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CURRENT STATUS OF INSTRUMENTATION FOR A FLUORIDE-SALT HEAT TRANSPORT DEMONSTRATION LOOP*

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ABSTRACT

A small forced-convection liquid-fluoride-salt loop is under construction at Oak Ridge National Laboratory (ORNL) to examine the heat transfer behavior of FLiNaK in a heated pebble bed. Loop operation serves several purposes: (1) reestablishing the infrastructure necessary for fluoride salt loop testing, (2) demonstrating a wireless heating technique for simulating pebble type fuel, (3) demonstration of the integration of silicon carbide (SiC) and metallic components into a liquid salt loop, and (4) demonstration of the functionality of distinctive instrumentation required for liquid fluoride salts. Loop operation requires measurement of a broad set of process variables including temperature, flow, pressure, and level. Coolant chemistry measurements (as a corrosion indicator) and component health monitoring are also important for longer-term operation. Two dominating factors in sensor and instrument selection are the high operating temperature of the salt and its chemical environment.

Key Words: Liquid Salt Loop, Fluoride Salt, High Temperature Instrumentation.

1 INTRODUCTION

The ever-increasing demand for higher system thermal efficiency necessitates power generation cycles transitioning to progressively higher temperatures. Similarly, the desire to provide direct thermal coupling between heat sources and higher temperature chemical processes provides the underlying incentive to move towards higher temperature heat transfer loops. As the system temperature rises, progressively fewer and fewer material combinations remain candidates for the loop. The requirement to operate at above 700°C (and the desire to continue to accommodate higher temperatures) eliminates all but a few materials from consideration. An earlier evaluation of molten salt reactor secondary coolants provides a broad overview of the requirements and issues for a similar heat transfer loop albeit focusing on somewhat lower temperatures [1].

All heat transfer loops consist of a heat source, a heat sink, and a heat transfer mechanism. A simplified overview of a liquid-fluoride-salt heat transfer (LSHT) loop is shown in Figure 1. As a single-phase, incompressible liquid, the loop also is required to have an expansion volume. A drain tank is also necessary to enable initial filling and to allow for servicing. Since the fluoride salts have melt points well above ambient, loop preheating is also required. Further, chemistry control is required since fluoride salts only maintain their relatively inert nature when the free fluorine potential is minimized.

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Effective high temperature thermal energy exchange and delivery at temperatures over 600°C has the potential of significant impact by reducing both the capital and operating cost of energy conversion and transport systems. High-temperature heat transport is one of the key technologies necessary for liquid fuel production from coal and could potentially enhance efficiencies of high-temperature solar systems. Today, no standard heat transfer fluids are commercially available above 600°C. The high pressures associated with water and gaseous coolants (such as helium) at elevated temperatures impose limiting design conditions for the materials in most energy systems. Liquid salts offer high temperature capabilities at low vapor pressures, good heat transport properties, and reasonable costs and are therefore leading candidate fluids for next generation energy production. Liquid-fluoride-salt-cooled, graphite-moderated reactors—referred to as Fluoride Salt Cooled High-Temperature Reactors (FHRs)— are specifically designed to exploit the excellent heat transfer properties of liquid fluoride salts. The FHR's outstanding heat transfer properties, combined with its fully passive safety, make this reactor the most technologically desirable nuclear power reactor class for next-generation energy systems.

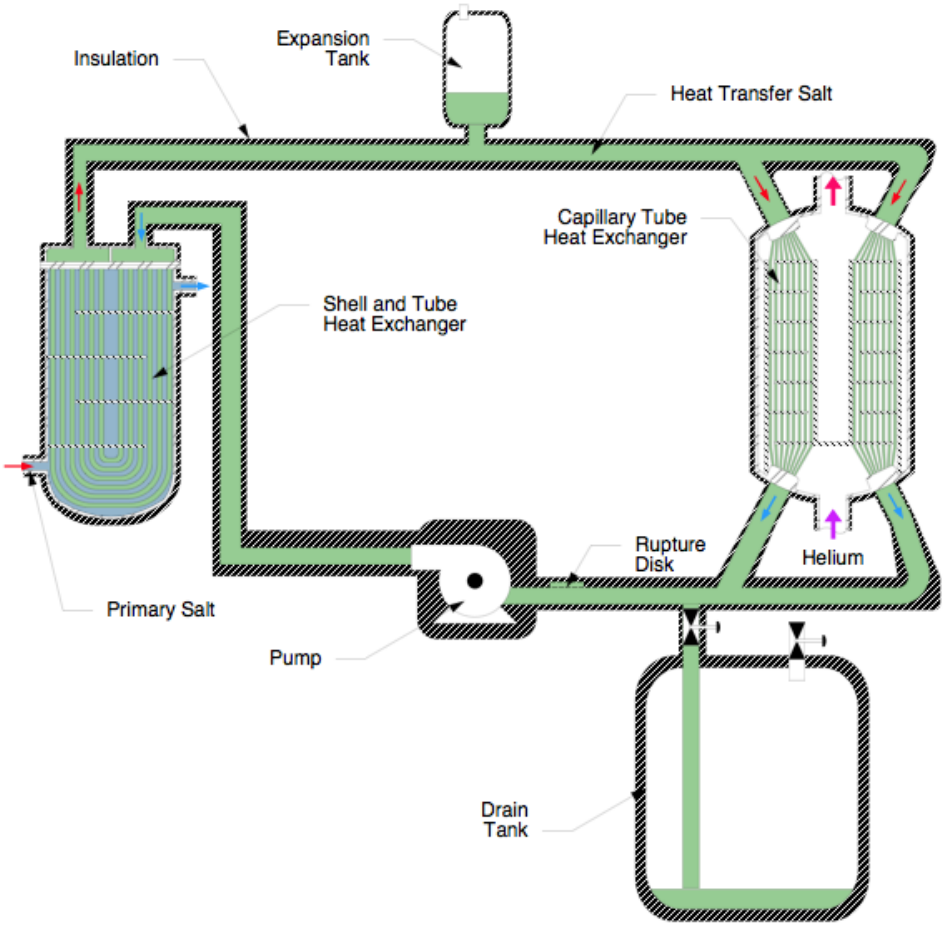

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Figure 1. Overview of a liquid salt heat transfer loop.

A primary advantage of liquid fluoride salts is their high boiling points (> 1400°C for relevant salts) and the consequent low system pressure at operating temperatures. Liquid fluoride salts are composed of the most electronegative element and highly electropositive elements resulting in highly chemically stable compounds that have low reactivity with the environment. Fluoride salts have viscosities a few times that of room temperature water at operating temperatures and a comparable heat capacity per unit volume to room temperature water, resulting in small volumetric pumping requirements and low pressure drop

during flow. The inductive pebble heating is intended to increase the FLiNaK (lithium fluoride, sodium fluoride, potassium fluoride 46.5-11.5-42 mole percent) temperature ~10°C across the test section.

This paper describes the current status of measurement instrumentation for the ORNL liquid fluoride salt loop. At the time of this writing several items are being designed and fabricated. It is expected that operation of the loop in 2011 will allow further investigation of instrumentation performance.

2 SYSTEM OVERVIEW

The salt loop will consist of an Inconel 600 piping system, a sump type pump, a high-purity SiC test section, and an air cooled heat exchanger, as well as auxiliary systems needed to pre-heat the loop, transport salt into and out of the loop, and maintain an inert cover gas over the salt. A 30 kHz inductive heating system will be used to provide up to 250 kw of power to a 15-cm interior diameter SiC test section containing a packed bed of 3-cm graphite spheres. A SiC to Inconel 600 joint will use a nickel/grafoil spiral wound gasket sandwiched between SiC and Inconel flanges. The loop system can provide up to 4.5 kg/s of salt flow at a head of 0.125 MPa and is intended to operate at a pressure just above atmospheric. Salt Reynolds numbers of up to 2600 in the pebble test section are possible with this configuration. A sump system is provided to drain and store the salt when not in use. Instrumentation on the loop will include pressure, temperature and flow measurements, while the test section will be instrumented to provide pebble and FLiNaK temperatures.

A detailed schematic of the ORNL demonstration salt loop system based on the reactor loop of Figure 1 is shown in Figure 2 indicating the instrumentation. Power is delivered to the pebbles through an induction coil mounted on the outside of the SiC tube, which holds the pebbles. Liquid salt is forced up through the pebble bed test section and through the loop where the heat is removed then pumped back through the test section. Temperature, flow, and differential pressures are measured to determine the heat transfer properties of the graphite pebbles in the test section. The flow velocity is about four meters per second in the 1-inch Schedule 40 loop piping. A further detail of the graphite pebbles loaded into the SiC test section is illustrated in Figure 3. Inconel 600 grids are located at the top and bottom of the test section to confine pebbles to the test section.

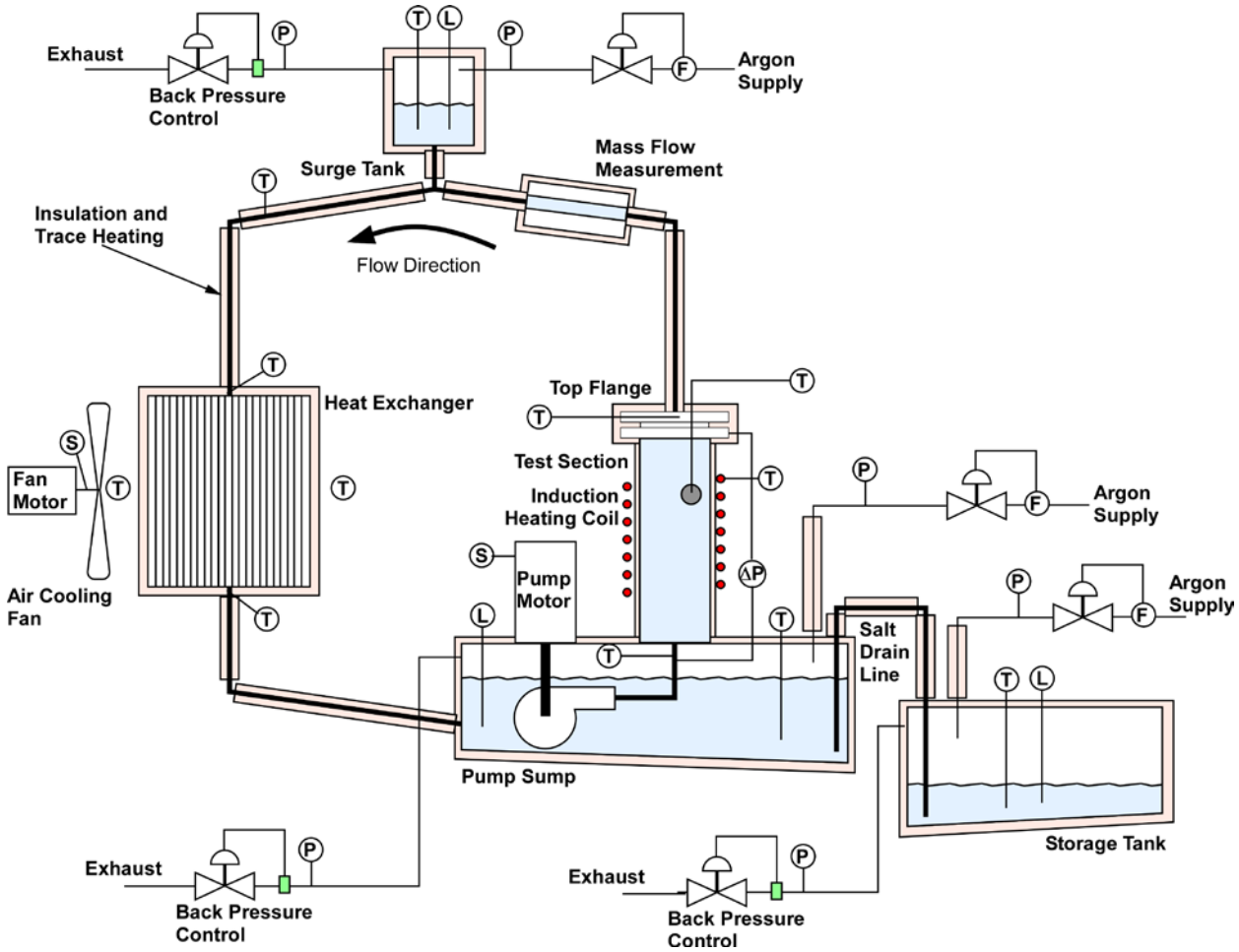

Figure 2. Liquid salt heat transfer test loop illustration showing measurement locations.

3 INSTRUMENTATION

LSHT loop operations require measurement of a broad set of process variables including temperature, flow, and level. Coolant chemistry measurements (as a corrosion indicator) and component health monitoring are also important for longer-term operation.

3.1 Temperature

Temperature measurement is indicative of both process conditions as well as a primary component of the energy balance calculations. Thermocouples are the most common transducer for process temperature measurement and will be used in the demonstration loop.

3.1.1 Liquid salt and piping temperature

Type N thermocouples have been selected as the loop temperature measurement technology outside of the magnetic field generated by the induction coil. Within the coil, precious metal (Type S) thermocouples will be used to measure both the salt and pebble temperatures.

Type N (nicrosil-nisil) thermocouples were developed as a lower drift alternative to other base metal (particularly Type K) thermocouples [2,3]. Nicrosil and Nisil alloy compositions feature increased component solute concentrations (chromium and silicon) in the nickel base to transition from internal to surface modes of oxidation. They also include solutes (silicon and magnesium), which preferentially oxidize to form oxygen diffusion barriers [4].

Piping measurements are made with thermocouples attached to the exterior piping. For tank measurements, thermocouples will be inserted in thermowells. The storage tank has three heating zones due to the expansion of the salt upon melting and the resulting requirement of heating from a free surface.

3.1.2 Graphite sphere temperature

Type S thermocouples are non ferromagnetic and consequently are not affected by the magnetic field generated by the induction coil. The Type N thermocouple, which is used elsewhere in the loop, contains nickel and has magnetic properties that undergo a step change in output when the magnetic material reaches its Curie point (see ref. [5] for magnetic field induced errors in thermocouples). The ac field strength produced by the induction coil at full power is about 0.05 T at 30 kHz, sufficiently high to introduce some uncertainty.

Nickel will be used for sheathing of the Type S thermocouples. Nickel will only slightly attenuate some of the high-frequency induction field. The ac field has the potential to generate exogenous voltages across the thermocouple leads, which can affect the thermocouple preamplifier input stage, increasing uncertainty in the temperature reading. Because of its lower resistivity, the skin depth of nickel is less than that of Inconel 600 (a commonly used sheathing material). For a standard 40-mil sheath, the wall thickness at about 130 μm offers no appreciable attenuation to the ac induction field since skin depth at 30 kHz (and 700°C) is about 760 μm. Nickel will soften at 700°C but has sufficient strength for use as sheathing.

Sphere internal temperature will be measured by inserting the thermocouple end into the sphere using a “fish hook” technique, which prevents the sphere from slipping off the thermocouple sheath. The thermocouple will pass once through the graphite sphere turn and reenter forming a “fish hook.” (Refer to Figure 3.) The temperature measurements will be made in the central portion of the test section with the thermocouple sheathing exiting through Swagelok fittings at the top flange.

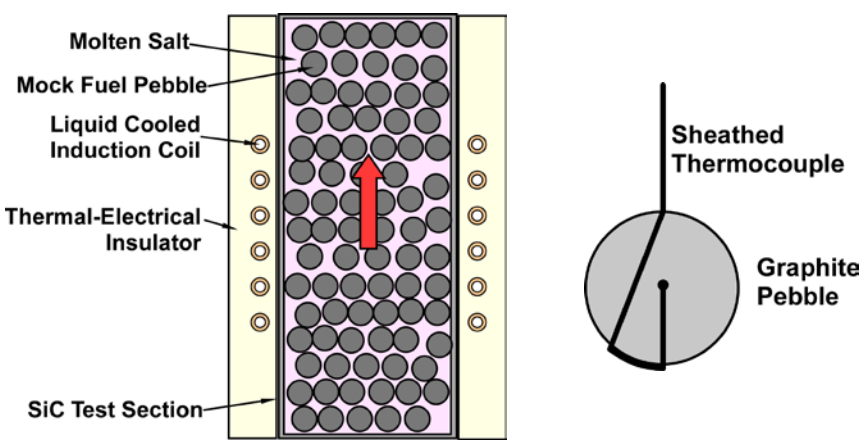

Figure 3. Left: test section shown filled with graphite pebbles. Select pebbles will be outfitted with internal thermocouples. Right: “fish hook” insertion method to prevent pullout.

3.2 Salt Flow

Liquid salt flow measurements are intended to be performed using an external, clamp-on, ultrasonic flowmeter. Ultrasonic flowmeters (shown schematically in Figure 4) are widely used across the industry due to their low uncertainty and stability. External ultrasonic flowmeters for high temperatures are semi-commercial with remaining development and demonstration of the thermal buffer rods and pipe coupling required to become a fully commercial component. ORNL is currently working with a commercial supplier to validate the performance of their instrumentation. The high temperature of the salt environment requires that mechanical stand-offs be used to limit the ultrasonic transducer temperature exposure. Typically, piezoelectric transducers are used at the cool end of the waveguide. External cooling may be required to keep the transducers below 200°C. The electronics, which is essentially the same for water and liquid salt ultrasonic flowmeters, would be located outside the immediate loop environment.

As an alternative, venturi-type flowmeters that use differential pressure gauges as their active element can be used. The differential pressure gauges required for Venturi base flow measurement either require diaphragm deflection measurement tolerant of salt temperatures or impulse line interconnection between a high temperature and a low temperature diaphragm, which would be instrumented with conventional low temperature diaphragm deflection technology. The impulse line fluid would be a lower melting point fluid such as a lead-bismuth eutectic (44.5%Pb-55.5%Bi) with a 123-°C melting point or a lower melting point salt.

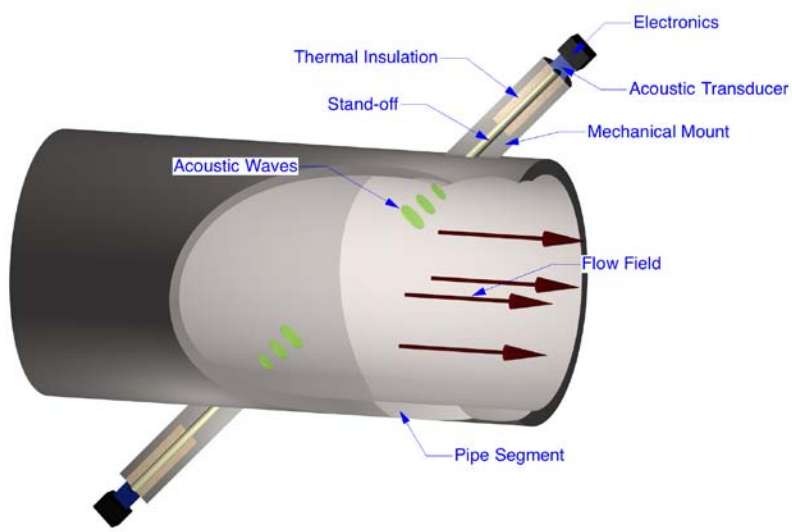

Figure 4. Schematic representation of an ultrasonic flowmeter and its operating principle.

3.3 Test Section Differential Pressure

The test loop operates at near atmospheric pressure (one or two atmospheres of argon to prevent in-leakage of moisture and oxygen). Expected differential pressure across the test section is about one atmosphere. Differential pressure measurement cross the test section is a challenge because of temperature and salt's corrosive nature. The impulse line method previously described in context with Venturi flow measurement can be used to shift the measurement to a lower temperature region. However, a direct measurement is preferable. Such direct measurement places a diaphragm in the full high-temperature salt environment. Diaphragm deflection can be measured by capacitance, optical (interferometric), or strain gauge methods. Diaphragms can be either solid or coated, in which the substrate is selected for high-temperature survivability, and the coating is chosen for salt compatibility — such as SiC or molybdenum. One issue that presents a serious fabrication dilemma is mating materials of

differing temperature expansion coefficients such as ceramics and metal alloys. No commercial pressure transducer has been found that meets these requirements.

Another complex but workable solution (somewhat similar to the impulse line approach) is to allow the liquid salt to partially fill a tank. Tank level is measured and maintained by adjusting gas pressure. The required gas pressure to maintain the reference level is calibrated to be the salt pressure. The approach illustrated in Figure 5 is the currently planned pressure measurement technique. In this arrangement, no pressure diaphragm is in contact with the liquid salt as would be the case for impulse lines or a capacitance gauge.

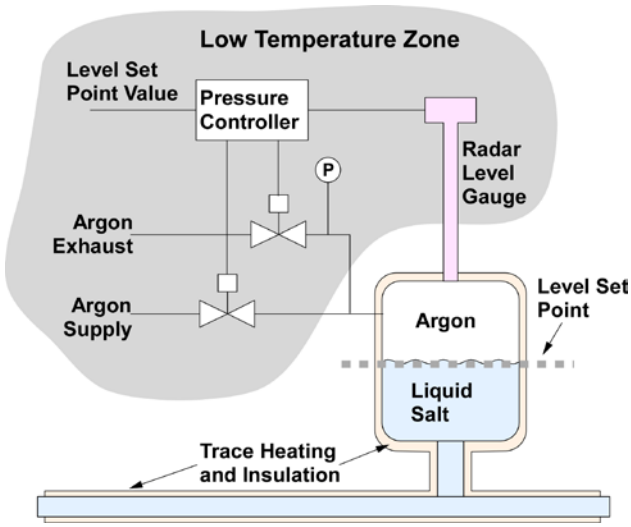

Figure 5. This method for pressure measurement determines gas pressure required to maintain a fixed salt level in a surge vessel.

3.4 Level Measurement

Several technologies are available for salt level measurement in the storage, sump, and surge tanks. Bubbler-type level measurements based upon the pressure required for minimal flow in a vertical tube are commercially available technologies. Gas pressure in the three tanks of the flow loop will be adjusted to move salt from storage to sump tank and to maintain level in the surge tank. Because of the use of argon gas pressure for level control, also using the same lines to function as bubblers for the level measurement introduces unnecessary complexity.

Another approach being implemented in the loop is a heated thermocouple lance. Because the presence of salt at the surface of the lance is more thermally conductive than argon gas, the liquid level can be determined by observing a characteristically lower temperature below the liquid level. This effect is illustrated in a highly simplified form in Figure 6. Techniques such as differential temperature measurement are used to better differentiate between random fluid temperature fluctuations and distinct liquid level. Additionally, a group of thermocouples can be wired to form a binary code that reduces the quantity of external connections required to represent a larger number of thermocouples and therefore a finer resolution [6]. Nevertheless, a drawback of this method is that measurements are discretized, i.e., finite quantity of thermocouples yields a finite number of level values. Also, material deposition, such as salt solidification on the lance, can introduce uncertainty in determining level.

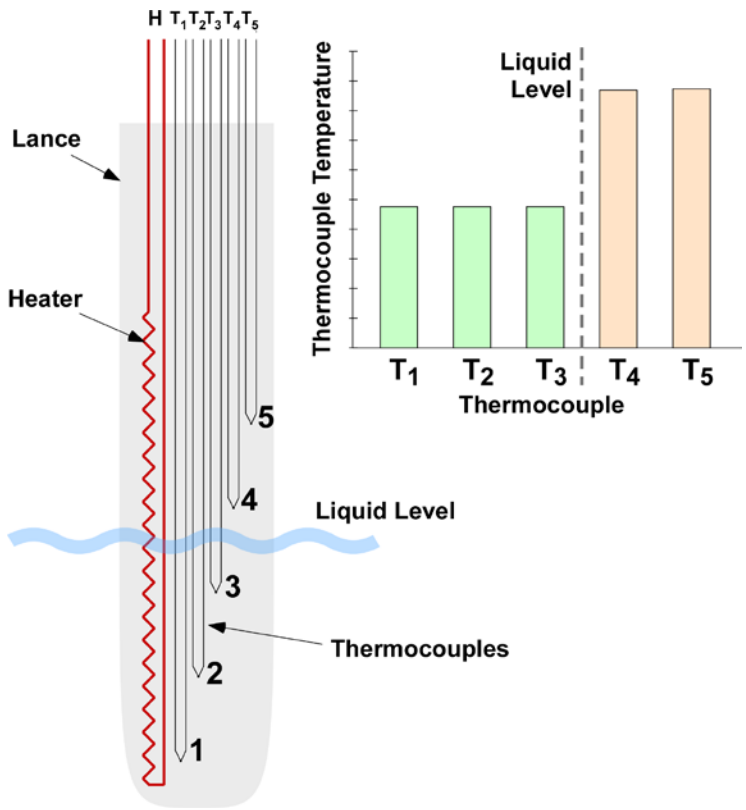

Figure 6. Simplified operation of a heated thermocouple level probe.

Microwave-type level measurements based upon reflection off the top surface of the salt are commercially available. This radar gun approach is being developed for the loop system measurement. The transducer, horn, and electronics will be located in a standpipe above the fluid well outside of the high temperature zone as illustrated in Figure 7. The standpipe acts as a waveguide for the microwave energy and prevents internal reflections from interfering with the return signal. The standpipe also calms any surface agitation. The standpipe must have either a slit up the side or one or more vent holes to prevent a gas pocket from allowing liquid to enter. The radar gauge provides a high resolution, continuous measurement. For this measurement it is essential that the head electronics be maintained at near room temperature. For this reason, the outer (pressure boundary) tube and inner standpipe extend sufficiently beyond the tank wall to allow room air to cool the end electronics to 50°C. Some industrial microwave heads employ cooling with compressed air.

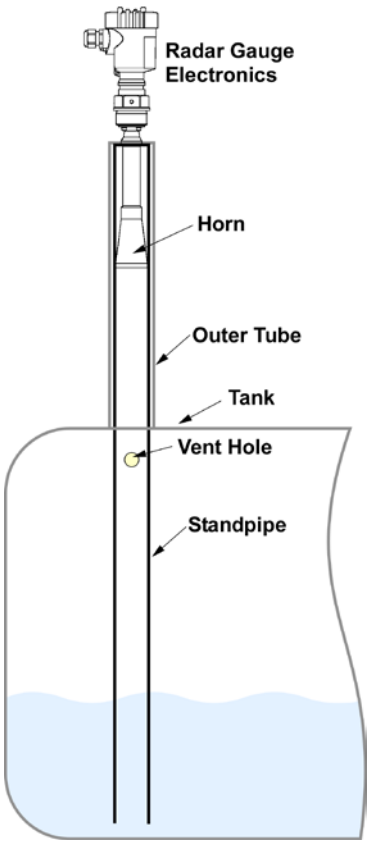

Figure 7. Microwave-based commercial level measurement spaced away from tank to allow electronics package to operate in a room temperature environment.

4 CONCLUSIONS

Much of the instrumentation for a high-temperature fluoride salt heat transport loop is commercially available but not qualified for use in a molten salt scenario without modification. The longer-term reliability and drift performance have not been established. In general, the specialized, high-temperature-tolerant, high-reliability transducers and the supporting electronics are only available as designs from the literature. A sufficient market has not existed for commercial vendors to establish and maintain sources of supply for the specialized instrumentation.

The demonstration loop will show salt loop operation under prototypic conditions and indicate performance of selected materials. A series of measurements will be made to characterize the heat transfer characteristics of salt and graphite pebbles. Selecting instrumentation and identifying weaknesses and limitations in instrumentation approaches are important outcomes of the loop demonstration.

5 ACKNOWLEDGMENTS

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