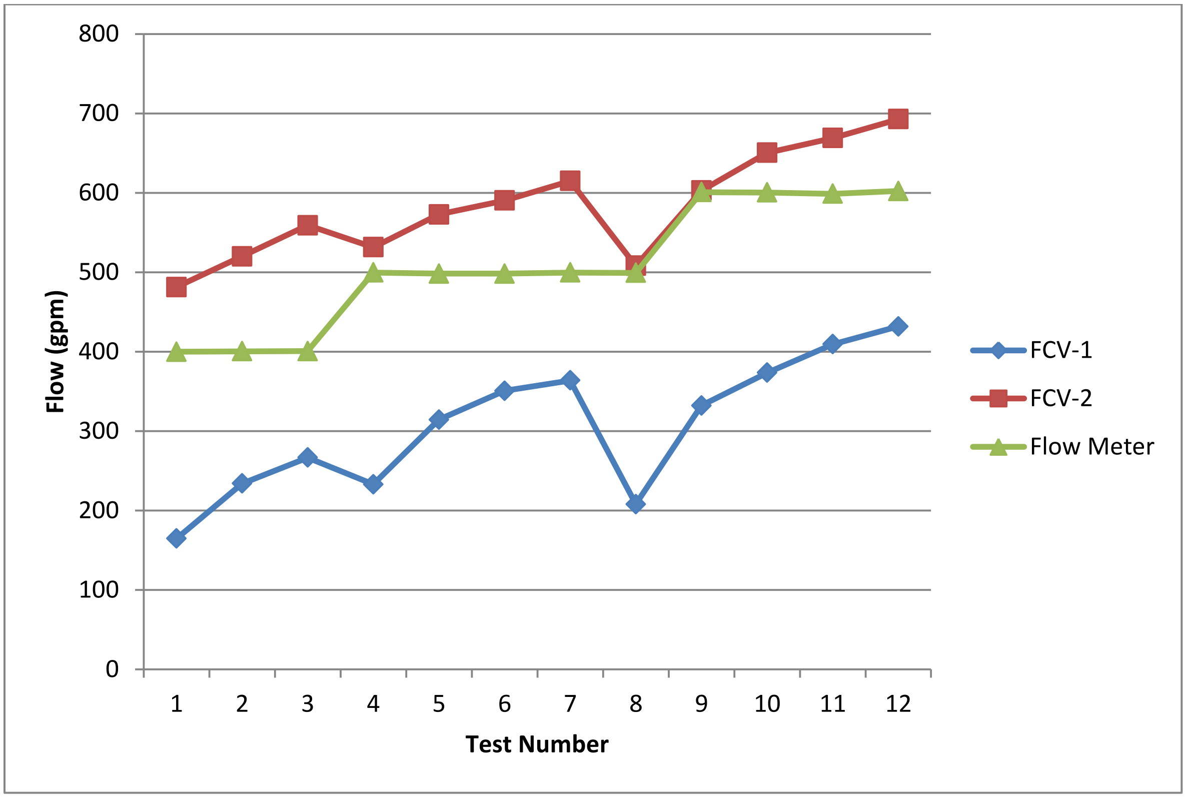


**Figure 12. Flow Results from Flowmeter and Pressure Drop Test Showing Poor Agreement Between the Pressure Drop and Flow Meter**

# 4. CONCLUSIONS

The pressure sensors provided with the Molten Salt Test Loop (MSTL) have not proven to give reliable pressure measurement. The sensors are severely affected by ambient temperature changes indicating pressure changes of 190psi when the pressure was in fact ambient. To counteract this pressure variation, several methods of reducing ambient temperature change were implemented including insulation, colocation of sensor and transmitter, and heating. A solution has been implemented that corrects much of the pressure variation and testing has shown the pressure transducers to change less than 20psig over a 22 hour time period.

At the same time, an alternative flow measurement method was needed as a back-up method for the MSTL flowmeters. Though the flowmeters have been reliable thus far, they are extremely important for the operation of the test loop and determining if there are salt leaks in a customer's test apparatus. Therefore, an additional method of measuring flow was determined to be important. Based on the improved pressure transducer measurements, an evaluation was conducted to see if the pressure drop across valves with know Cv would be accurate enough to utilize. A test was performed and the flow measurement using the pressure drop was not sufficiently accurate to be usable.

There remains a significant need to develop both pressure and flow metering equipment that will be usable in temperatures over 535°C. This need is significant and will have a deleterious effect on efforts to achieve the SunShot goals with sensible fluid heat transfer and storage materials.

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