# Testing of An Impedance Heating System for Solar Power Tower Applications

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## Abstract

A non-conventional type of heating system is being tested at Sandia National Laboratories for solar thermal power tower applications. In this system, called impedance heating, electric current flows directly through the pipe to maintain the desired temperature. The pipe becomes the resistor where the heat is generated. Impedance heating has many advantages over previously used mineral insulated (MI) heat trace. An impedance heating system should be much more reliable than heat trace cable since delicate junctions and cabling are not used and the main component, a transformer, is inherently reliable. A big advantage of impedance heating is the system can be sized to rapidly heat up the piping to provide rapid response times necessary in cyclic power plants such as solar power towers. In this paper, experimental results from testing an impedance heating system are compared to MI cable heat trace. We found impedance heating was able to heat piping rapidly and effectively. There were not significant stray currents and impedance heating did not affect instrumentation.

## BACKGROUND

In a solar, molten-salt central-receiver power plant, heliostats focus sunlight on to a receiver mounted on top of a centrally located tower. The heat transfer fluid, molten nitrate salt (60% sodium nitrate, 40% potassium nitrate), is pumped from a "cold" storage tank and heated by the illuminated receiver from 290°C to 565°C. The hot salt is stored in a "hot" tank where it can be used to produce steam to power a Rankine turbine and generate electricity [1]. The key advantage of molten salt is its useful operating temperature range is well matched to the Rankine thermodynamic cycle.

Unfortunately, nitrate salt has a high freezing point (approximately 220°C) [2], so all the salt piping must be heated. Mineral insulated (MI) heat tracing has been used extensively in molten salt applications to maintain the temperature of piping and components above the salt freezing point, typically at 290°C. If mineral insulated heat trace is not installed correctly it can be unreliable, cause non-uniform heating, especially in large pipes, or cause difficulties with controlling pipe temperature. In addition, the amount of power applied to the pipe by heat trace is limited by its watt density and physical constraints of attaching the cables to the pipe. This makes the thermal response of the system relatively slow - limiting the rate at which the plant can be brought into operation and reducing overall plant efficiency.

Impedance heating generates heat directly in a pipeline by flowing electrical current through the pipeline or vessel wall by direct connection to an ac voltage source from a dual-winding transformer. This type of heating uniformly heats the pipe circumferentially. It has been used in several petrochemical applications at very high temperatures. An impedance heating system can be designed to heat up the piping rapidly so the system can respond quickly.

## OBJECTIVE OF THE TEST

Manufacturers of impedance heating systems claim thousands of highly reliable systems have been installed in the past thirty years. Despite this track record, there are concerns whether this type of heating system is complementary with high temperature solar thermal applications where there is deep temperature cycling, thermal shock, and molten salt containment problems. Also, since high currents are flowing through the pipe, there is a safety concern for site personnel who may come in contact with electrically energized piping. Another concern is the effect of these currents on instrumentation and components. The following objectives have been set to address these issues and evaluate the relative merit of MI cable heating versus impedance heating systems for molten-salt, central-receiver applications:

1 Verify the safety of an impedance system - the presence of stray currents in the branch loop, pipe supports, and on instrumentation shields as well as the voltage of the energized pipe itself.
2. Determine the affects of an impedance system on thermocouples, transducers, and other forms of instrumentation.
3. Quantify the relative power consumption (kWhr) between impedance heating versus MI cable heating.
4. Determine the rate at which each system will bring dry piping to temperature.
5. Determine the rate at which each system will unthaw a pipe filled with frozen salt.
6. Determine if an impedance heating system will provide a longer life of the pipe after repeated freeze/thaw cycles.
7. Quantify installation costs for the two systems - both time and material.
8. Quantify installation time differences - subjective evaluation.
9. Evaluate the relative ease of repair and modification of the two systems - subjective evaluation after using.
10. Determine if MI cable can safely be used as supplemental heating at valves in impedance circuits.
11. Perform a subjective evaluation of the relative maintenance requirements for each system.

## DESCRIPTION OF THE HARDWARE SYSTEM

The impedance heating system was purchased from Industrial Engineering and Equipment Company (INDEECO) for this test. The system employs a 9 KVA transformer with a secondary voltage set to 5.8 volts and a current output of approximately 932 amps. The electrical connectors to the pipeline have been designed for the amperage requirements of the test section, but small enough so that they are not a heat sink to the pipe.

It was installed on a 15.8 m (52 feet) section of 5.1 cm (2.0 inch - nominal) schedule 40 stainless steel pipe. The current can be fed through a pipe in one of three ways: 1) a midpoint feed where the current flows from the electrical mid point of the pipe with the return paths at each end of the pipe, 2) an end feed connection where current is fed from the beginning of the section desired to be heated and the current returns at the other end of the pipe, and 3) a dual-line feed connection which is similar to an end feed connection but applied to parallel pipes. The parallel pipes are jumpered together at the electrical midpoint. The current feeds from the end of one pipe, through the electrical midpoint to the parallel pipe and returns to the transformer.

For this system, we chose a midpoint feed because the pipe can be electrically isolated from the rest of the piping. This is also the most likely configuration to be used in a molten-salt central-receiver system. The end-feed connection requires the pipe use non-conducting flanges to electrically isolate the pipe, which could add complications to the piping design.

The heat trace system consisted of 54 feet of single-element mineral-insulated heat trace with a total power rating of 2680 W that operated on 120 VAC. It was installed on a similar 15.8 m (52 feet) section of 5.1 cm (2.0 inch - nominal) schedule 40 stainless steel pipe. The heat trace cable was attached to the pipe with band wires parallel to its axis in a slightly serpentine fashion. It was covered with metal foil to provide a protective cover and to distribute the heat over a larger area of the pipe. At the ends of the heat trace cable were hot-to-cold junctions to transition from the heat element to the conductor wire.

Both pipes were insulated identically. Two and one-half centimeter thick of soft Koawool insulation was installed over the pipe. This was covered with ten centimeter of fiberglass insulation made from three layers: a 3.8 cm layer covered with a 3.8 cm layer, covered with a 2.5 cm layer. The insulation joints were lapped to prevent air infiltration as the pipe heated up and expanded. The insulation was then covered with aluminum lagging and the cracks sealed. A schematic of the setup is shown in Figure 1. Each system had three sheathed, ungrounded type K thermocouples. We installed additional instrumentation in the impedance heating system to determine any effects of stray currents. These instruments included: resistive temperature detectors (RTDs), a pressure transducer and a valve positioner.

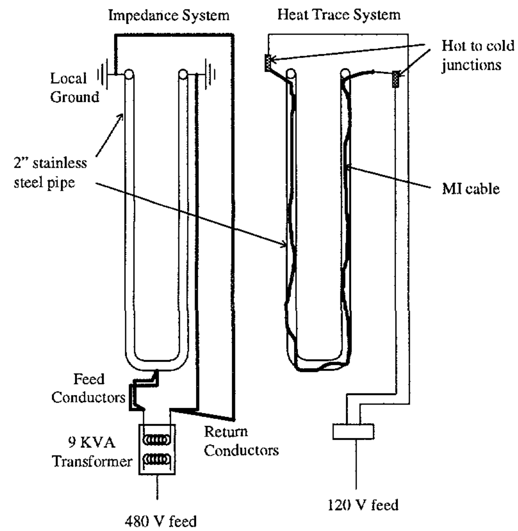


Figure 1. Schematic of impedance heating and MI heat trace system.

## STRAY CURRENTS AND VOLTAGES TEST

This test was designed to measure the level of stray currents and voltages in the piping beyond the grounded elbows and in the surrounding support structures (caused by induction). Also, we measured stray current in the instrumentation wire shielding. This test applied only to the impedance pipe system.

In this test, we activated the impedance heating system and brought the temperature of the pipe to 125°F. We measured the currents between the grounded elbows at both ends of the pipe loop using an amp-probe. The current flow from north end of the pipe to the south was 6.9 amps. There was no current to ground. These stray currents are not a hazard since the voltage was very low, only 5.3 mV. They are due to an imbalance in current between the two flow paths.

We measured and recorded the return current to the transformer secondary from each end of the pipe loop. In the north return leg, the current was measured to be 471 amps and in the south leg, 461 amps. Ideally, the currents in both legs would be equal.

No measurable stray currents were found in the piping support assembly that may have been induced from the larger currents in the impedance-heated piping. Next we measured stray currents on the instrumentation wire shieldings. It is critical when installing instruments in an impedance system that they are not grounded. We found no measurable current in the wire shieldings of any of the instruments. The instruments were not affected by the current flowing through the pipe.

## EMPTY PIPE HEAT UP TEST

In this test, we measured the rate and power consumption of each heater necessary to heat the empty pipe from ambient temperature (10°C) to 260°C. We also measured their power consumption to maintain its temperature at 260°C for 48 hours. Figure 2 shows the temperature response of each pipe. The results of these measurements are shown in Table 1. As can be seen, the impedance system heated the pipe to 260°C in about 1/3 the time it took the MI cable system. The impedance system, though, consumed about 20% more energy. The average power consumed by the impedance system to maintain the pipe at the set point was 65% more than MI cable system.

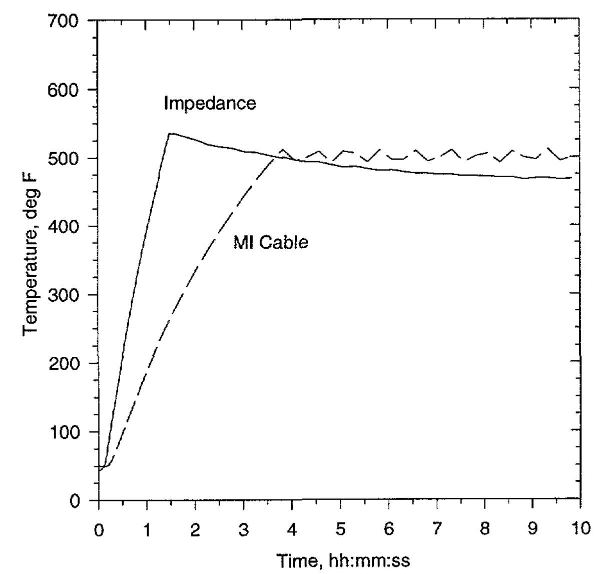


Figure 2. Temperature responses of the impedance and MI cable pipe loops during heat up with pipes empty.

Table 1. Summary of measurements from dry heat up test.

| System | Time to Reach 260°C from 10°C, hrs:min | Energy Usage to Reach 260°C, kWhr | Average Power to Maintain 260°C, W |
|---|---|---|---|
| Impedance | 1:25 | 7.65 | 1400 |
| MI Cable | 3:50 | 6.41 | 870 |

## FILLED PIPE TEST

Both pipes were filled with nitrate salt to a level approximately half full to determine if there were any non-uniform temperature distributions along the length of the pipe with the impedance system. This is a concern with electrically conducting fluids because the resistance in the pipe will change where there is the fluid. There were no problems with heating a pipe half full of salt.

Next we completely filled both pipes with salt and measured their steady state power consumption to maintain 260°C. To determine if the difference in power consumption between the two systems was due to inefficiencies in the impedance system or due to thermal loss, we heated both systems to approximately 370°C and let them cool. See Figure 3. By measuring the rate of change of temperature at 260°C, we estimated the thermal heat loss of the pipe accounting for the mass of the pipe and salt based on one of three thermocouples in each circuit. All the thermocouples followed the same rate. Table 2 summarizes the results. As can be seen, the impedance system had much higher *thermal* losses. This is significant because both sets of pipes were insulated the same. The impedance heating system, though, has large electrical connectors at the mid point and the ends of the pipe, which act as fins. These add to the heat loss; they have since been insulated and we plan to repeat this test.

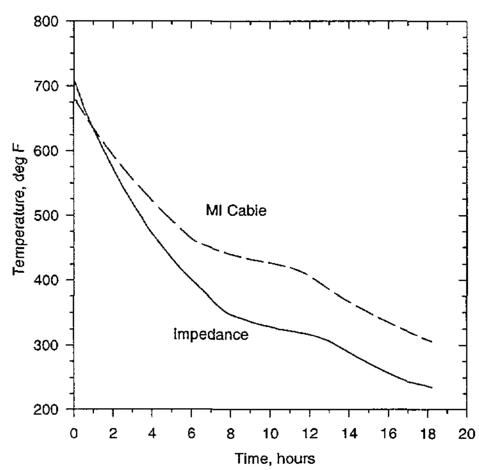


Figure 3. Measured cool down of each heating system with pipes filled with salt.

Table 2. Measured power consumption and heat loss for pipes full of salt.

| System | Measured power to maintain 260°C, W | Measured heat loss at 260°C, W |
|---|---|---|
| Impedance | 1530 | 1250 |
| MI Cable | 850 | 790 |

## REPEATED FREEZING AND THAWING TEST

The last test is currently being conducted. It will attempt to determine differences in the way the two systems handles freezing and thawing of molten salt in a pipe. Since the impedance heating system uniformly heats the pipe in the circumferential direction, frozen salt will melt from the edges inward and may allow the salt to slide as it thaws. Thawing molten salt in pipes can be very damaging since nitrate salt expands upon melting. In this test we will cycle the temperature between approximately 25°C and 260°C until either a pipe ruptures or 15 cycles have elapsed.

## CONCLUSIONS

The impedance heating system is a safe, easy-to-install alternative to MI cable. It is best suited for long runs of piping without components (e.g., valves) so it can easily be installed and balanced. There are not significant stray currents induced in the support structure that could be hazardous to personnel. It can be sized to rapidly heat up a section of pipe to respond to changes in the state of plant. We found the power consumption to be higher in the impedance heating system. We believe this was primarily due to higher thermal losses in the pipe, though we are in the process of conducting further tests.

## ACKNOWLEDGEMENTS

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