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Electric Heating for High-Temperature Heat Transport Fluids

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Electric Heating for High-Temperature Heat Transport Fluids

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Abstract

Recent experiences with electric resistance heaters at the solar Central Receiver Test Facility are described. These heaters are used to preheat or maintain equipment used with molten nitrate salt or liquid sodium heat transfer fluids. Results of extensive testing performed to improve the reliability of similar heating systems used in the development program for the sodium-cooled liquid metal fast breeder nuclear reactor are also reviewed. Recommendations are made for increasing the reliability of trace heating systems for high-melting-point heat transfer fluids including thermal design, heating element selection, installation, insulation, and controls.

Acknowledgment

I thank all of those in the solar molten salt test programs who have agonized over the poor reliability of the heating systems that we have used at the Central Receiver Test Facility. I especially thank S. Dunkin, B. O. Ellis, P. Flora, J. Griego and C. Matthews, who have installed and repaired our MSEE heaters and insulation time after time. Bill Delameter's critical review was invaluable for completing the recommendations section of this report. I also thank those in the nuclear breeder reactor development program who have systematically studied the reliability issues and who have provided guidelines for my recommendations.

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Electric Heating for High-Temperature Heat Transport Fluids

Summary

This report reviews the experience with electric resistance heaters used at the solar Central Receiver Test Facility (CRTF) to preheat or maintain equipment used with molten nitrate salt or liquid sodium heat transfer fluids. Also reviewed are the results of extensive testing performed to improve the reliability of similar heating systems used in the development program for the sodium-cooled liquid metal fast breeder nuclear reactor (LMFBR).

The recommendations I make, which are based on currently available information, can be used to maximize the reliability of trace heating systems for high-melting-point heat transfer fluids. My recommendations cover these areas:

- Thermal Design
- Heating Element Selection
- Installation
- Insulation
- Controls

Background

Equipment used with high-melting-point heat transfer fluids such as molten salts (0.60 sodium nitrate, 0.40 potassium nitrate, mp 429-473°F) or liquid metals (sodium, mp 208°F) must be preheated and maintained at a temperature above the fluid melting point to prevent freezing when the working fluid is in use. During more than 30 years of research and development exploring the use of sodium as a nuclear reactor coolant, electrical resistance heaters have been used to maintain equipment at temperatures of 300°F to 400°F. Extensive studies by Rockwell International's Energy Technology Engineering Center (ETEC) have shown that commercial electrical resistance heaters may not be reliable enough for use in sodium-cooled nuclear power plants designed for 20- to 30-year operating lifetimes.[1,2]

During our rather short experience (four months) with the use of liquid sodium as a solar central receiver working fluid, electric resistance heaters were highly reliable.[3] No heaters failed during that period. Mineral-insulated cable was used for the trace heating elements. (Details of the heater types and sources were not documented.) The sodium supply and heat rejection loop was provided by the General Electric Company, and Rockwell International's Energy System Group provided the solar receiver panel and connecting pipes and valves.

In contrast to the excellent results obtained with liquid sodium, we have had very poor results in our attempts to heat equipment for use with molten salt coolant,[4-6] which has a high melting point. This report documents our poor experience and recommends steps to improve methods for heating the equipment used with high-melting-point coolants.

Trace Heating Experience With Molten Salts

In three solar receiver technology development programs conducted at the CRTF, mineral-insulated (MI) cable has been used to heat vessels, pipes, valves and other equipment containing the molten nitrate salt heat transport fluid: the 5-MWt solar receiver test in 1980,[4] the 7-MWh thermal storage test in 1981 and 1982;[5] and the Molten Salt Electric Experiment (MSEE) now nearing completion.[6] The MSEE integrated the previously tested solar receiver and thermal storage subsystems with a new steam generator that provided steam to a turbogenerator. Failures in trace heating elements have been numerous in all these solar molten salt programs.

Description of Trace Heating

In our experience with molten salt coolants, we have used heating elements commonly known as MI cable manufactured by the G. S. Nelson Electric Company. These elements are magnesium oxide insulated, single or double nickel-chrome alloy heating wire sheathed in a 0.015-in. thick Inconel 600 outer cover.

(Some of the heaters used on the MMC solar receiver test in 1980 had a lower temperature alloy resistance wire.) The sheath is seam-welded along the entire length of the cable before being swaged to its final diameter. The copper power conductor is also magnesium oxide insulated and is encased in a stainless steel sheath. The hot-to-cold junction (the junction between the heater wire and the copper conductor) is a silver solder braze. This hot-to-cold junction is encased in a stainless steel sleeve that is brazed to the sheath of the heater wire and to the sheath of the copper wire.

The pipes are heated with one pass of MI cable heating element. Flanges, valves and other non-pipe components have multipass lengths (serpentine bends) of the heating element to accommodate their size. The MI cable is attached to pipe with stainless steel wire or strapping at about 1-ft intervals. The MI cable and adjacent area of the pipe are covered with 0.003-in. stainless steel foil that is spot-welded to the component. The foil keeps insulation from getting between the cable and the pipe and also creates an "oven" to assist the radiant and convective heat transfer to the pipe.

The hot-to-cold junction is located outside the thermal insulation. The hot cable, contained in an open foil sleeve, passes through the insulation. The sleeve allows air convection and radiation and prevents the cable from becoming overheated when it is not in good thermal contact with the component. The temperature of externally located hot-to-cold junctions may exceed the component temperature and form a more severe environment for the brazed joint. The hot cable that penetrates the insulation may also overheat if it is not thermally isolated from the insulation. There is no agreement that this is the best location for the hot-to-cold junction. Other suppliers of MI cable recommend locating the hot-to-cold junction on the component. They claim this location limits the temperature of the heater and its hot-to-cold junction to slightly above that of the component.

5-MWt Solar Receiver Subsystem

Martin Marietta Corporation conducted the 5-MWt solar receiver subsystem test at the CRTF in 1980 to demonstrate the feasibility of the central receiver power system. The receiver and its air-cooled heat rejection system located on top of the CRTF tower was in operation with the solar beam for more than 350 hours. In the final report documenting this test, MMC noted that the trace heating system produced by far the greatest number of serious operational hardware problems.[4] (Heating elements used in this test were purchased from the G. S. Nelson Electric Company.)

Over 40 heater failures occurred during four months of the test program. Approximately 75% of these were at the hot-to-cold transition joint. Most of the remaining 25% were at the tip, where the dual-wire heater was terminated to complete the electrical current loop. After analyzing the failures, MMC made these recommendations:[4]

1) Use single-conductor heaters whenever possible.
2) If dual-conductor heaters must be used, use a hot junction sheath designed to allow greater separation between the conductors.
3) Place all hot junctions outside the insulation
4) Use relatively dry flux when making junction repairs.
5) Make the cold section of the heater as short as possible and construct it from a more flexible material
6) Use only nickel-chrome alloy resistance wire larger than 22 gage.

7-MWh Thermal Storage Subsystem

A 7 MWh thermal storage subsystem was constructed and tested at the CRTF in 1981 and 1982 to demonstrate the operation of molten salt thermal energy storage using an internally insulated storage tank. The trace heating was similar to that used for the 5-MWt Solar Receiver, but with the recommendations made by MMC incorporated into the trace heating system. The main change was the exclusive use of nickel-chromium resistance wire and single conductor cable. Although no trace heating failures are documented in the final report,[5] five of the heaters did fail during the test. One special failure in that program was the very short life (a few days) of the immersion heater in the hot salt storage tank. The heater was a coil of MI cable (G. S. Nelson) located inside the tank at the bottom. Because removing the heater is difficult, the failure has not been analyzed; instead, procedures have been changed to eliminate the need for that heater. The immersion heater in the cold tank has performed continuously since 1981. The other failures in this program occurred in two conductor heaters that were wired with the two resistance wires in parallel. The thermal storage heaters were left on continuously; they did not cycle on and off to control the temperature of the heated pipe or component.

Molten Salt Electric Experiment

The Molten Salt Electric Experiment (MSEE)[6] conducted at the CRTF was the first attempt in the US to demonstrate the technical feasibility of operating a solar control receiver power plant by using molten nitrate salt as the heat transfer fluid and thermal storage medium. This experiment integrated the previously tested solar receiver and thermal storage subsystems with a new salt-heated steam generator and other non-salt subsystems. Because of the previous problems with trace heating on the receiver, all of the old heating elements were replaced in preparation for MSEE operations. We again used heating elements fabricated by G. S. Nelson.

The thermal design strategy was to use the lowest heater power and watt density required to offset the predicted heat losses. The electrical power was to be left on continously except when the presence of solar-heated salt caused the heaters in the hot-salt lines to turn off at 750°. This method of operation conserves energy when hot salt is produced and prevents overheating of the heating elements. To balance the heat input and the heat losses, the insulation thickness was adjusted by trial and error to achieve the desired component temperature. Insulation adjustments were very time consuming and proved to be undesirable, as described in detail in the insulation section of this report.

Trace heaters in the thermal storage area were reused as much as possible. Where valves were added or piping changes were made, new heaters were installed. The new salt riser and downcomer piping from the receiver had new heating elements that use the passive, always-on control strategy. The thermal design did not adequately take account of wind as an ambient heat loss variable. There are occasions when the temperatures of the salt riser and downcomer piping outside the tower drop below the melting point for salt because the heating elements and insulation thickness inside and outside the tower and the same on the riser and downcomer.

Trace Heating Failures

The MSEE equipment includes over 95 MI cable heaters, using an average of 3200 ft of MI cable. Most of these heaters have built-in spare heating elements. About 180 heating elements are installed on the MSEE salt systems.

At the end of the Utility/Industry training phase (December 1984), 24 heating element failures had occurred during the total MSEE operating time (about 14 calendar months). Some of the heaters in the thermal storage system had been on continuously since 1981, and most of the heaters were active during that period. Table 1 indicates the general location of the failures that occurred during the 14 months of MSEE operation.

Of the MSEE failures that have not been analyzed, slightly over half are hot-to-cold junction failures. The other failures occurred in the heating section of the elements. We are using many of the Nelson heaters at much higher power densities than Nelson recommends for their heaters and for our component temperatures.

Two major causes were discovered for the failures at the hot-to-cold junction. First, most of our factory-fabricated single-conductor cables were unintentionally assembled with a two-hole ceramic insulator at the hot-to-cold junction. The single conductor had to be bent sharply to pass through the second of these insulator holes, and this sharp bend may have created a weakened or thinned area that over-heated and caused premature failure. Second, limited study of other failures that occurred in the hot-to-cold junction indicates the wires may have been inadequately fluxed (cleaned) before the braze alloy was applied. Both these failures are the result of inadequate quality control and inspection at the manufacturing plant. Also, they are probably accelerated by the on-off control (fatigue from thermal cycling) used in some zones of the MSEE salt systems.

One heating section failure involved catastrophic corrosion of the sheath, apparently caused by the

Table 1. MSEE Heat Trace Element Failures

		Heater Wires		Power Control	
Subsystem	Failures	Single	Double	Active	Passive
Receiver	18	18	0	16	2
Thermal Storage	9	7	2	0	9
Steam Generator	3	2	1	3	0

presence of salt from a minor salt leak near the heater; however, other heaters contaminated with salt have not exhibited similar corrosion. The excessive corrosion in this case may be related to a short circuit between the heater wire and the sheath. Two other MSEE failures resulted in extensive melting of the Inconel sheath, but without the corrosion (Figure 1). These sheath-melting failures are similar to the ones documented by ETEC.[2] The cause of this kind of failure was postulated by ETEC to be a short circuit from the internal heater wire to the Inconel sheath. Should metal oxide films cause the sheath to become imperfectly grounded to the pipe, the sheath would temporarily become the current conductor. The sheath could then overheat, melt, and arc to the pipe and to the stainless steel foil. It may be that the catastrophic corrosion failure was actually initiated by the very high temperatures (2500°F) generated when the sheath melted.

Our MSEE experience led to no definite conclusion as to whether active or passive control contributed to heater failures. Heater failures on the receiver drain and purge valves occurred mainly after the wide dead-band, on-off control was implemented. Nineteen of our failures were in areas where we were using on-off control. MI cables on our valves are bent in a serpentine configuration to provide even heating of the valve body. ETEC found that bending heaters reduces their service life,[1] and we conclude that the combination of many bends and on-off thermal cycling may have accelerated the failures. The other 11 failures were in always-on passive control circuits.

At the end of the Utility/Industry training phase (December 1984), the MSEE was shut down to refurbish zones (mainly receiver purge valves and drain valves) where we had lost the primary heating element and were operating on the spare. We replaced 11 heated areas (22 primary and spare elements). The

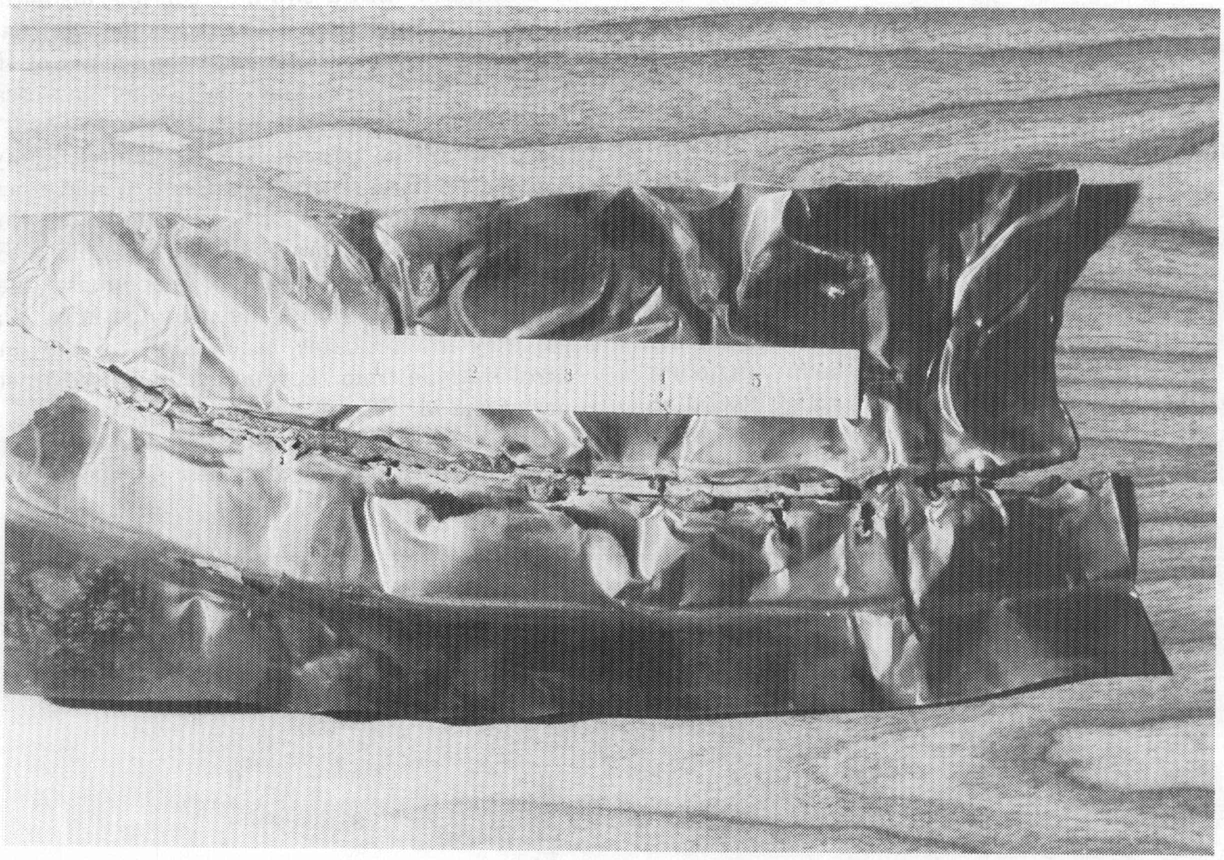


Figure 1. Failed MI Cable Showing Melted Sheath

failed elements in these areas could not be repaired by simply remaking the hot-to-cold junction. The job involved numerous procedures:

- Removing insulation
- Removing the heater and foil
- On-site brazing of termination attachments to bulk MI cable
- Installing heater and foil
- Installing thermal insulation
- Performing an electric and thermal check.

Refurbishing these MSEE trace heating areas required about 720 man-hours and caused a shutdown of MSEE operations for 40 calendar days. Of the 720 man-hours, about 500 were devoted to insulation work, and about 220 to the heating trace itself.

The total cost of refurbishing was about $30,000 (in 1985 dollars) for materials (25%) and labor (75%). If a heating element fails at an accessible hot-to-cold junction we can usually cut out the bad junction and remake it in about 2 hours. Insulation repair is not needed in this case.

MSEE Insulation

After the receiver was raised to the top of the tower and thermal checkouts began, we experienced great difficulty in keeping the purge and drain valves and their piping headers at temperatures above that of the melting point for salt. The thickness of the preformed calcium silicate insulation had been trimmed to give the proper heat loss for the always-on heaters. This trimming was done on the inner surface of the insulation while the receiver was located inside, at the base of the tower. The outer diameter was retained for the aluminum cover. Exposing this system to the tower-top temperature and wind environment produced two problems.

First, winds caused large and often very rapid drops in the temperature of the heated items. The affected area and the extent of the temperature drop were dependent on wind speed and wind direction, but neither was predictable or reproducible. This problem was solved by enclosing the entire receiver piping and valve system in a sheet-metal wind shield. The enclosure provided walk-in access for our operators and maintenance technicians.

Second, not all temperature drops appeared to be caused by winds. We eventually identified air convection within the chamber, created between the calcium silicate insulation and the piping header valve, as the cause of these temperature drops. It was necessary to reinsulate all of the receiver problem areas with overlapping layers of a soft ceramic-fiber blanket material to prevent air convection near the component and eliminate the unexpected temperature drops. During this process, we overinsulated and implemented the on-off power control strategy for the trace heaters in those areas. The heaters in each zone turn on when the temperature falls below 480°F and shut off when the temperature reaches 650°F. The on-off control involves about 20 to 30 cycles per day, depending on the wind and ambient temperature.

Although insulated pipe supports and hangers have not been a problem for the MSEE, these items must be part of the thermal design. These supports must thermally isolate the pipe or component from the structure.

Liquid Metal Fast Breeder Reactor Experience

The sodium-cooled LMFBR has been under development for over 30 years in the US and for almost as long in France, Great Britain, Japan, and Russia. Many of the conditions and requirements of the heat tracing system for the LMFBR are similar to those of solar receivers. While the melting point of sodium (208°F) is lower than that of the 60/40 nitrate salt (429°F - 473°F), the hot leg temperatures are similar (1000°F to 1100°F) since the desired stem conditions are the same for modern turbogenerators. Sodium systems are normally heated to 300°F - 350°F, whereas molten salt systems must be preheated to 500°F - 550°F, but both heating systems must survive 1000°F to 1100°F in the hot leg. Because of these and other similarities, much that has been learned in the trace-heating technology developed for the LMFBR program is directly applicable to solar molten salt trace heating systems.

Two excellent reports summarizing the state-of-the-art of high-temperature trace heating technology have recently been prepared by ETEC.[1,2] The work described was undertaken to provide guidelines for the selection of a highly reliable trace heating system for the first commercial size LMFBR in the US. In the first report,[1] MI cables manufactured by ARI Industries (US), Pyrotenax (France), and Vacuumschmelze (Germany) are evaluated. (The Nelson brand of MI cable used at the CRTF for molten salt programs was not part of the ETEC test program.) All the cables are similar, with minor material and fabrication differences. Each uses an Inconel sheath and a nickel alloy resistance wire insulated from the sheath by compacted magnesium oxide. The cables differ mainly in the way the transition from the resistance wire to power conductor (hot-to-cold junction) is made. The MI cable heaters were tested to determine

- Effect of bends on heater life
- Best termination design for heater life
- Life of heaters in a prototype pipe application
- Life of heaters in an accelerated test (temperature 1500°F and 1700°F)
- Heat-up rate effects on heater life.

ETEC also tested tubular heaters ("Calrod") for use as trace heating elements.[2] Tubular heaters manufactured by Rama, Hesco, and Chromalox (US companies) were evaluated. They are all similar in design. The nickel-chrome alloy resistance wire is a coil configuration inside the Inconel sheath. Magnesium oxide insulates the resistance wire from the sheath.

The tubular heaters were tested in prototype applications and under cyclic power application at elevated temperatures (1500°F and 1700°F) in an attempt to shorten the time to failure. The cycles were 5 minutes on and 10 minutes off. Some heaters failed in as few as 77 cycles, and others lasted more than 36,000 cycles at these high temperatures.

In both studies, ETEC drew a number of conclusions concerning MI cable and tubular heaters that are pertinent to solar receiver trace heating systems:

- Because of the ease of installation, MI cable offers a distinct advantage over tubular heaters for odd-shaped components such as valve bodies and heated instrument sensors.
- Hot-to-cold junction design and fabrication techniques affect MI cable life.
- During installation of MI cable and tubular heaters, allowance must be made for differential thermal expansion of the heater and the heated component.
- Bending for installation should be minimized.
- The purity and compacted density of the M_gO insulation must be controlled to obtain satisfactory heater reliability.
- Tubular heaters are more reliable than MI cable. The large-diameter (0.5 in.) tubular heaters were more reliable than the small-diameter (0.375 and 0.25 in.) heaters.
- Heaters should be used at a derated voltage. To lengthen heater life, 480-volt rated heaters should be operated at 277 volts.
- Ground fault interrupters should be used to restrict damage to the sodium containment boundary caused by arcing that may occur when a heater fails.

Supporting ETEC's conclusions is a wealth of operational experience from the Fast Flux Test Facility (FFTF) and the Experimental Breeder Reactor II (EBR II). Trace heating systems at both of these sodium-cooled nuclear reactors have proven to be highly reliable. The FFTF heating system (in operation for 5 years) is based on the ETEC technology. The system uses 1/2 in. diameter tubular heaters on pipes and large components and MI cable on valves, small components and small piping loops. Overall experience has been good. EBR II (in operation for over 20 years) has had good results with ARI Industries' MI cable on small piping loops, valves, and components. In this system, the cable is derated to a low-watt density and is used with EBR II's hot-to-cold junction design.

The large piping of the EBR II secondary (not radioactive) sodium system has a unique, 60 cycle, ac induction trace heating scheme.[5] Because the induction coil is on the outside of the thermal insulation, repair is easy, and the coil is not exposed to the heated environment. The induction heat is highly reliable and is used in both inside and outside environments. However, the system works only on ferromagnetic components. It could be made to work on stainless steel piping if the pipe were surrounded by a ferromagnetic susceptor. Valves and other components use MI cable heaters. I am not sure why this system is not used more widely. It probably has to do with energy efficiency, the very large lengths of electrically insulated copper wire used to encircle the thermal insulation (1- to 2-in. spiral pitch), and the cost of its control system.

Recommendations for Trace Heating of Solar Molten Salt Systems

As a result of our experience at the CRTF and the experience and test programs conducted in the nuclear breeder reactor program, I recommend that the following guidelines be followed for solar molten salt trace heating systems that use electric resistance heating elements. Table 2 is a summary of the recommendations.

Table 2. Summary of Recommendations for Trace Heating Molten Salt Heat Transport Systems

	Recommendations
Design	
Thermal	• Provide heat input of at least 125% of the highest possible calculated heat loss • Provide separate heaters on valves and other components
Electrical	• Select element to operate at or below 50% of rated voltage
Maintenance	• Design for ease of replacement or repair of each element • Install spare elements prior to insulating
Heating Element Selection	• Select tubular or MI cable heaters for piping systems based on a reliability/cost study using ETEC heater failure rates as the reliability criteria • Use band, ring, or strip elements on regular geometric shapes • Use Inconel sheathed MI cable on irregular-shaped components • Do not use immersion heaters in salt
Installation	• Attach heater elements at 1-ft intervals • Cover elements with stainless steel foil • Locate hot-to-cold junctions of heater elements as recommended by the manufacturer • Locate element terminations where they will be accessible for repairs
Controls	• Use active, proportional voltage control system on all areas that experience environmental changes • Install spare, welded-on thermocouples for each control zone • Provide a separate control circuit for each component or heater zone
Insulation	• Block air convection around the pipe or component with ceramic blanket insulation • Use preformed block insulation as the outer insulating layer on straight runs of pipe only • Use ceramic blanket layers for irregular shapes • Use wind shields for valves and non-pipe components

Design

Thermal Considerations – Common heat transfer engineering practices should be used to estimate the optimum insulating thickness and heat loss for the component operating temperature, the minimum ambient temperature, and the maximum anticipated operational wind speed. The heat loss estimated under the most severe operating conditions of wind and temperature should be multiplied by 1.25 to size the required thermal input for the trace heating system. The 1.25 factor conservatively takes into account variations in the quality of the thermal insulation, variations in the heat output from the heating elements, and deficiences in the heat transfer correlations used to estimate the requirements. The 1.25 factor is a "rule of thumb" recommended by most heating element suppliers. Because more heat will be supplied than is necessary to achieve the desired temperature, an active power control system will be required. (This requirement is discussed below.)

Special thermal design consideration must be applied to valves, flanges, pumps, vessels, instruments, pipe supports, and other non-pipe components. Heat loss will be unique for each component and must be compensated by added heat input or insulation. I recommend that all non-pipe components be treated as separate thermal problems. The heat loss of non-pipe components should be estimated, taking into account any "fin cooling" effect. All components should have separate trace heating elements to provide good temperature control and to allow for easy repair or replacement of the elements. The heating element on the piping system should stop at the non-pipe component. A separate heater(s) should be used on the component. If the piping system continues past the component, a new pipe heater should start on the other side of the component.

Electrical Derating – Heating elements should be selected to operate at no more than 50% of rated voltage (25% of rated power). This derating is considered good practice by the LMFBR users of electric resistance heaters for achieving long life. Most of the MSEE heaters are actually operated above the manufacturer's recommended watt density for our operating temperatures.

Maintainability – The heating system should be designed for ease of heater repair and replacement. Equipment should be located so that access to all trace heatingcomponents is possible. We have found that if the failure is in the hot-to-cold junction of MI cable, repairs are possible as long as the junction is accessible. We have not attempted to repair failures in the heating cable itself. Tubular heaters are not repairable and must be replaced when they fail.

Because of the finite life of heating elements for this high-temperature application I recommend that at least two elements be installed on all piping runs and components. The spare element should not be activated unless the primary element fails. Care should be taken not to overlay heating elements. Power and control wiring for one heater should be provided in a junction box. The primary and secondary heater leads should terminate in the same junction box with the active heater connected to the power source.

Heating Element Selection

Selection of the heating element for a specific application should be based on a reliability/cost analysis. Even though ETEC data on the failure of tubular and MI cable heaters is not exactly comparable, the data shows that 3/8- or 1/2-in.-diameter tubular heaters will have about twice the life of MI cable. Since the tubular heaters provide the most reliable system, the designer should compare the installed cost of an equally reliable MI cable installation (with multiple spares) with a tubular heater installation (with one spare element). Currently 1/2-in.-diameter tubular heaters cost about three times as much as an equal length of MI cable, and 3/8-in.-diameter tubular heaters about two times as much. For the use of either MI cable or tubular heaters, I recommend installing at least one spare element on all heated zones in a molten salt heat transport system.

Only one US manufacturer's (ARI Industries) MI cable was tested by ETEC. European MI cable heaters had no clear advantage over the ARI heaters. The results over 20 years of experience at EBR II have been good using ARI bulk heater cable and EBR II's hot-to-cold junction design.

Because we have not had good results at the CRTF using G. S. Nelson Company's MI cable, I recommend that Nelson products not be used unless an improved quality assurance program is implemented by Nelson. Without additional testing information, I recommend the use of heating elements from the US manufacturer, ARI, if MI cable heaters are selected. Other manufacturers' products may be as good as those from ARI, but test data is not currently available.

Strip, band, and ring heaters are available from a large number of manufacturers. These provide convenient, low cost heaters for valves, flanges, and vessels that are on the low temperature side of a molten salt system. I recommend their use wherever possible if their advertised temperature-use-limit is not exceeded. I recommend a cost analysis comparing MI cable to band, ring, or strip heaters. Information on failure rates is not available for the band, ring or strip heaters, but our experience with band heaters on a few valves and flanges has been good. The only failures have occurred in areas where the terminals were exposed to rainwater. Tubular heaters should not be used on small components.

The use of immersion heaters should be avoided in tanks and vessels containing molten salts. Without extensive long-term data on the corrosion of specific heater sheath materials, the immersion of thin-walled heaters in salt is not advised. External heaters should be used on tanks and vessels wherever possible to avoid the potential of in-salt corrosion problems.

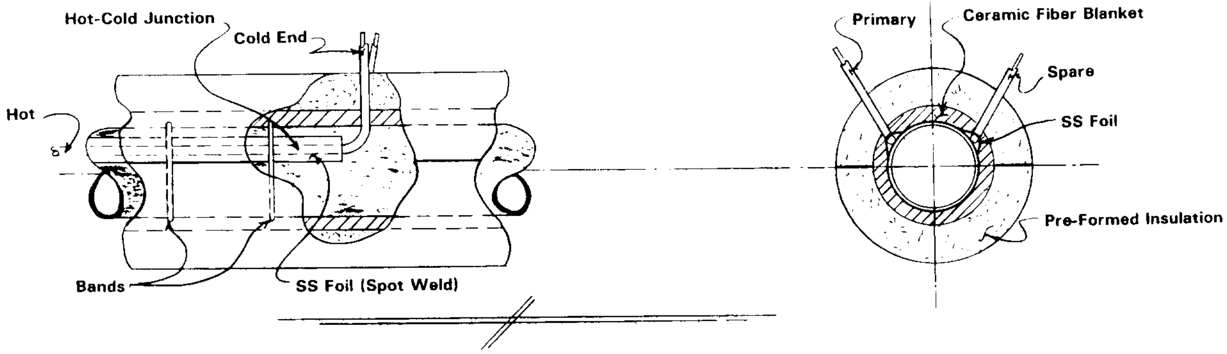
An induction trace heating system[7] should be considered in the reliability/cost analysis for trace heating full scale central receiver power plants. Such a system has proven to be highly reliable and easily maintained at EBR II for more than 20 years in both indoor and outdoor environments (Southeastern Idaho). The induction heating system probably is not warranted for laboratory or pilot-scale molten salt systems.

Installation

Tubular heaters and MI cable heaters should be secured to the component at 1-ft or less intervals by stainless steel bands or wires.

The heating element should be covered by 0.002- to 0.004-in.-thick stainless steel foil. Placement of the hot-to-cold junction of MI cable elements should be in accordance with the manufacturer's recommendations. For all tubular elements, the cold end should pass through the insulation so that the electrical power connection can be made outside the insulation. The hot-to-cold junction of MI cable to be located outside the insulation should have the end of the hot section pass through the insulation in a loose-fitting sleeve of stainless steel foil. These recommended installations are shown schematically in Figure 2.

Typical Tubular Heater Installation (or Welded-Junction MI Cable)



Typical Mineral-Insulated Cable Installation (Brazed Hot-to-Cold Junction)

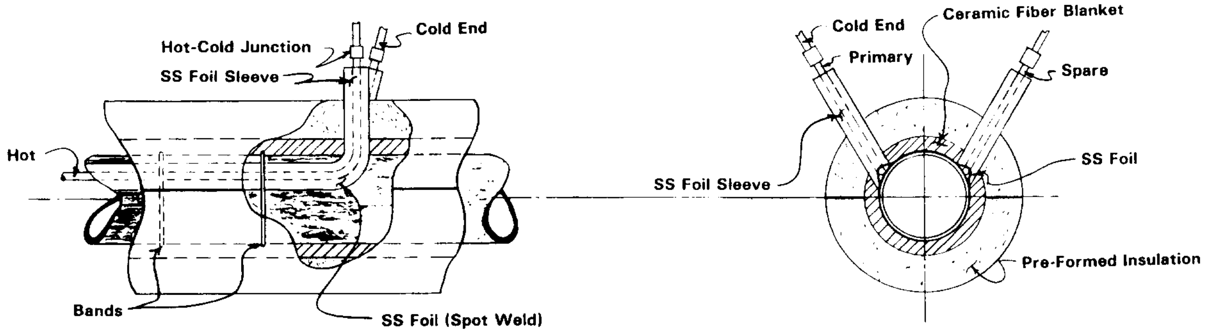


Figure 2. Recommended Installation of Typical MI Cable Heaters and Tubular Heaters

Bends in tubular heaters or MI cable should be minimized. Once tubular heaters or MI cable have been bent, they should not be straightened or bent again. If possible, bends should be in the cold ends only. All bends should be no less than twice the minimum bend radius recommended by the manufacturer.

Heaters and their terminations should be located for ease of maintenance and repair, whenever possible. If the component is inaccessible, additional spares should be installed or the heating elements should be derated by more than 50%.

Controls

Active control of the electric power is recommended because active controls accommodate ambient temperature and wind effects. Always-on control should be used only if the heated component is in an area not subject to environmental changes. The active control system should sense the component temperature and provide only the required power to maintain the desired temperature. I am not aware of any studies that link the type of active control system to the length of heater life. In all the ETEC heater life studies, simple on-off control was used with the on-cycle at or near the heater elements' rated voltage. ETEC prefers the use of commercially available time-proportioning automatic controllers for operating systems. These controllers essentially drop (or add) cycles from (or to) the 60-Hz wave form to supply the power to maintain a selected temperature. In effect, these are very rapid (fractions of seconds) on-off cycles. This kind of power cycling probably does not induce measureable thermal cycles in the heating element wire or in its hot-to-cold junction. In the absence of other information, I recommend the use of commercially available time-proportioning active heater controls for all trace heating zones.

For temperature control feedback, mineral insulated, stainless-steel sheathed, ungrounded thermocouples with weld-pad ends should be used. A spare should always be installed. The weld pad should be tack welded to the component. For long runs of pipe, multiple thermocouples should be used (15- to 20-ft spacing) and incorporated into an "or logic" control system. The "or logic" will act on the lowest temperature along the line and will reject signals from failed thermocouples. A high limit should be provided by the control system.

Each individual component (valve, vessel, instrument, etc.) and section of pipe should have a dedicated heater power control. A ground fault interrupter should be included in the power wire circuitry for each heated zone.[9]

Insulation

Insulation thickness should be predicted by standard engineering practices that account for the desired temperature and both the ambient temperature variations and winds at the site of the installation.

Care must be taken to prevent heat loss due to convection inside the insulation. Convection blocks must be provided along the axis of the pipe or component. A good way to accomplish this is to use a compressable ceramic fiber blanket (8 lb/ft^3) as the first layer over the heating element and its foil cover. A small piece of the same material should also be used inside the foil at 3-ft intervals to prevent gross axial convection inside the foil.

The remainder of the insulation layers may be made of blanket or preformed calcium silicate. Care must be taken to use thin layers (2-in. maximum) with overlapping radial and axial joints. Elbows, valves, and other odd-shaped components should be insulated totally with overlapping ceramic fiber blanket. Hand-mitered, preformed insulation should not be used on these irregular components in a molten salt heat transport system.

The outer surface of the insulation should be covered and waterproofed.

Special attention must be given to pipe and other equipment supports. Commercial products are available that thermally isolate the trace heating component from other structural components. These devices normally use a hard, thermal insulating material inside a holder to carry the structural load.

Wind shields must be provided for all valves and other components that have noninsulated parts exposed to the environment. The effect of wind has been shown to be difficult to accommodate even with an overinsulated component using an active electric power control scheme.

Other Recommendations

I also recommend the following long-range considerations for the molten salt central receiver heating problem.

1. Should the American Society for Testing and Materials (ASTM) ever reissue its currently inactive standard (E 420) for tubular heaters, it should be used as part of the specification for purchasing heating elements. But many quality issues must be resolved before the standard can be reissued, and the ASTM moves slowly at best.
2. Options to electric resistance trace heating should be studied. Obvious options that may be worth investigating are
   - Use inductive heating on large-scale salt piping systems (EBR-II experience)
   - Use steam or other high temperature heat transport fluids for trace heating
   - **Eliminate trace heating for large-diameter pipes**
   - **Operationally add heat with the solar receiver or other auxiliary heater and drain the system only in emergencies. This would require only a relatively low temperature, normally off, start-up heating trace.**
3. A test program should be considered to evaluate MI cable and tubular heater products from a larger number of manufacturers and to establish failure rates for band, ring, or strip heaters in typical applications.

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